

TERRI COBBETT

Shore-based laboratories are located in the village of Woods Hole and on the 200-acre Quissett Campus a mile and a half away.

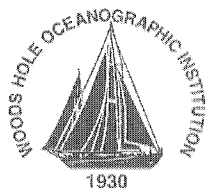
The Woods Hole Oceanographic Institution (WHOI) is a private, nonprofit research facility dedicated to the study of all aspects of marine science and engineering and to the education of marine scientists and engineers. With staff and students numbering about 1,000, it is the largest independent oceanographic research institution in the nation.

Most WHOI investigators are based in five scientific departments: Applied Ocean Physics & Engineering, Biology, Geology & Geophysics, Marine Chemistry & Geochemistry, and Physical Oceanography. Others work at the Marine Policy Center, where social scientists consider economic, legal, and policy problems associated with human use of the oceans. The Coastal Research Center

provides an umbrella for investigators from various disciplines to cooperatively study processes in nearshore waters.

More than 350 WHOI research projects are under way at any given time. About 80 percent of the operating budget comes from federal contracts and grants, and the remaining 20 percent is provided by private sources. The Institution operates three research vessels, the submersible *Alvin*, and a variety of autonomous and remotely controlled vehicles as well as a fleet of small boats. About 140 students are enrolled in the Institution's joint graduate program with the Massachusetts Institute of Technology, and other education offerings include Postdoctoral and Summer Student Fellow programs.

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1995 Annual Report

Woods Hole Oceanographic Institution

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Front Cover: R/V Knorr undertook an extensive survey of the Indian Ocean for the World Ocean Circulation Experiment Hydrographic Programme from December 1994 to January 1996. The cruise track covered more than 50,000 miles from antarctic ice to the southwest monsoon area off Oman. Investigators from 7 nations and 26 institutions collected more than 400,000 water samples from 1,244 stations.

Back Cover: Submersible Alvin is lifted aboard support ship Alantis II following a dive. Photo by Craig Dickson

Woods Hole Oceanographic Institution

1995 Annual Report

Comments from the Director

The year 1995 was witness to many successes, opportunities, and challenges. In the last Annual Report, I commented that our biggest challenge for 1995 was developing a trusting and respectful relationship with the new national leaders in a time of change for the National Science Foundation, the Navy, and the US Congress. By working with various groups within the oceanographic community and with the commitment to keep science and engineering research highly placed in the national agenda, we made significant strides in 1995 toward articulating to the country and the Congress the importance of ocean science and engineering research and education. We have worked hard to establish with our Washington partners a collaborative foundation composed of shared goals for the nation and a respect for the importance of investing in the future through commitment to research and higher education.

During 1995 we initiated a strategic planning exercise to identify the key elements of a future vision for WHOI. Through this process we articulated as our vision an institution that will achieve world-class science and engineering research, technology, seagoing capability, and graduate and postdoctoral education in an environment where independence, creativity, and innovation flourish. We also identified key strategic issues inherent to achieving this vision:

- maintaining an environment that attracts and keeps the best people by nurturing their creativity and competitiveness,
- communicating the importance of the oceans to the public and to Congress and federal agencies, and



Director Robert B. Gagosian

- doing both of these well in a world with reduced funds from traditional sources.

Successfully working through these issues will remain a key objective for at least the next few years. We have, however, achieved significant strides in 1995, not only in our external articulation of the case for research and education, but also internally as we continue to reshape and refine the way we do business so that we can continue to operate at maxi-

mum efficiency in our changing environment.

Our superb ability to access the sea made 1995 one of our most productive seagoing years. A significant accomplishment was the 3,000th dive of our famous submersible *Alvin*. We are very proud of the skills and dedication of the *Alvin* group, which over the sub's 32-year career has completed more than 90 percent of scheduled dives, a record unsurpassed by any other submersible. R/V *Knorr* logged more than 50,000 miles crisscrossing the Indian Ocean between December 1994 and January 1996 for the World Ocean Circulation Experiment, and, after its midlife refit, R/V *Oceanus* returned to serving science in first-rate form. The ship's increased laboratory space and scientific berthing have really made a difference.

In the meantime, construction of



Barrie Walden, back to camera, introduces California Congressman Jerry Lewis, second from left, to the autonomous vehicle ABE during the Congressman's September 1995 briefing visit to WHOI. Lewis is chair of the House Appropriations Committee for Veterans Affairs, Housing and Urban Development and Independent Agencies, including the National Science Foundation. Lewis's chief of staff Arlene Willis and Dick Pittenger are at right.

Director's Comments

our new research vessel, *Atlantis*, continues on time and with skill. We look forward to its spring 1997 arrival and are very pleased that it will be the support ship not only for *Alvin* but for the world's most advanced remote and autonomous deep submergence technology. It will, indeed, be a vessel with a unique capability that clearly supports our vision of the WHOI of the future. Overall, our fleet has not been in better shape.

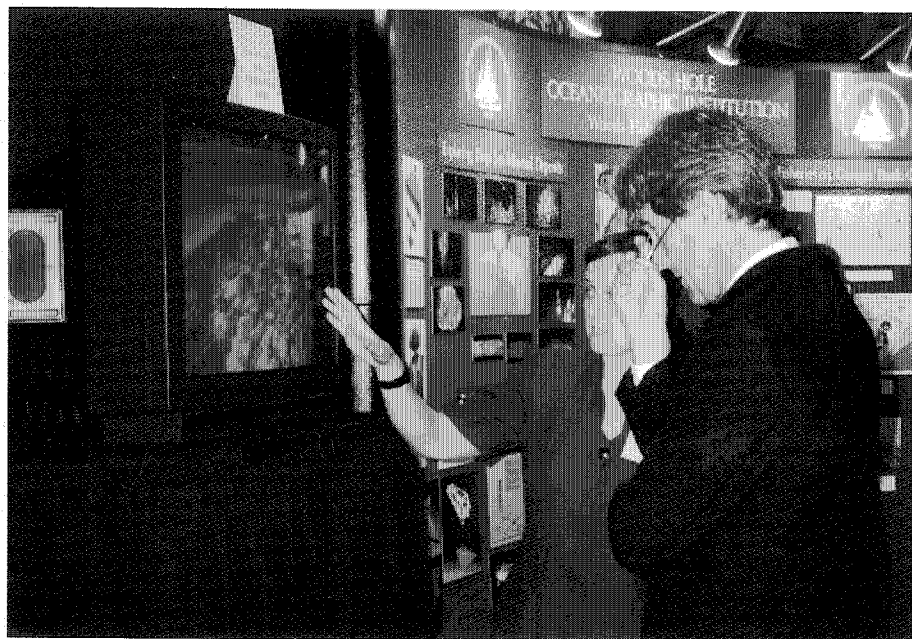
The year 1995 also heralded the end of a decade of dedicated and unwavering leadership from our Chairman of the Board, Guy W. Nichols. From 1985 to 1995, Guy enthusiastically supported the Institution in its most important challenges. We heartily thank Guy for his wisdom and foresight, and look forward to continuing a rewarding association with him. Frank V. Snyder succeeded Guy as Chairman in May 1995. No stranger to either leadership or the taking of helms, the former Commandant of the New York Yacht Club has already earned trust and respect within the Institution, and he continues to inspire us with his earnest and straightforward "can do" approach. We are, as an Institution, in good hands.

The Capital Campaign is progressing very successfully toward its \$50



TOM KLEINDIENST

Bob Gagosian presented the tenth B.H. Ketchum Award to Christopher Martens of the University of North Carolina at Chapel Hill in April 1995. The award cites Martens's innovative work on the biogeochemical recycling of carbon in coastal systems as well as his leadership in the scientific community, inspiration to younger colleagues, and translation of research results into the policy arena.



SHERLEY LAUZON

A display prepared for a May 1995 Congressional reception at the Smithsonian Institution's Museum of Natural History Ocean Planet exhibit featured several aspects of WHOI research. Here Susan Humphris describes hydrothermal vent work to Massachusetts Senator John Kerry at the reception.

million goal. Over \$8 million was raised in 1995, bringing the current total of secured or committed funds to nearly \$42 million. We are especially grateful that the dedication of our Trustees and Corporation Members continues to have a significant Campaign impact.

We are proud to announce the commitment of matching funds to meet the spring 1995 challenge of Charles F. Adams, who served as Chairman of the Board from 1973 to 1985. He offered the Campaign's first Senior Scientist Chair and challenged fellow Trustees and Board members to match it with two additional chairs. We were delighted that Walter A. and Hope Noyes Smith were the first to accept this challenge, and are pleased that details for the third chair are being worked out. This match increases the total number of WHOI research chairs from six to nine, a very exciting advance for WHOI science. In addition, the generosity of the Richard K. Mellon Foundation gave us the opportunity to announce that, for the first time in WHOI history, our long-term commitment to engineering and instrumentation development will be supported

through nine three-year awards to members of the senior Technical Staff. This dovetailing of our Campaign with strategic planning is most rewarding.

As Director of this great Institution, I firmly believe that the key to our continuing success is the integration of mission and vision in the planning process. It is essential that we focus on what we want this Institution to be in the future and not that we merely react to the uncertain budgetary situation in Washington. We must concern ourselves with the highest standards of excellence in all that we do, and we must continue to work hard to convince the public and the Congress that it is important to place science and engineering research and education high on the national agenda. If we keep focused and stay deliberate, the future will be ours to shape. I look forward to continuing to work on this challenge.

A handwritten signature in dark ink, reading "R. B. Gagosian".

—Robert B. Gagosian
Director

1995 was a remarkable year for ocean sciences and research at the Woods Hole Oceanographic Institution. Federal support of fundamental global change research reached a new level as many programs developed during the 1980s were engaged in active fieldwork at sea, representing perhaps the largest concentration of seagoing observations in decades. Innovative technology, such as the Autonomous Benthic Explorer (ABE) saw its first use in the field, while many other programs continued their evolution.

In most cases, an observational program in the field or the first deployment of a new instrument culminates five or more years of design and analysis effort involving many colleagues and co-workers. The scientists are testing their model or understanding of ocean/earth processes against the real ocean, and this is often a difficult and unpredictable process. The ocean offers an uncompromising and unforgiving environment for observing Earth's intimate processes. Once an observational program is complete, an entirely different phase begins, that of analyzing and synthesizing the research. Most scientists and engineers have several projects and programs in various stages along this continuum, with a mixture of tasks all under way at the same time: design of future research, current fieldwork, analysis, and synthesis.

The Global Change Initiative began in the early 1980s with the fundamental concept that Earth's climate as well as its physical, chemical, and biological processes could only be understood by taking a global perspective. Ocean, atmosphere, and land systems were known to be strongly coupled and interacting, but new observational tools that would allow such a global perspective were just beginning to be available. The World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux Experiment (JGOFS), the Ridge Interdisciplinary Global Experiments (RIDGE) and the Global Ocean Ecosystems Dynamics Program (GLOBEC) were all spawned

from these ideas, and all are now in various stages of intensive fieldwork.

WOCE and JGOFS completed major field programs in the Indian Ocean during 1995, observing an oceanwide view together with an intensive study of the response of the Arabian Sea to strong atmospheric forcing by the monsoons. The cover features R/V *Knorr's* extensive Indian Ocean WOCE Cruise. Many of our scientists and research groups also participated in JGOFS and RIDGE cruises during 1995 in the Indian and Pacific Oceans. The initial phase of GLOBEC, which involves a detailed study of the physical, chemical, and biological environment that comprises the fisheries ecosystem on Georges Bank, was under way in the Atlantic aboard *Oceanus* and other ships. This will likely be a model for subsequent studies, since it represents the first time that a broad suite of environmental observations has been made simultaneously on the same spatial and temporal scales.

The mix of research programs funded at the Institution is rich and varied. During 1995, our staff produced 399 publications in 123 different journals. There were 375 active research grants, while 695 proposals were submitted to various Federal and other agencies. As the competition for Federal research support becomes more intense, more time is spent writing proposals. Taken to extremes, this process erodes a principal investigator's most precious time—that for reflection and synthesis, which is the breeding ground for new ideas and fresh perspectives. Funding for this “thinking time” through Institution endowment of scientific chairs and direct Assistant Scientist support is critical to the health and well-being of the Institution's mission of excellence in research and education in ocean sciences and engineering.

The quality of our Scientific and Technical Staff is extraordinary. The essential criterion for promotion is excellence in the quality and impact of the individual's scientific research and/or engineering. Numerous awards received in 1995 by members of the Scientific Staff are detailed in the departmental reports that follow. Perhaps the most prestigious of these are award of the American Meteorological Society's Sverdrup Gold Medal to physical oceanographer Jim Price and election of microbiologist Holger Jannasch as a Foreign Associate of the National Academy of Sciences.

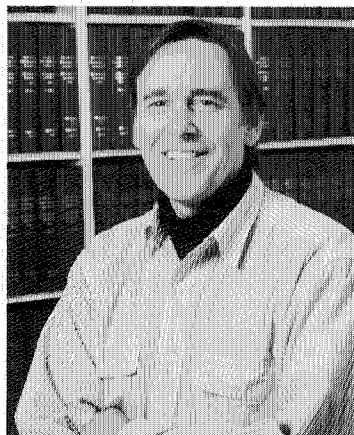
The newfound zeal in Congress to balance the Federal budget has put enormous stress on funding for scientific research. This comes at a time when the public's interest in and appreciation of the value and importance of fundamental science to the nation is low. The priority of funda-

mental research, and of ocean sciences in particular, as vital to national security was taken for granted for several decades, and now is a matter of intense debate. Institution staff and management are both actively involved in this debate, participating with national organizations, such as the Consortium on Ocean Research and Education, in stress-

ing the role of ocean sciences in the national research agenda. Much of this activity involves articulation of the excitement and importance of ocean sciences as key to understanding Earth's climate and general habitability. Oceanography is a science of discovery, and one in which the role of direct observation at sea is critical to uncovering the principles and underlying processes that control the evolution of the atmosphere and ocean and land ecosystems.

—James Luyten

Associate Director for Research



Associate Director for Research
James Luyten

Applied Ocean Physics & Engineering Department

The Applied Ocean Physics and Engineering (AOP&E) Department, with 146 staff members and 34 graduate students, had a very productive year in 1995. Forty-three principal investigators led 128 basic and applied research projects in ocean acoustics, coastal and ocean fluid dynamics, air-sea interaction, ocean systems and moorings, deep submergence, and oceanographic instrumentation.

Personnel actions included the promotions of ocean physicists Rocky Geyer and John Trowbridge and engineering scientist Mark Grosenbaugh to Associate Scientist with Tenure. In addition, meteorologist Jim Edson and acoustical oceanographer Tim Duda were promoted

to Associate Scientist, and electrical engineer Ned Forrester to Senior Engineer. There were two notable retirements on the senior engineering staff. Principal Engineers Neil Brown and Don Koelsch were honored at a joint retirement event that recognized their pioneering contributions to the design and development of oceanographic and geophysical instrumentation.

Robert Ballard was the recipient of the Explorer's Club medal in 1995.

AOP&E research and development activities encompass laboratory experiments, field programs, and theoretical work. Three projects representative of these efforts are described here.

Autonomous Benthic Explorer Makes First Science Dives

The Autonomous Benthic Explorer (*ABE*) can survey the seafloor to depths of over 5,000 meters. Designed to complement WHOI's existing vehicles such as *Alvin* and *Jason*, *ABE* operates without a tether or human supervision. As its capability evolves, *ABE* will be available to observe time-varying phenomena lasting from days to months, particularly in active hydrothermal vent areas.

During the summer of 1995, *ABE* successfully completed its first set of science dives on the Juan de Fuca Ridge at depths to 2,400 meters. Many of *ABE*'s features were proven from an engineering perspective, and *ABE* made maps of seafloor magnetic anomalies (see article on page 13), took video snapshot images of the new lava terrain, and mapped the conductivity and temperature of an active hydrothermal vent. *ABE* operated from *Atlantis II*, utilizing the nighttime periods between *Alvin* dives.

Each dive began with a controlled descent to a specified spot on the seafloor. Navigating by the same acoustic transponders *Alvin* uses, *ABE* took about two hours to reach the seafloor. While the vehicle could not be controlled from the surface, its movements could be observed from the ship through the transponder navigation system. *ABE* sent out a



Scientists and crew launch *ABE* from *Atlantis II* during the vehicle's first science dives in the summer of 1995.

DOWNRIGHT

coded acoustic signal to indicate when it had successfully reached the bottom and again when it had released its descent weight and started its mapping run.

To map the lava terrain, *ABE* executed a sequence of tracks, each at constant heading and constant forward speed. The vehicle could run at constant depth, or it could follow the bottom using a single beam fathometer and a control algorithm to ascend, descend, or slow down to maintain a preset height off the rugged seafloor. At the end of the prescribed set of tracklines (lasting up to three hours), *ABE* dropped its ascent weights and headed for the surface. The scientists recovered *ABE* at first light, read the data files, charged the batteries, and prepared for the next mission.

ABE's final dive of the series, to the edge of a hydrothermal plume previously discovered using *Alvin*, was perhaps the most exciting. The vehicle executed an expanded survey pattern while negotiating the most rugged terrain it had experienced. After the dive, *ABE*'s temperature and bathymetry data revealed a large diffuse plume centered over a graben, or shallow valley. The vehicle's video showed the lava terrain as well as the hydrothermal plume.

ABE's first science mission produced detailed maps of 35 kilometers of bottom tracks during seven dives, and provided detailed records of vehicle performance. Based on this success, *ABE*'s designers and developers, which include Dana Yoerger, Al Bradley, and Barrie Walden, plan to extend *ABE*'s endurance in order to capture long-term, dynamic events.

Improving Weather Forecasts with Better Marine Measurements

Numerical weather forecasts have markedly improved over the past several decades. Unfortunately, there are still times when the model predictions lead to inaccurate forecasts.

Ongoing improvements to these models and their forecasts involve three major areas of research:

- development of faster computers that would allow modelers to include more physics and higher resolution,
- planning for a better and denser network of surface and upper air observations to initialize these models, and
- improvements to the way we include processes that even high-resolution models cannot resolve.

With or without better computers,

accurate prediction of weather over the sea would greatly benefit from any improvements in the last two categories. Weather observations over the world's oceans are sparse, and modelers must work with little or no information from vast regions of the ocean as they initialize forecast models. In addition, the fluid ocean surface presents unique challenges to marine researchers attempting to describe ocean/atmosphere coupling.

With support from the Office of



CARL FRIEHE UC-IRVINE

Jim Edson examines a 50-foot mast deployed off *FLIP*'s port boom for his spring 1995 work in the Pacific with Carl Friehe and Scott Miller (University of California, Irvine). Along with colleagues from Scripps and New Zealand they are using their measurements to investigate ocean/atmosphere coupling.

WHOI Scientists Worked Aboard *FLIP* in 1995

Erik Bock and Jim Edson worked aboard *FLIP* (Floating Instrument Platform) on two different research projects in 1995. The 355-foot (108-meter) *FLIP*, operated by the Scripps Institution of Oceanography, is ingeniously designed with hinged equipment that can be used with the vessel in either its horizontal or vertical position. *FLIP* is towed to a research site where ballast tanks are flooded with 1,500 tons of seawater to "flip" it to the vertical position (while scientists and crew literally "walk up the walls" to stay upright). With only 55 feet (17 meters) of the vessel above the surface and the remaining 300 feet (91 meters) extending into the stable water column, scientists can pursue their measurements almost unaffected by surface motion. This allows many scientific measurements that would be difficult or impossible to make from a conventional research vessel. At the end of the experiment, which may last up to the 35 days, compressed air is blown into the ballast tanks, and the vessel returns to its horizontal position.

Naval Research (ONR), marine meteorologist Jim Edson is actively involved on both of these research fronts. As part of ONR's High Resolution program, he and his colleagues have been working to improve the way scientists estimate surface winds over the open ocean from satellites. For example, radars can be used to infer wind speed and direction by bouncing (scattering) microwaves off the ocean surface. Basically, the method relies on the observation that, in general, the higher the wind speed the rougher the ocean surface, and the rougher the ocean surface the larger the returned (backscattered) signal. Edson and his colleagues are refining this simple concept to improve the accuracy of these observations and widen their application.

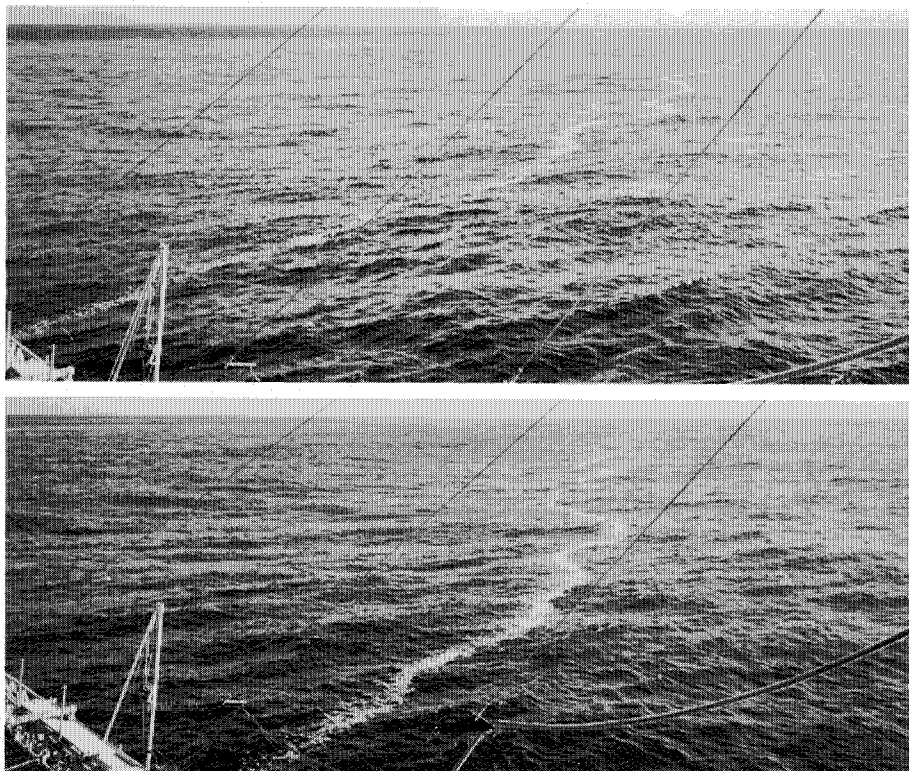
Over the past three years he has also been working with a team of US and European researchers to investigate how ocean waves influence the behavior of near-surface atmospheric turbulence. In the spring of 1995 he spent a month off the Monterey coast aboard the research platform *FLIP* with Carl Friehe and Scott Miller (University of California, Irvine) as part of ONR's Marine Boundary Layers program.

Once "flipped," Edson and Friehe assembled a heavily instrumented 50-foot mast that they deployed off *FLIP*'s port boom. Their instrumentation allowed them to measure the wind profile and the transport of energy and momentum to and from the ocean surface. Additional measurements made aboard *FLIP* included radar images of the sea surface by researchers from the University of Massachusetts and New Zealand's National Institute of Water and Atmospheric Research, Ltd., and upper ocean measurements by the Scripps scientists. The researchers are currently combining all the *FLIP* measurements in order to describe the coupling of the atmospheric and oceanic boundary layers.

Experiment Compares Direct and Radar Measurements of Internal Waves

Erik Bock also worked aboard *FLIP*, participating in the Coastal Ocean Process Experiment (COPE) off the Oregon coast, near the towns of Garibaldi and Tillamook. This experiment, sponsored by the Department of Defense and conducted by the Environmental Technology Laboratory located in Boulder, Colorado, was designed to learn how radars image internal waves. Internal waves propagate beneath the sea surface at the depth where there is a difference in density between lighter surface water and the heavier deep waters. The density difference is caused by temperature or salt concentration differences, or a combination of these. Resulting internal waves can produce current surges that cause the short surface waves to "bunch up" and become unusually rough. This roughness can be measured both directly and by radars.

For the direct measurements from *FLIP*, Bock used a specially designed 18-foot research catamaran, equipped with an instrument that directly measures the short waves that are affected by internal waves. The catamaran was moored between *FLIP* and a separate, anchored buoy. A multi-week experiment allowed a comparison between direct measurements of waves at the *FLIP* site and remote measurements by radars mounted on top of Onion Hill 14 miles away on the Oregon coast. The two photos below show the passage of an internal wave as photographed from *FLIP*. The two images, taken a few minutes apart, show that the internal wave (evidenced by the brighter band of short, breaking waves extending off in the distance) traveled an appreciable distance between the two photographs. Radar measurements, because they have greater spatial coverage, can be useful in relating observations that span kilometer scales to ocean properties like bathymetry. Results from the radar experiment are not yet available.



Two photos taken a few minutes apart from *FLIP* show the surface effect of an internal (subsurface) wave.

Biology Department

Scientists in the Biology Department continue to carry out a rich and diverse research program on marine organisms from virtually all the world's oceans, oriented both to organismal and process studies. In the current difficult funding climate, staff scientists have been successful in diversifying their research interests and obtaining funding from numerous sources. In particular, the staff is well represented in the major global oceanographic research initiatives including the US Global Ocean Ecosystems Dynamics Program, the Joint Global Ocean Flux Study, and the Ridge Inter-Disciplinary Global Experiments Initiative.

Michael Moore, a 1991 MIT/WHOI Joint Program graduate and recent Visiting Investigator, was appointed to the Technical Staff as Research Specialist to continue his work on fish and mammal toxicology. Overall, the activities of 25 scientific staff members, 13 technical

staff members, 8 postdoctoral scholars and investigators, 34 students, and 30 support personnel resulted in 58 publications and 116 proposals submitted in 1995.

Notable achievements for the year included election of Holger Jannasch to the National Academy of Sciences as a Foreign Associate, Judy McDowell's fellowship award in the Pew Scholar Program in Conservation and the Environment, and Mark Hahn's becoming a full member in the Society of Toxicology. In addition, Freddy Valois received WHOI's Linda Morse-Porteous Award.

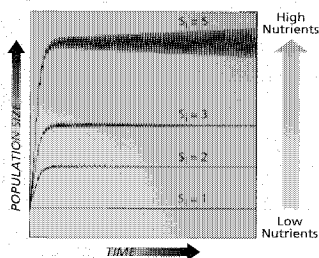
Sadly, we report the passing of Scientist Emeritus Stanley Watson, who first joined the Biology Department in 1956. He was instrumental in helping develop the microbiology and molecular programs in the department, and he established the Stanley W. Watson Chair for Excellence in Oceanography, whose current recipient is department member Don Anderson.

Exploring the Role of Life Cycles in Population Dynamics

Populations change because of the birth and death of individual organisms, and the probabilities of birth and death change as an individual develops through its life cycle. This means that mathematical models of population dynamics must include some description of the life cycle in order to capture the mechanisms responsible for population growth or decline. Situations where the environment impinges directly on the life cycle are especially interesting. With funding from the Office of Naval Research, Environmental Protection Agency, and National Science Foundation, Hal Caswell studies such problems in a variety of specific applications. For example, suppose that a population is exposed to a pollutant. The exposure will produce a complex set of cellular and biochemical responses that affect individual survival, growth, maturation, and reproduction—and, eventually, the growth of the population, causing

either a decrease or, in the case of some pollution-tolerant species, an increase.

Working with Lisa Levin (a former WHOI Postdoctoral Fellow now at Scripps Institution of Oceanography), Caswell analyzed an experiment on two estuarine polychaetes (*Streblospio benedicti* and *Capitella* sp.1) exposed to fuel oil, sewage sludge, and blue-green algae (all common hazards for species living in polluted or eutrophied estuaries).

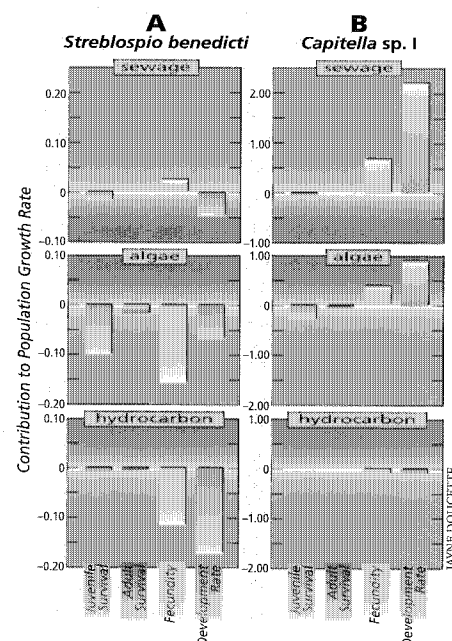


Output from a phytoplankton population growth model that includes the cell division cycle. High nutrient levels produce "generation cycles," oscillations that do not occur in traditional models, which neglect the cell cycle.

decline in *S. benedicti* growth rate was a reduction in fecundity, while the increased growth rate in *Capitella* was mostly due to more rapid development. Pinpointing the physiological mechanisms responsible for

population-level responses to pollutants is one of the major benefits of this kind of mathematical modeling.

Although polychaetes and other multicellular animals are known to have interesting life cycles, what about the single-celled organisms of the phytoplankton? Their life cycles



Pollution by blue-green algae had different effects on the population growth of two species of polychaetes in the laboratory. *Streblospio* populations grew more slowly, mainly because of reductions in fecundity (left graph). *Capitella* populations grew more rapidly, mainly because of increased development rate.

are defined by the cell division cycle: growth, replication of genetic material, and division. There is evidence that the environment, in the form of nutrients and light, affects the rate of development throughout this cycle. Caswell and Joint Program student Mercedes Pascual-Dunlap analyzed the effects of such environmental factors on models of phytoplankton population dynamics. What they found were populations with an increased tendency to oscillate. Nutrient limitation sets up cohorts of hungry cells that develop slowly, thus reducing population growth and allowing nutrient levels to rise. The next cohort of cells benefits from these nutrients and moves rapidly through the cycle, the population increases, and nutrient levels decline, setting the stage for a repeat of the

cycle. When these “generation cycles” interact with environmental variation, the result can be complicated, aperiodic fluctuations in phytoplankton populations, fluctuations that occur only because of the interaction of the environment and the life cycle.

Modeling of population dynamics in terms of individual movement through the life cycle has broad application, including analysis of field and laboratory data and studies of a wide range of organisms both small and large. Caswell has examined larger animal population dynamics in considering the effect of the sink gillnet fishery on the Gulf of Maine harbor porpoise population and is currently seeking funding to analyze the populations of the North Atlantic right whale, the most endangered of the large whales.

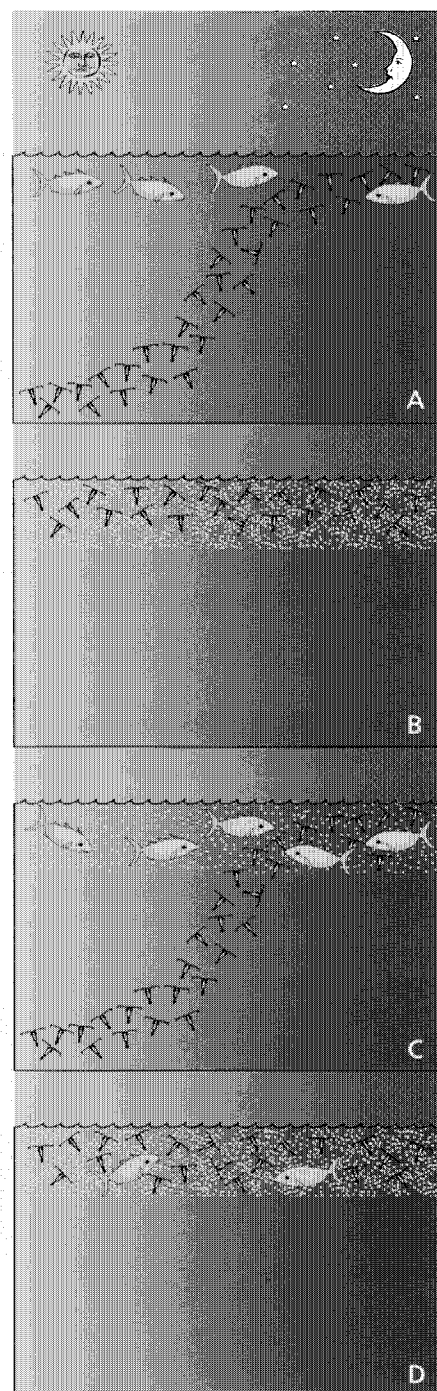
Diel Vertical Migration in Zooplankton: Trade-offs Between Predators and Food

Why do so many aquatic organisms, including zooplankton, undertake vertical migrations of tens to hundreds of meters between deep, darker waters during the day and surface waters at night? The answer to this question has long eluded scientists, despite the fact that this behavior, known as diel vertical migration, has been recognized for over a century as one of the most conspicuous and important types of animal migrations on earth. Recent experiments by Steve Bollens and collaborators at the University of Washington and the Max Planck Institute of Limnology shed new light on this enigmatic phenomenon.

Bollens and his colleagues borrowed from a theory developed primarily by terrestrial ecologists that predicts individual animals should select a habitat or set of habitats (or depths, in the case of zooplankton) that allows them to maximize energy gain via feeding (such as on algae) while minimizing the probability of death via predators (such as fish). To test this intuitively appealing theory, the researchers designed two experiments. The first test was based in a

marine lagoon in 1994 on San Juan Island, Washington, where large (3-cubic-meter) plastic enclosures contained the marine copepod *Acartia hudsonica*. More recently the scientists worked with the freshwater cladoceran *Daphnia hyalina* in the 11-meter-tall “Plankton Towers” at the Max Planck Institute in Germany. US funding for this work was provided by the National Science Foundation and the Office of Naval Research. In both systems the abundances of algae and predatory fish—which could be quantitatively related to feeding gains and the probability of predation mortality, respectively—were manipulated in the experimental containers.

Both types of zooplankton behaved largely as the theory predicted. Manipulations of either fish or algae alone triggered migratory and nonmigratory behavior, respectively. That is, in the presence of fish, zooplankton entered food-rich surface waters only under cover of darkness, when risk from visual predators such as fish was low. However, in the presence of abundant food but no fish, zooplankton remained in the surface layer day and night. A more interest-



Zooplankton in experimental chambers exhibit diel vertical migration in the presence of visual predators such as fish to avoid being eaten during the day (A), but remain in the surface day and night to feed on algae (green dots) when fish are absent (B). Moreover, zooplankton can make subtle trade-offs between the risk of predation and the benefit of feeding when both food and predators are present, such as occurs in nature—zooplankton migrate under conditions of low food and high fish abundance (C), but are nonmigratory under conditions of high food and low fish abundance (D).

JACK COOK

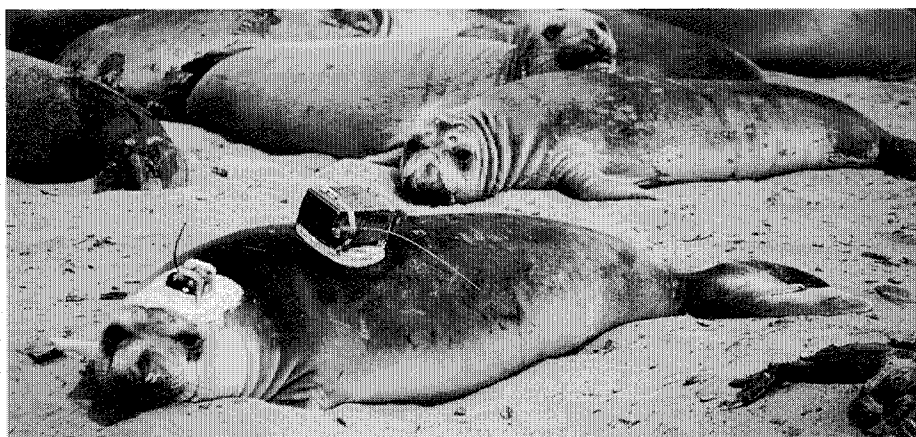
ing result emerged in the subtle interactions between fish and algae when both were manipulated simultaneously: Diel vertical migration was triggered only under precise conditions of high fish and low food abundance, whereas slightly lower fish abundance and slightly higher food abundance resulted in nonmigratory behavior. In short, individual zooplankters seemed to choose to reside in particular depths at particular times of day and night based on subtle trade-offs between gains from feeding on algae and the risk of being eaten by fish.

There is much more to be learned about different behaviors of aquatic animals, including diel vertical migration, and collaborations between experimentalists and theoreticians that cut across marine, freshwater, and even terrestrial systems may prove to be a particularly effective approach.

New Data Logger Tells How Seals Hear The World

For tens of millions of years, marine mammals have been evolving ways to take advantage of ocean acoustics. Whale sounds below the human range of hearing are used for long range communication, and dolphin clicks octaves above it are used to find sonar targets a football field away. In the past 50 or so years, humans have also begun to use underwater sound for communication, to navigate, and to find out about the oceans. This can lead to problems if both humans and marine mammals are trying to use the same channel, for an oceanographer's signal may be a whale's noise. Very loud sounds from underwater explosions, shipping, and industrial activity could harm these animals or disrupt biologically important activities.

The Office of Naval Research (ONR) has initiated research programs both to find out about the influence of low frequency sound on marine mammals and to build research tools for questions that cannot yet be addressed. Peter Tyack is

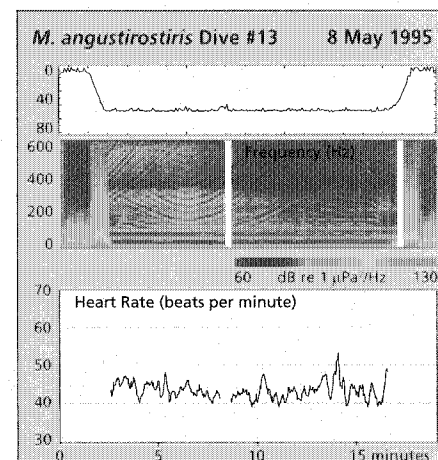


An elephant seal is equipped with a unique data logger for studies of sounds marine mammals make and hear in their native environments. The logger is removed after the seal returns to the beach, and tagged seals show no ill effects from carrying this package.

participating in a study of elephant seals, which produce low frequency sounds in air and whose ears appear to be specialized for low frequency hearing. In collaboration with Burney LeBoeuf and Daniel Costa (University of California, Santa Cruz) and 1993-1994 AOP&E Postdoctoral Scholar Bill Burgess (Monterey Bay Aquarium Research Institute), he has led a development many thought impossible—a hydrophone tag for recording in the ambient environment sounds heard and made by a free-ranging marine mammal.

The May 1995 photo above shows the first acoustic data logger deployed on an elephant seal (*Mirounga angustirostris*) on the beach. The seal was transported to the southern end of Monterey Bay, where the logger was started and the seal was released. The device logged swimming speed, depth, temperature, and acoustic data below 1 kilohertz from every fourth dive as the seal swam back to its rookery north of Monterey Bay. The figure at right shows a sound spectrogram, a plot of sound frequency against time, during one dive to 60 meters. The seal's breathing on the surface is indicated in red at left and right. Flow noise increases as the seal dives; augmenting the time resolution of this segment reveals each flipper's swimming strokes. At the bottom of the dive, the logger registers noise as faint as 60 decibels. The one elephant seal

whose hearing has been measured at 100 hertz could not hear sounds this faint, indicating that the scientists can hear everything the diving seal hears at this frequency. The pattern of blue and green lines in the middle of the spectrogram indicates a boat passing above the seal, and the data include many different ambient noises. When the seal was quiet at the surface or bottom of a dive, there is a signal that sounds like heart beats, and the data points at the bottom of the figure show the heart rate of the seal estimated from these sounds as the boat passed overhead. The next step will be to deploy acoustic data loggers on many seals to evaluate both what the animals hear and how they respond to natural and artificial noises in their world.



Information recorded by the instrument shown above includes dive depth, acoustic data, and heart rate of the animal.

Geology & Geophysics Department

The diverse interests of Geology and Geophysics Department scientists span many fields of marine geosciences. In 1995 these included the structure and evolution of oceanic crust, chemical evolution of the mantle, the ocean's role in the history of Earth's climate, and the processes affecting nearshore and coastal environments. At year end, the department consisted of 29 scientific staff, 21 technical staff, 26 support staff, 32 graduate students, and 9 postdoctoral scholars and investigators.

Department Chair Mike Purdy became Director of the National Science Foundation Division of Ocean Sciences, and was succeeded as chair in November by Senior Scientist Bill Curry.

Geophysicist Debbie Smith was promoted to Associate Scientist with Tenure, and two outstanding new Assistant Scientists joined the department: Neal Driscoll, from the Lamont-Doherty Earth Observatory, and Peter Clift, from the Ocean Drilling Program at Texas A&M University. Neal's expertise focuses on seismic stratigraphy and the structure and evolution of continental margins and nearshore environments, and Peter's major interest lies in basin analysis.

Senior Scientist Bill Berggren received the 1995 Joseph A. Cushman Award for excellence in foraminiferal research from the Cushman Foundation for Foraminiferal Research. A two-day symposium in honor of Stan Hart's 60th Birthday brought friends and colleagues from around the world to discuss Earth Science topics of special interest to Stan.

Dick von Herzen retired in 1995, though he continues his active research on ocean heat flow. Associate Scientist Scott Lehmann took a leave of absence to pursue his research at the University of Colorado.

Department members produced 75 scientific publications in 1995, submitted 138 research proposals to various funding agencies, initiated 50 new projects, and participated in a total of 22 research cruises. Large, interdisciplinary research program participation included the Ridge Inter-Disciplinary Global Experiments, process studies in the Arabian Sea as part of the Joint Global Ocean Flux Study (JGOFS), and the Marine Aspects of Earth System History research program. Research Specialist Susan Humphris and Associate Scientist Pat Lohmann both served as Co-Chief Scientists on Ocean Drilling Program *JOIDES Resolution* cruises.

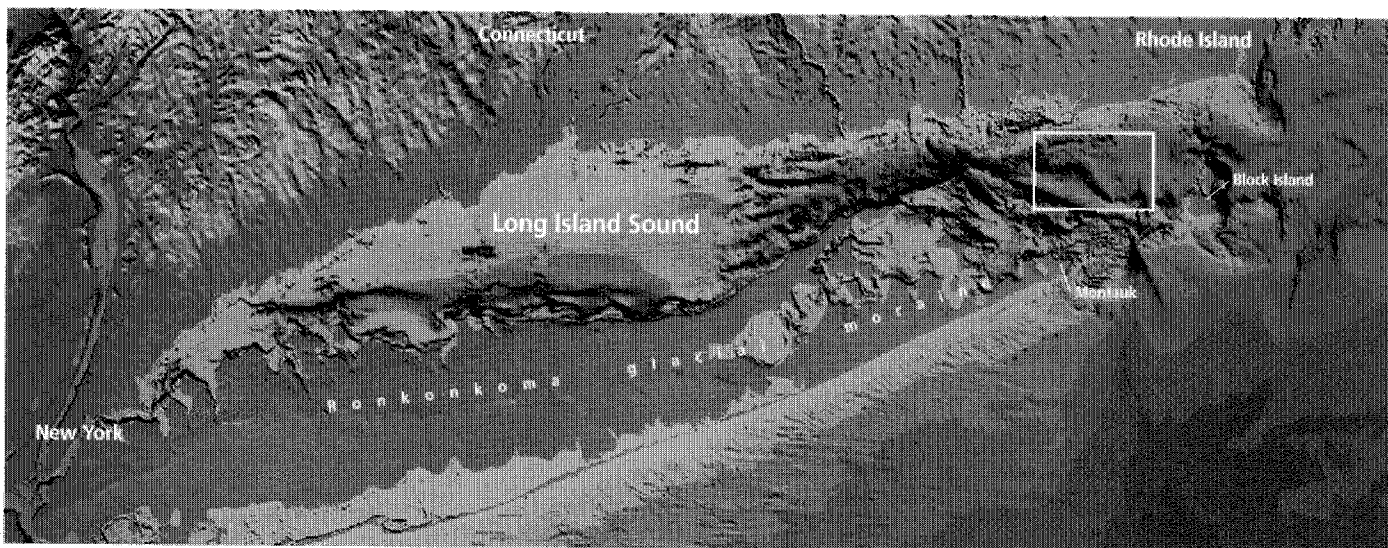
Scientists Study Large Storm and Human Effects in Block Island Sound

When Nor'easters, hurricanes, and other large storms pummel the US East Coast, resulting property damage ashore is highly visible. However,

knowledge of how large storms affect the shallow water regions of the continental shelf remains limited, at best. Increased societal pressure on these environments indicates a need for better understanding of fundamental physical processes that shape them. By determining the natural variability of shallow water regions, society can assess the interplay of anthropogenic

and natural effects on these regions and develop strategies for responsible management of their resources.

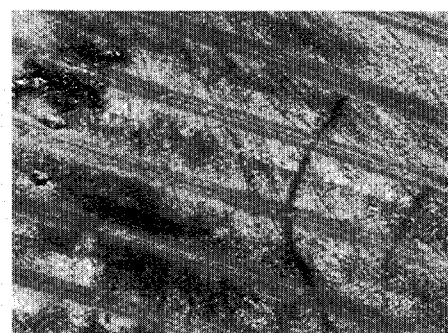
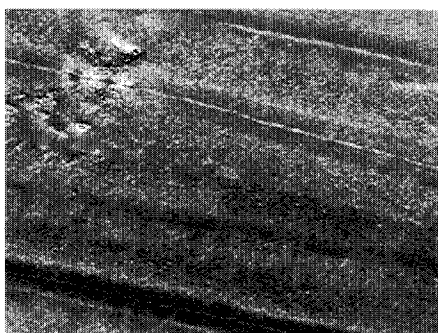
Toward this goal, Neal Driscoll and David Twichell (US Geological Survey) led an Office of Naval Research-sponsored expedition to survey portions of Block Island Sound before and after large storms. Recent improvements in navigation, afforded



White rectangle shows Block Island Sound area surveyed in 1991 and 1994. Lighter shades of green denote regions with higher elevations above sea level and darker shades of blue indicate regions with greater water depth.

by the differential Global Positioning Satellite System (GPS), allowed the researchers aboard R/V *Cape Henlopen* (University of Delaware) to reoccupy in 1994 an area in Block Island Sound where similar geophysical and geological data were acquired in 1991. Their objective was to establish a "natural laboratory" where repeated surveys monitor how the seafloor and its sediments change with time. These data then can be used to describe the influence of hurricanes, large storm events, and anthropogenic activity on the distribution and type of bedforms, sediment composition, and the acoustic character of shallow water sediments. The researchers collected sonar images of the seafloor both in cross section and in map view, recovered surface sediments from the seafloor, and recorded seafloor roughness and megafauna with an underwater camera sled. Combination of these data sets allows characterization of the geologic features in Block Island Sound both before and after the passage of large storm systems. The scientists also examined the region's benthic biology to assess how biological activity might affect seafloor erodibility.

Analysis of the Block Island Sound data indicates that large storm systems have had little effect on large-scale morphology and sedimentary bedforms. One explanation for this surprising observation is that the submerged portion of the Ronkonkoma glacial moraine that extends from the eastern tip of Long Island to Block Island and continues northward toward Point Judith, Rhode Island, acts as a natural jetty at the mouth of Block Island Sound, dissipating much of the storms' wave energy. The shallowest portions of the submerged moraine are 8 to 10 meters deep, whereas the study area is shoreward of this shoal in 30 to 50 meter water depths. Much of Block Island Sound is in the lee of both the subaerial and submerged portions of the glacial moraine and thus protected from large, storm-induced waves. Consequently, the glacial morphology imparted by the Laurentide



The boulders in the upper left corners of these photos were used to coregister the 1991 (left) and 1994 images for comparison purposes. Note that the trawl marks visible in 1994 do not appear in the 1991 image.

ice sheets almost 18,000 years ago still influences present-day sediment transport, erosion, and deposition in Block Island Sound.

However, on a smaller scale (meters), some portions of the study area have undergone dramatic changes. One obvious change in the 1994 data set compared to the 1991 survey is the increase in the distribution and density of trawl door scars caused by fishing gear dragged across the seafloor (see photos above). This suggests that anthropogenic effects are having a greater impact on re-

working surface sediments in Block Island Sound than large storms. A long-term research goal is to develop additional natural laboratories in a variety of shallow water settings to examine the relative effects of storms, anthropogenic activity, and other processes on different portions of the continental shelf. Increased knowledge about the processes that shape and sculpt the present-day continental shelf will yield important insights into both interpreting the geologic record and responsible management of an invaluable resource.

Exploring Atlantic Ocean Volcanoes, Earthquakes, and Mountain Building

Each year hundreds of thousands of earthquakes shake the ocean floor along the Mid-Atlantic Ridge. Only the largest of these quakes are detectable by seismic stations on land, but they are part of a continuous mountain building process along the 50,000-kilometer-long mid-ocean rift that circles the globe. In the past several years, Jian Lin and colleagues have been using a variety of acoustic sonars and marine geophysical sensors to explore underwater volcanoes and earthquakes, aiming at a better understanding of the submarine mountain building process that has shaped more than 70 percent of Earth's solid surface.

In July 1995, the US Navy declassified precision gravity data collected by the Navy Geosat satellite from 1985 to 1990. This newly available information on the world's ocean basins is 30 times more detailed than

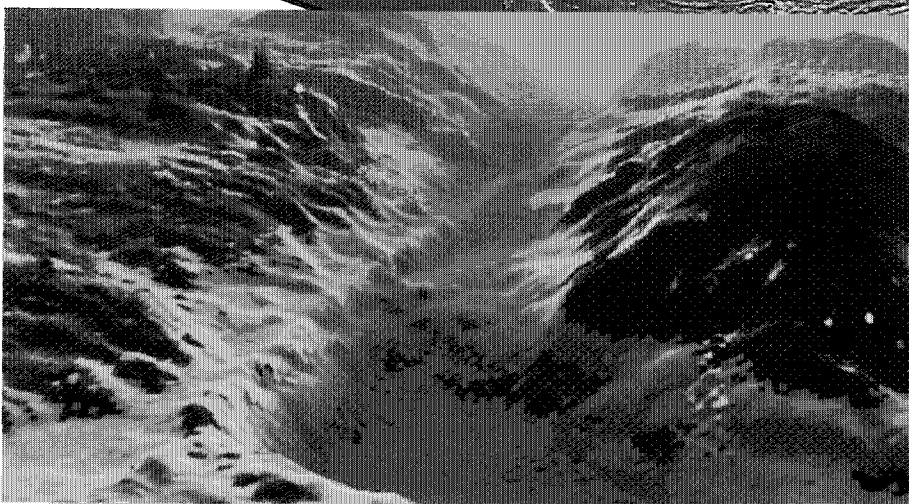
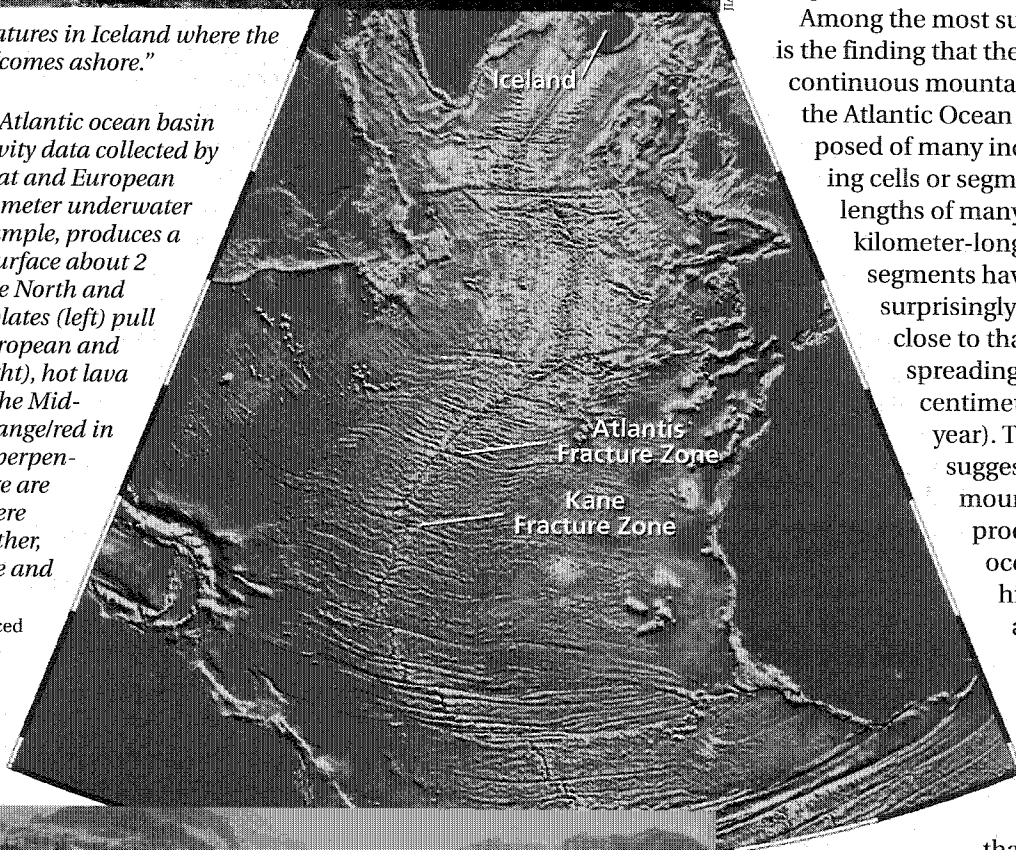
data previously available. Geosat's radar recorded the precise shape of the ocean surface, which reflects the contours of underwater mountains and valleys (see figure overleaf). Lin and MIT/WHOI Joint Program students Javier Escartin and Garrett Ito have analyzed some of the newly released data for the Atlantic to study the geology of many fascinating submarine features. These include "fracture zones," which are deep valleys produced by seafloor earthquakes, and submarine "hot spots," where an unusually large amount of molten lava has oozed onto the seabed near such prominent islands as Easter, Iceland, and the Galapagos.

While Geosat's 2-to-10-kilometer resolution provides a good overview, finer resolution of seafloor features relies on the use of surface ships equipped with the latest marine technologies. Supported by the National



Rifted volcanic features in Iceland where the mid-ocean ridge "comes ashore."

Map of the North Atlantic ocean basin as revealed by gravity data collected by the US Navy Geosat and European satellites. A 2,000-meter underwater mountain, for example, produces a bump at the sea surface about 2 meters high. As the North and South American plates (left) pull away from the European and African plates (right), hot lava oozes up to form the Mid-Atlantic Ridge (orange/red in the center). Lines perpendicular to the ridge are fracture zones where plates pass each other, offsetting the ridge and producing earthquakes. (Map produced by Javier Escartin, MIT-WHOI, with data from David Sandwell, Scripps Institution of Oceanography and Walter Smith, NOAA.)



Computer-generated image shows view from the Mid-Atlantic Ridge rift valley looking into the Atlantis Fracture Zone.

Science Foundation and the Office of Naval Research, Lin and colleagues have focused especially on a 1,000-kilometer-long stretch of the Mid-Atlantic Ridge between the Kane and Atlantis fracture zones and a 250-by-400-kilometer area of 0-to-30-million-year-old crust. They have employed a variety of acoustic sonars and geophysical sensors to measure the precise shape of the seabed, sediment thickness, and the magnetic and gravity properties of Mid-Ocean Ridge rocks.

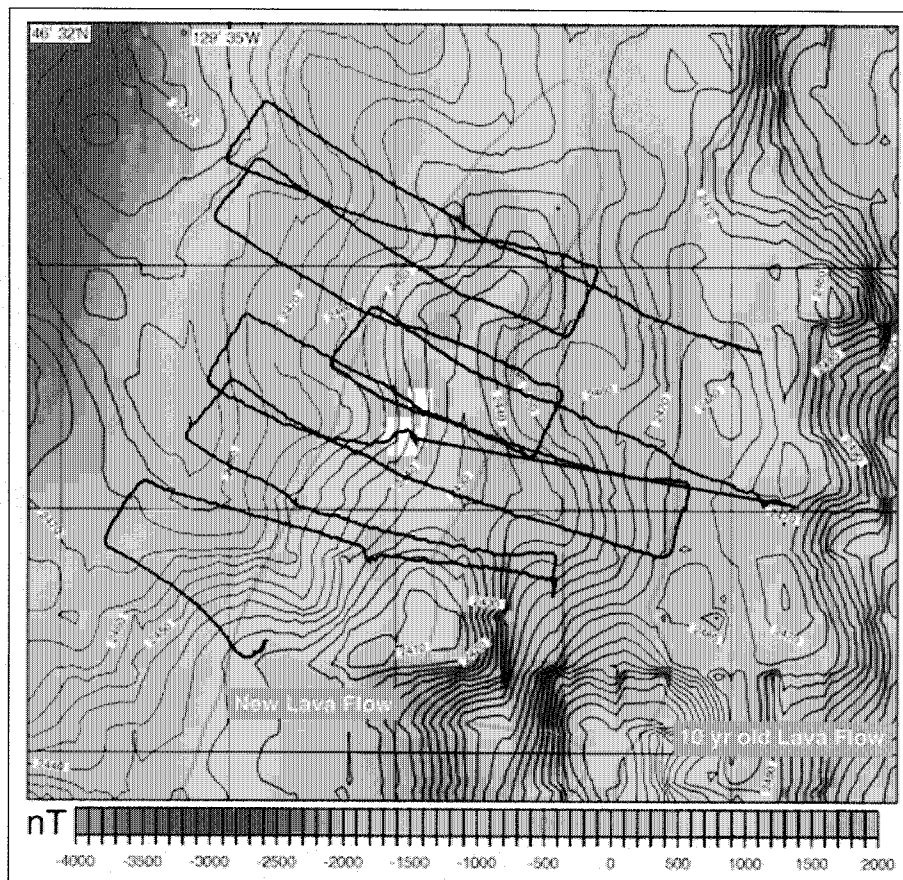
Among the most surprising results is the finding that the seemingly continuous mountain range under the Atlantic Ocean is in fact composed of many individual spreading cells or segments. The lengths of many 20-to-100-kilometer-long spreading segments have changed surprisingly fast, at a rate close to that of seafloor spreading itself (about 1 centimeter, 0.4 inch, per year). These results suggest that the mountain building process along the ocean ridges is highly punctuated in space and time, especially in relatively slow-spreading crust like that found in the Atlantic basin.

With support from the National Science Foundation's RIDGE (Ridge Inter-Disciplinary Global Experiments) program, Lin and colleagues will mount two major expeditions in summer 1996 to directly image the internal structure of volcanoes and mountain ranges under the Atlantic Ocean using seismic waves from artificial sources and natural earthquakes as they continue to seek new information about the underwater volcanoes, earthquakes, and mountain ranges that shape two-thirds of our planet's surface.

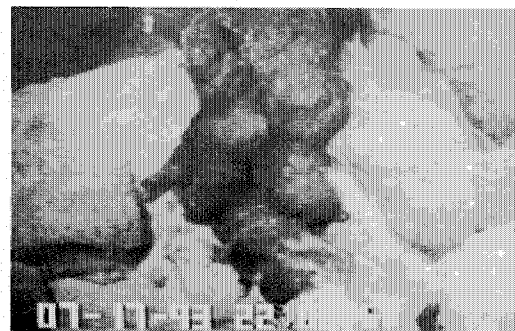
Scientists Track Change Over Time in a Young Lava Flow

Marine geologist Maurice Tivey is part of a team afforded a unique opportunity to monitor changes in a seafloor lava flow nearly from its inception. In the summer of 1993, just days after National Oceanic and Atmospheric Administration scientists activated a new real-time earthquake monitoring network, seismic activity was detected on the Juan de Fuca ridge in the northeast Pacific. This activity indicated that an eruption was underway, and research vessels were dispatched to locate it. The eruption, which formed a lava flow 30 meters thick, 1,500 meters long, and 300 meters wide, was fed from what is thought to be a subsurface feeder dike (a fissure that serves as a conduit from a body of molten material to the seafloor). Using conductivity/temperature/depth instruments, scientists aboard research ships were able to detect hot water plumes from vents created by the cooling lava as it heated the seawater. Echosounding ships repeating previous mapping tracks also recorded a difference in the depth of the seafloor where the lava flow had erupted. Together the diking event and lava flow represent the basic building block of oceanic crust—investigating this newly placed seafloor feature will bring better understanding of the process by which almost 70 percent of Earth's surface has formed.

The physical properties of the new lava are still pristine, and knowing the precise age of the rocks allows scientists to monitor their changes over time. One important property is magnetism and new lava is highly magnetic. As the molten lava is rapidly "quenched" or cooled on contact with seawater, the magnetic minerals it contains quickly "freeze," recording the direction and strength of Earth's magnetic field, which varies over time. The feeder dike, however, lies beneath the seafloor and cools more slowly, so its magnetism is much



The figure above shows ABE's data collection track (black lines running left and right) over the new lava flow superimposed on a magnetic map of the area. An image of the fresh lava, right, was captured by the Canadian remotely operated vehicle Ropos.



weaker. This difference in magnetic properties can be used to map the extent of the dike zone beneath the new flow and helps to explain the sources and placement of lava. In summer 1995, Tivey and Paul Johnson (University of Washington) led a National Science Foundation-funded *Alvin* submersible cruise to map the magnetic and gravity fields of the new flow and dike and to establish a benchmark set of measurements for future surveys.

As part of the nighttime survey plan, the WHOI-developed autonomous underwater vehicle *ABE* carried out its first science mission. Complementing *Alvin*'s close-up views of the seafloor obtained during daytime submersible operations, *ABE* mapped the magnetic field over the new lava

flow and dike zone. The vehicle successfully carried out over 35 kilometers of tracklines, measuring not only the magnetic field but also the bathymetry, and took digital photographs of the seafloor lavas. This relatively simple exercise belies the technological expertise that allows *ABE* to operate reliably in the deep ocean (see article on page 4). Building on this successful pioneering effort, autonomous vehicles like *ABE* hold promise for long-term remote monitoring as marine scientists continue to explore the seafloor.

MAURICE TIVEY

Marine Chemistry & Geochemistry Department

The Department of Marine Chemistry and Geochemistry (MC&G) consists of 18 scientific staff, 20 technical staff, 22 graded and administrative staff, and 5 individuals with postdoctoral appointments working on a total of approximately 80 research projects. In addition there are 16 Joint Program students, 11 of them in residence at Woods Hole.

Research in the department covers a broad spectrum of topics related to global climate change, present and past ocean circulation, biogeochemical cycles, remote sensing of the ocean, trace metals, radioactive contamination, organic geochemistry, sediment diagenesis, and the geochemistry of seafloor hydrothermal systems. Material transfers within the ocean and across boundaries with the air, the land, and the oceanic crust are common themes of much MC&G research. 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), World Ocean Circulation Experiment, Earth Observing System, Ridge Inter-Disciplinary Global Experiments, and Ocean Drilling Program.

The year saw a number of personnel changes in the department, including promotion of Bill Martin to Associate Scientist with Tenure, the departure of Asso-

ciate Scientist Mark Altabet, who joined the faculty at the University of Massachusetts, Dartmouth, and the retirement of Research Assistant Nancy Hayward after 17 years of service. Assistant Scientist Kathleen Ruttenberg was named a 1995 Office of Naval Research Young Investigator. Assistant Scientist Jeffrey Seewald received an award from the Geochemical Society for the Best Paper in Organic Geochemistry for 1994. An important event during the year was the opening on the Clark Laboratory's fifth floor of the department's new library, which was named the Geoffrey Thompson Reading Room in honor of the immediate past Department Chair.

The department mourned the loss of Joint Program student George "Gera" Panteleyev, who died while leading a sampling expedition on the Ob River in Siberia. Gera's work, earlier results of which were highlighted in last year's Annual Report, was a key part of an Office of Naval Research study to assess the level of radioactive contamination of the Arctic. Gera's quiet good humor, ready smile, dedication, and enthusiasm for his research are sorely missed by his many friends in the department, the Joint Program, and the Institution.

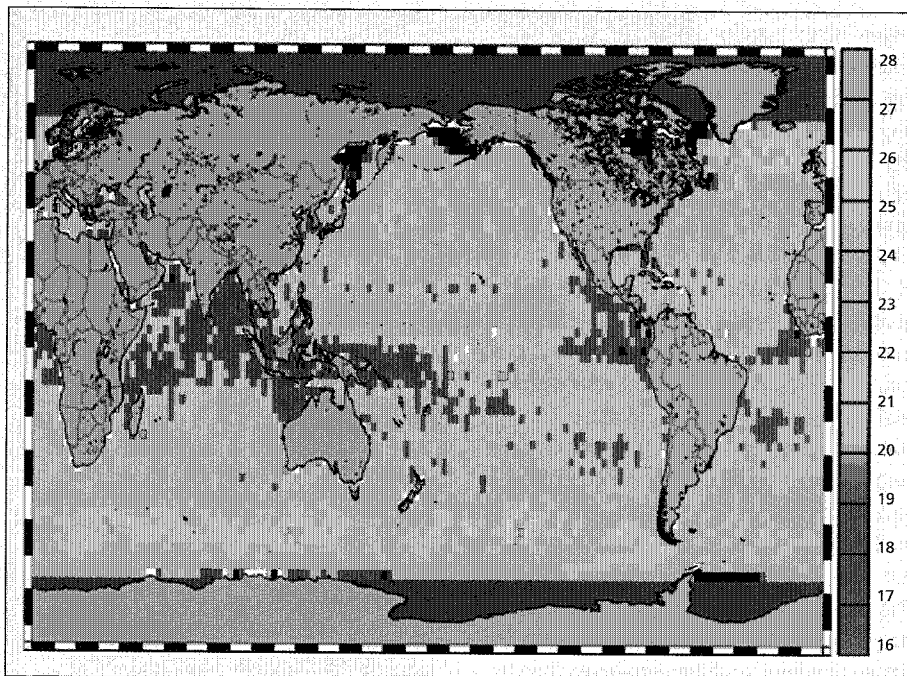
Of the department's many diverse research projects, three have been selected for presentation here.

A New Method for Estimating Air-Sea Gas Exchange Rates

Increasing concern about the accumulation of greenhouse gases such as carbon dioxide (CO_2) in the troposphere and its potential impact on climatic change challenges oceanographers to better understand ocean-atmosphere interactions. The oceans play a significant role in removing and sequestering the CO_2 added to the atmosphere by human activities. The removal process is controlled by several factors, including physical gas exchange mechanisms in the surface boundary layer, biological processes that fix CO_2 as organic matter, and vertical mixing between the surface and deep ocean. Current flux estimates suggest that the world's oceans are a net sink for atmospheric CO_2 , to the tune of about 2 gigatons of carbon per year. However, the timing and spatial distribution of this uptake are very poorly known, and there is

an inherent uncertainty of a factor of two in the models used to estimate gas exchange rates, which currently are based on ocean wind speeds. Gas

exchange is a wind-driven process because it is the wind that produces waves and the associated turbulence that promotes equilibration of the gas

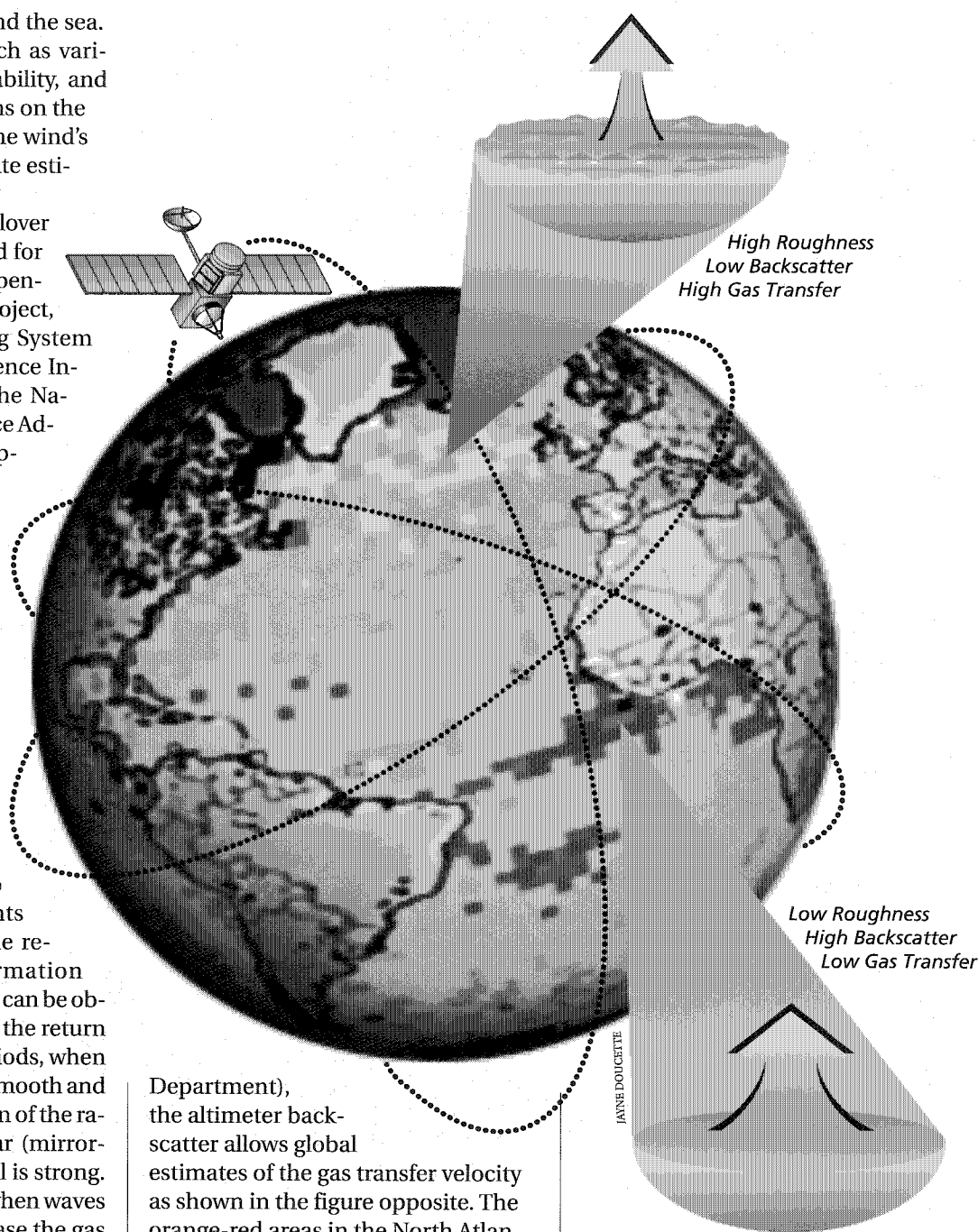


Global map shows gas transfer velocity in centimeters per hour estimated from TOPEX/Poseidon altimeter backscatter observed during March 1995.

between the atmosphere and the sea. However, other factors, such as variable fetch, atmospheric stability, and the presence of organic films on the sea surface can modulate the wind's stirring effect and complicate estimates of gas transfer rates.

Nelson Frew and David Glover are exploring a new method for estimating gas transfer independent of wind speed. Their project, part of an Earth Observing System (EOS) Interdisciplinary Science Investigation sponsored by the National Aeronautics and Space Administration, focuses on applying satellite-derived information to studies of chemical and biological processes in the surface ocean. The new approach uses the data stream from the TOPEX/Poseidon satellite altimeters, which illuminate a 10-kilometer-wide swath of the earth's surface along the flight path with pulsed microwave radar at a frequency of 13.6 gigahertz. While the primary use of the altimeter is to measure sea surface heights using the travel time of the reflected radar pulse, information about sea surface roughness can be obtained from the intensity of the return signal. During low wind periods, when the sea surface is relatively smooth and gas transfer is slow, reflection of the radar beam is nearly specular (mirror-like) and the reflected signal is strong. During high wind periods, when waves and turbulent mixing increase the gas transfer rate, the intensity of the backscattered signal is weaker, since the waves act as facets that scatter the altimeter beam randomly in many directions. The backscattered radar intensity thus is inversely proportional to sea surface roughness. Combined with knowledge gained from fundamental studies relating surface roughness to gas transfer rate (a National Science Foundation-funded project Frew undertook with Erik Bock and Wade McGillis of the Applied Ocean Physics & Engineering

Department), the altimeter backscatter allows global estimates of the gas transfer velocity as shown in the figure opposite. The orange-red areas in the North Atlantic and the high latitude regions of the Southern Ocean represent high-wind, high-transfer-rate regimes, while the dark blue and purple areas (the equatorial regions) represent low-wind, low-transfer-rate regimes. The new methodology offers the advantage of providing much greater spatial and temporal coverage than can be achieved with buoy or ship-based observations, and it avoids the uncertainties inherent in the model function for gas transfer velocity as a function of wind speed.



The TOPEX/Poseidon satellite measures the intensity of backscatter from its 13.6 gigahertz radar beam. Here the beam illuminates two regions of the sea surface, one smooth, one wind-roughened. Yellow arrows represent air-sea gas transfer rates. The magnitude and direction of the carbon dioxide flux (into or out of the ocean) depends on the local air-sea carbon dioxide concentration gradient.

Radionuclide Studies Indicate an Historically Hardy "Conveyor Belt"

The broad features of modern deep ocean circulation are often described as a thermohaline "conveyor belt" initiated by the formation of North Atlantic Deep Water (NADW) as it sinks in the Norwegian, Greenland and Labrador Seas and flows southward into the Circumpolar Deep Water (CPDW) around Antarctica. This general pattern of circulation affects global climate as it drives warm, low-latitude surface waters to the north to replace the sinking water. It also influences the sequestering of carbon dioxide into deep water, thereby regulating the carbon dioxide concentration of the atmosphere and the "greenhouse" effect on the earth's heat balance.

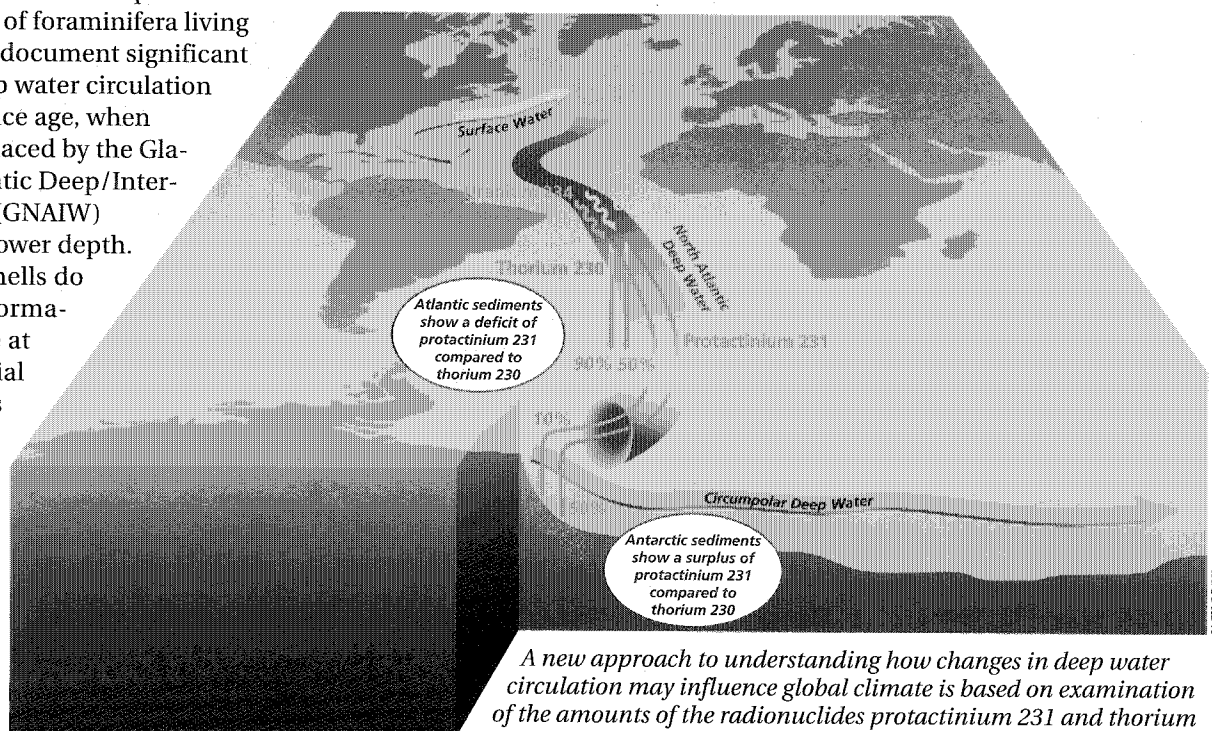
Changes in deep water circulation may have played an important role in controlling global climate during the geological past, especially during the last million years, a period characterized by cyclical climatic oscillations between ice ages and warm interglacial periods. Variations in the isotopic and chemical composition of calcite shells of foraminifera living on the seafloor document significant changes in deep water circulation during the last ice age, when NADW was replaced by the Glacial North Atlantic Deep/Intermediate Water (GNAIW) flowing at shallower depth. However, the shells do not provide information on the rate at which this glacial water mass was produced or whether it even reached the ocean around Antarctica and mixed with CPDW.

In an effort to evaluate past changes

in the rate of "conveyor belt" circulation and document whether GNAIW reached the CPDW, Ein-Fen Yu, Michael Bacon, and Roger François are taking a new approach based on the partitioning of two radionuclides, protactinium 231 (^{231}Pa) and thorium 230 (^{230}Th). These two long-lived radionuclides (half-lives: 32,000 years and 75,000 years) are the decay products of two natural isotopes of uranium dissolved in seawater. Both are "particle-reactive," that is, they are rapidly removed to the seafloor by adsorption onto sinking particles. ^{230}Th , with a very strong affinity for particles, resides in the water column for only a few decades, while the somewhat less particle reactive ^{231}Pa resides in seawater for more than a century. In the modern ocean, deep water resides on average 200 years in the Atlantic before being exported into the CPDW. Because its mean residence time in seawater is 10 times shorter, 90 percent of the ^{230}Th produced in Atlantic water is removed to the underlying Atlantic sediments. In contrast, with a residence time similar to that of deep water in the Atlantic, only 50 percent of the ^{231}Pa produced is removed to Atlantic sedi-

ments. The remainder is exported with NADW into the CPDW for eventual deposit in Antarctic sediments. Consequently, there is a deficit of ^{231}Pa compared to ^{230}Th in Atlantic sediments, and a surplus in Antarctic sediments.

The contrast between the two oceans depends primarily on the flow rate of the deep thermohaline circulation. A significant decrease in the rate would result in a lesser ^{231}Pa deficit in Atlantic sediments, while a surplus of ^{231}Pa in Antarctic sediments would indicate addition of deep Atlantic water into CPDW. Yu, Bacon, and François measured ^{231}Pa and ^{230}Th in Atlantic and Antarctic sediments deposited during the last glacial maximum and compared it with the post-glacial values. After correction for radioactive decay, they found very little difference between the two time intervals, indicating that GNAIW reached CPDW and there was essentially no change in the rate of the global "conveyor belt" circulation. This important information bears on our understanding of the influence of deep water circulation on the global climate and atmospheric carbon dioxide level during the last ice age.



Protozoan Grazers May Relieve Iron Limitation of Phytoplankton

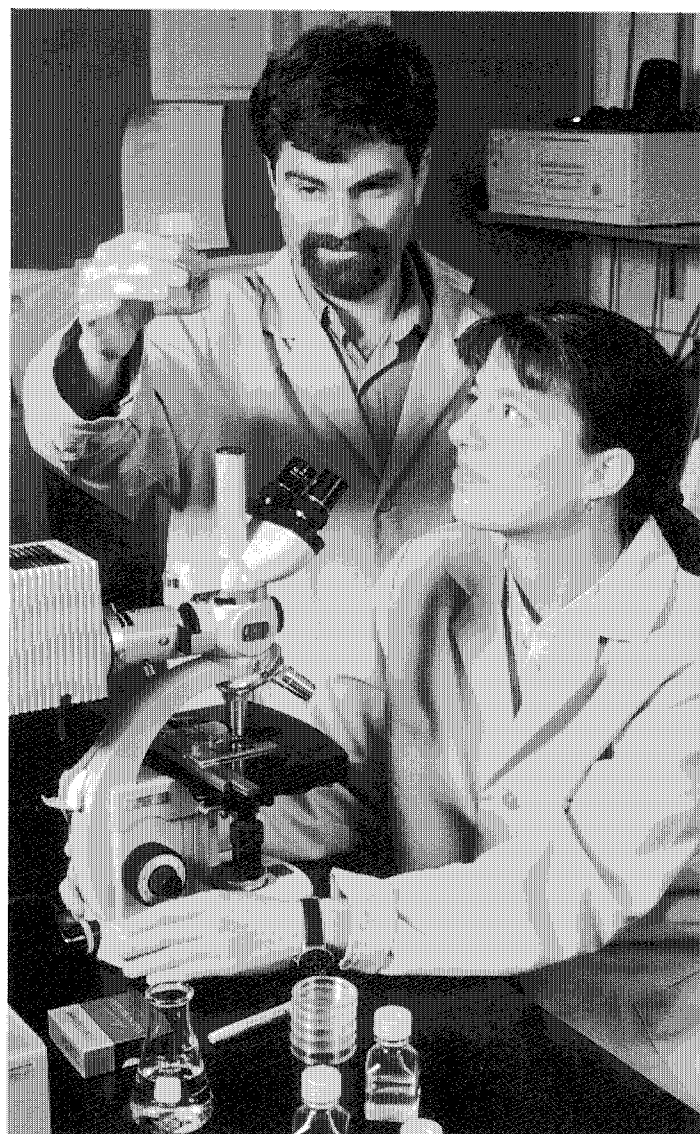
Iron is an essential micronutrient for marine life, yet it is highly insoluble in seawater. Dissolved iron concentrations in the oceans are exceedingly low, and much of the iron that is present occurs in relatively refractory forms, such as very fine particles (colloids), which are difficult for organisms to assimilate. Some scientists propose that, in many areas of the world's oceans, iron may actually limit the growth of marine phytoplankton, the primary producers in the oceanic water column. Biologists and chemists at WHOI and elsewhere are currently investigating the mechanisms phytoplankton use to obtain the iron they need. Considerable attention is focused on how the refractory forms of iron, including iron oxide minerals and iron bound to dissolved or colloidal organic matter, are converted into forms that phytoplankton can use. Two processes that have been particularly well-studied are the dissolution of refractory iron by sunlight through a photochemical mechanism, and the dissolution of refractory iron by siderophores, compounds produced by bacteria and some phytoplankton.

Katherine Barbeau, a Joint Program student working with Jim Moffett, recently identified an additional mechanism that may contribute to the supply of available iron for phytoplankton. Barbeau has been studying how heterotrophic nanoprotozoans, tiny grazers less than 20 micrometers in size, can influence iron chemistry in seawater. These organisms are ubiquitous, important components of marine food chains: The principle fate of bacteria in seawater is to be consumed by nanoprotozoans! Protozoans engulf their prey and incorporate it into a food vacuole within the cell, where it is subjected to harsh chemical treatment involving digestive

enzymes and acidic conditions. Barbeau and Moffett are interested in how this process can affect particulate forms of various trace metals, including iron, by accelerating dissolution processes that would not occur significantly in seawater. Nanoprotozoans could be particularly important since they ingest particles in the 0.2 to 1 micrometer size class, a very important size class for particulate metals.

Barbeau has studied what happens to colloidal iron oxides ingested by protozoans in the laboratory. Her work shows that

protozoan grazers can greatly accelerate the production of dissolved and chemically reactive iron from colloidal iron oxides in seawater. Most significantly, it shows that protozoan grazers can convert refractory colloidal iron oxides into a form of iron that is biologically available to diatoms, an important group of phytoplankton. Given the abundance of protozoans in the upper ocean, this may be an important mechanism for the production of biologically available iron. The next step will be to conduct field experiments, studying colloidal iron dissolution in freshly collected seawater samples spiked with tracers and incubated under a



Jim Moffett and Joint Program student Katherine Barbeau examine cultures of protozoans for studies of how these tiny grazers influence iron chemistry in seawater.

variety of conditions. Barbeau will also study the ability of protozoans to dissolve atmospheric dust particles, which are an important source of trace metals to the open ocean.

Protozoans may play an even wider role in ocean chemistry. Through their digestive process, they create a chemical "microenvironment" very different from that of bulk seawater. Marine chemists are only beginning to study important processes occurring within this microenvironment that may include dissolution of anthropogenically produced particles such as fly ash, transformation of organic contaminants, and production of new colloidal phases.

Physical Oceanography Department

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 inter-institutional and international field programs such as the World Ocean Circulation Experiment, Global Ocean Ecosystems Dynamics Program, Ridge Inter-Disciplinary Global Experiments, Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment, Joint Global Ocean Flux Study, and Arabian Sea Experiment. Specific research efforts include theoretical and field work, analysis of observations, remote sensing, laboratory experiments, and analytical and numerical modeling programs. Three of the department's many research projects are highlighted here.

The Department of Physical Oceanography consists of 32 scientific staff, 24 technical staff, 40 graded and administrative staff, 6 postdocs, and 29 Joint Program

students. There are 40 principal investigators working on 208 research projects. During 1995, 107 new research proposals were submitted and 59 proposals were funded.

Assistant Scientist Audrey Rogerson, who joined the department in 1995, is working on the generation and propagation of coastally trapped disturbances in the marine atmospheric boundary layer. Two Assistant Scientists, Amy Bower and Glen Gawarkiewicz, were promoted to Associate Scientist, and three Associate Scientists, Kathryn Kelly, Karl Helfrich, and Steve Lentz were promoted to tenured Associate Scientists. Two scientists are on leave from Woods Hole for visits to other institutions: Kathryn Kelly is at the Pacific Marine Environmental Laboratory in Seattle and Roger Samelson at Oregon State University. Al Plueddemann temporarily left Woods Hole to serve as a Program Manager at the National Science Foundation.

The Department was saddened by the death of Scientist Emeritus Valentine Worthington, a valued colleague and mentor to many of us.

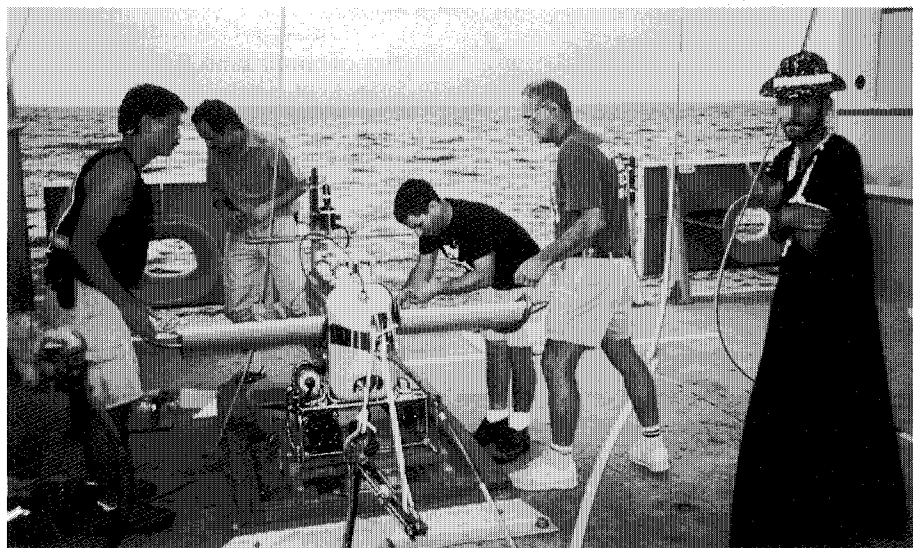
Changing Winds and Ocean Mixing: Studies of the Arabian Sea Monsoon

The Arabian Sea, located between the Arabian peninsula and the Indian subcontinent, is unique among the world's ocean basins because its basin-scale winds reverse completely during the course of the year in a

phenomenon known as a monsoon. While this happens locally along some coastlines (such as off Oregon), it is indeed unusual to have it happen on so large a scale. The implications of these reversals are considerable as they imply a tendency for the whole circulation to switch directions each year. Imagine, by analogy, the Gulf Stream changing direction each summer! The winds driving the currents are even more interesting:

Hot summertime winds blowing in a concentrated jet off desert Africa towards India constitute the strongest sustained winds to be found anywhere over the ocean except near Antarctica, where the ocean's structure is quite different.

One of the basic concepts in physical oceanography is that when a wind blows on the ocean surface, the earth's rotation causes the turbulent flow in the upper 50 meters of the water column to move to the right of the wind in the northern hemisphere. The implications of this well-demonstrated idea are shown in the top figure opposite. When winds are strong, such as under the Arabian Sea jet, then upper ocean currents flow strongly to the right. When winds are weaker, there is still a transverse flow, but it is less intense. This implies that some water moves upward on the left of the jet and downward on the right of the jet in order to make up the differences. The result is that cold, deep, nutrient-rich water comes to the surface close to shore and to the left of the jet. As part of a broader 1994–1995 Office of Naval Research/National Science Foundation research effort



From left, Craig Lee, Frank Bahr, Paul Fucile, and Jerry Dean prepare SeaSoar for deployment while Omani observer Rashid Al-Fahihi looks on.

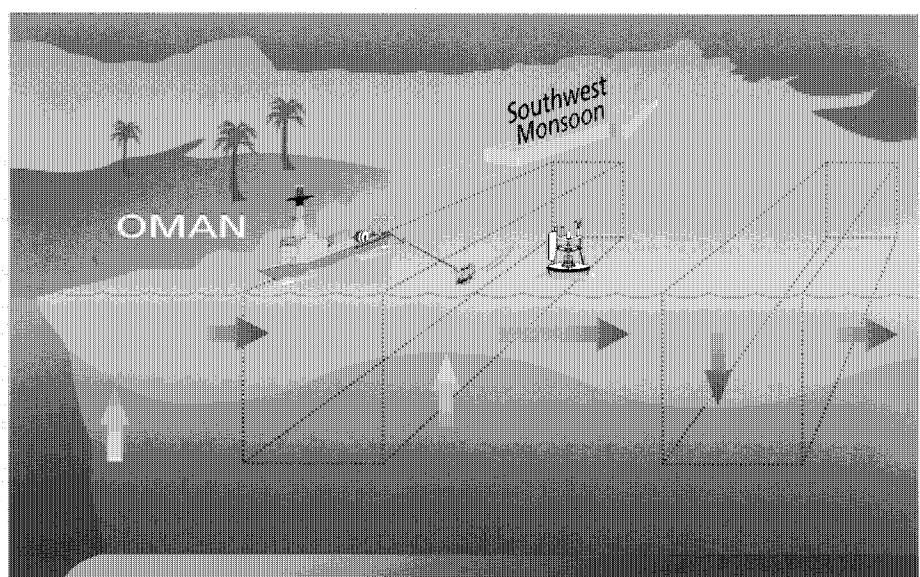
in the Arabian Sea, the SeaSoar group, led by Ken Brink and funded by ONR, studied the strength of this upwelling response and how it affects ocean mixing.

They participated in four cruises in the Arabian Sea to observe the consequences of the monsoon wind cycle. They used the towed, undulating sampler SeaSoar to measure temperature, salinity, and other variables in boxes on either side of the main summertime jet. While they are still processing the measurements, preliminary results show promise of some striking new insights on upper ocean circulation in this area. For example, the data show strong analogies with the summertime flow patterns off the coast of California.

Bobber Floats Measure Currents' Vertical Component in the Subduction Experiment

Generally we think of the open ocean as very deep and cold, and, indeed, it is in most respects. However, if we were to observe an entire ocean basin from a distant vantage point, say the moon, then our impression would be that the oceans are actually very thin—for example, the North Atlantic is only about 4 kilometers deep while it is about 4,000 kilometers wide. The size and shape of some of the most important ocean currents, such as those associated with the subtropical gyre, which includes the Gulf Stream, are constrained in large part by this aspect ratio, which thus has a major consequence for the character of ocean currents. In particular, the vertical component of large-scale ocean currents is necessarily very much smaller than their horizontal component. Thus when oceanographers discuss “currents” in the context of observations, it is usually understood that they mean the horizontal component only.

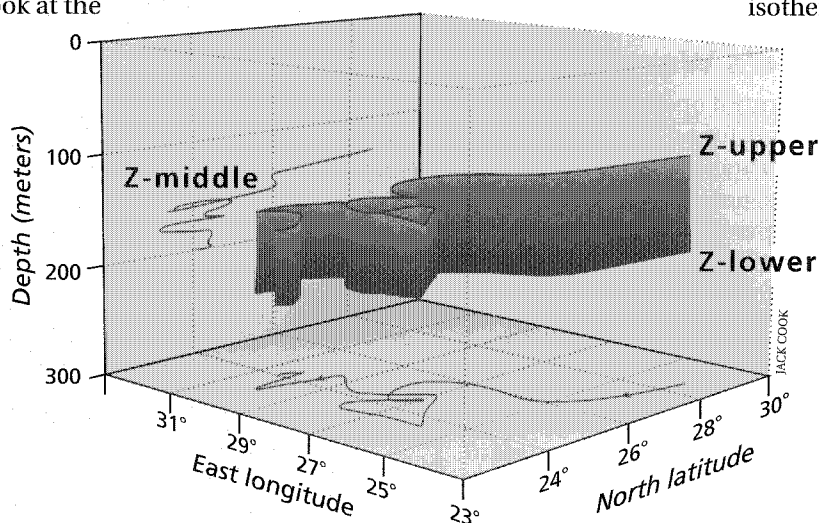
The vertical component of ocean



Schematic of winds and circulation in the Arabian Sea during the summer. The boxes denote the portions of the ocean WHOI physical oceanographers sampled most closely.

currents, though small, has an importance for ocean dynamics that is in some crucial respects equal to that of the much larger horizontal component. Because vertical measurements are more difficult to make, oceanographers have only recently begun to develop measurement techniques for them. During the 1991 to 1993 Office of Naval Research-funded Subduction Experiment, designed to examine the descent of surface layer water as it moves south in the eastern portion of the subtropical gyre, Jim Price and colleagues tried an approach that appears to provide a first look at the

three-dimensional currents in the subtropical gyre. The idea was to track a new and clever float, called a Bobber, that was developed and constructed by Doug Webb of Webb Research Corporation (Falmouth, Massachusetts). Bobbers drift freely with the horizontal currents at their depths, similar to conventional subsurface floats. Bobbers are among the first of a new generation of subsurface floats that can vary their buoyancy under programmed control. Bobbers may be programmed to move up and down once each day between upper and lower isotherms—

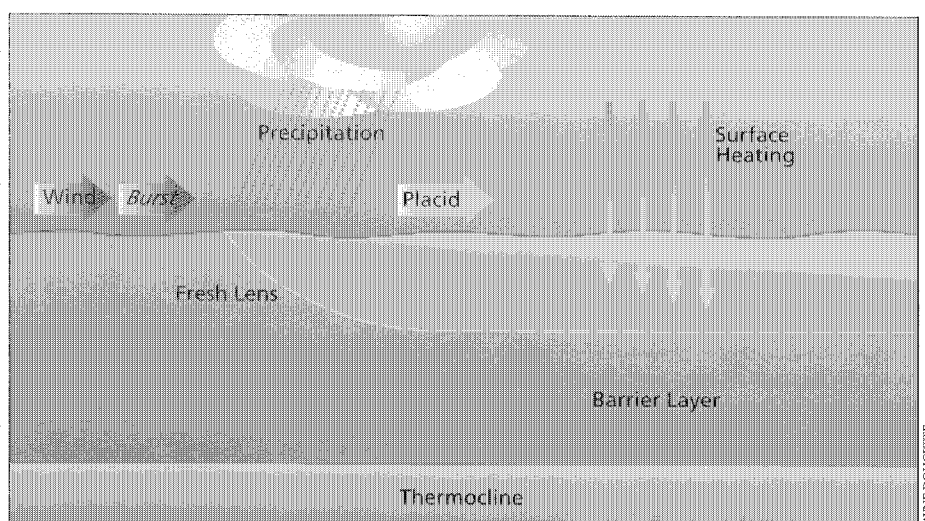


The three-dimensional trajectory of a Bobber float launched in the eastern subtropical gyre of the North Atlantic. This trajectory is about 1,000 kilometers in length and two years in duration. Notice that the Bobber descends about 80 meters.

19°C and 17.5°C in the case of Bobber 15 shown in the bottom figure on page 19. The depths at which the Bobber found these isotherms, Z-upper and Z-lower, was encoded into an acoustic signal and telemetered daily to give the slowly varying, vertical component of the trajectory. During a two-year lifespan, Bobber 15 moved southward from about 29°N to about 23°N, and at the same time it descended, following the target isotherms, from a mid-depth (Z-middle) of 125 meters down to about 200 meters. The downward displacement is quantitatively consistent with the expected downward "Ekman pumping" that results from the anticyclonic wind stress curl of the overlying Azores high pressure system. Note that the thickness of the current defined by the target isotherms decreased from about Z-lower - Z-upper = 80 meters, when the Bobber was farthest north, to about 50 meters when it was farthest south. This decrease in current thickness is qualitatively consistent with the convergence of the vertical velocity expected in the wind-driven subtropical gyre. Indeed the decrease in current thickness is a little more than expected, perhaps indicating an effect of vertical mixing in the heat balance.

New Findings On The Western Equatorial Pacific's Warm Pool

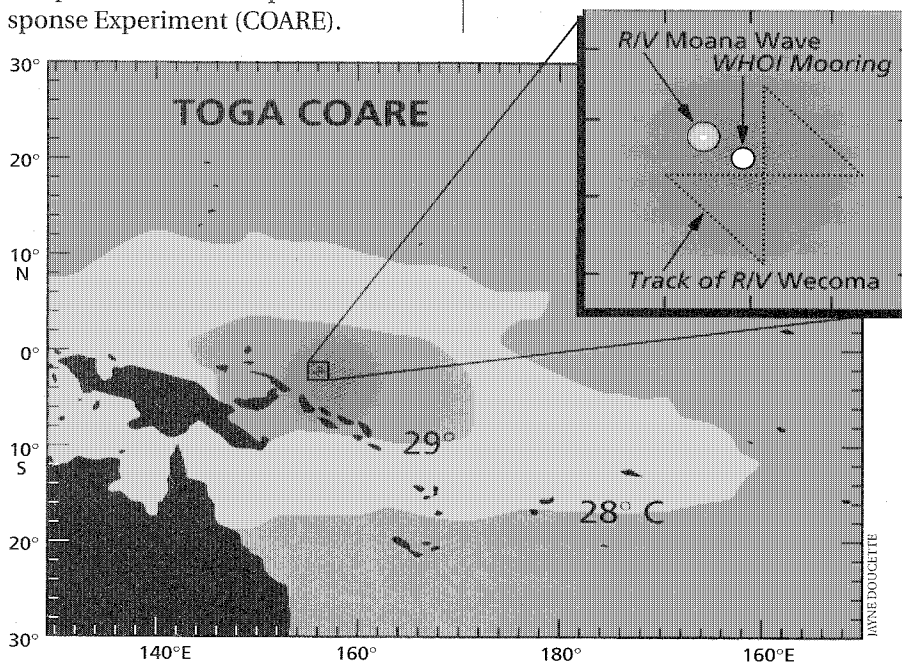
The warmest open ocean waters in the world are found in the western equatorial Pacific. In an area the size of Australia, annual average upper ocean temperatures exceed 29°C. This warm pool is closely associated with a combination of intense upward transport in the atmosphere, cloud cover, and rainfall that constitutes a major driving force for global atmospheric circulation. Eastward displacement of this warm pool system during El Niño/Southern Oscillation (ENSO) events every 3 to 5 years results in pronounced midlatitude weather pattern changes. Understanding the processes that couple



Schematic diagram illustrates the "barrier layer" theory. During a strong wind burst, the surface mixed layer extends down to the top of the thermocline (region of rapid temperature decline). Following the wind burst, the additional buoyancy from precipitation and strong surface heating results in a relatively warm and fresh, thin surface mixed layer. Below this thin layer is a strong salt-stratified or barrier layer, which effectively decouples the surface forcing from the deeper water.

the ocean and atmosphere in the warm pool is a crucial step toward improving predictions of seasonal-to-interannual global climate variability. Pursuit of this understanding is the primary objective of the Tropical Oceans-Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE).

What maintains the high ocean temperatures found in the warm pool? After all, other regions of the ocean have less cloud cover, and thus more solar heating, yet do not get as warm as the western equatorial Pacific. One hypothesis ascribes an important role



Cruise tracks and mooring location are shown for Tropical Ocean/Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE) research on the western equatorial warm pool. Annual mean sea surface temperature was calculated by the National Oceanic and Atmospheric Administration National Meteorological Center Climate Analysis Center. Moana Wave is operated by the University of Hawaii and R/V Wecoma by the University of Washington.

to the large amount of precipitation—greater than 4 meters per year—that falls in the warm pool region. This rain forms a shallow, fresh—and thus buoyant—layer on the ocean surface that supports the accumulation of heat. A salt-stratified or “barrier” layer beneath it effectively insulates surface waters from cooler waters found at depth. The barrier layer is maintained over the long term through freshening of the near-surface, warm pool by rainfall that is balanced by sporadic mixing with saltier waters transported by the South Equatorial Current from the central tropical and subtropical Pacific.

As part of COARE, a multi-national group of scientists using several research vessels mounted an intensive field observation program in the warm pool from October 1992 through March 1993. The data collected is being used to study the basic processes that link the atmosphere to the ocean in the region. A central part of this observational program was a discus buoy moored in the middle of the warm pool by the WHOI Upper Ocean Processes group led by Robert Weller, Albert Plueddemann, and Steven Anderson. The mooring instrumentation included a complete meteorological set on the buoy to observe the local atmosphere, and oceanographic sensors on the mooring line to monitor salinity, temperature, and currents in the upper ocean.

Anderson and Weller are analyzing the response of the warm pool surface layer to local surface forcing using the mooring observations made during COARE. To test the barrier-layer hypothesis, they are using numerical ocean models to examine local rainfall's role in determining the vertical structure of the near-surface waters of the warm pool and its net effect on sea surface temperature. Their findings support the salt-barrier-layer theory. Anderson and Weller are now working with climatologists to improve the warm pool surface layer's mathematic representation in the global, coupled atmosphere-ocean models currently used for long term climate prediction.

Marine Policy Center

At the Marine Policy Center (MPC), scholars engage in research to improve the management and conservation of coastal and marine resources. Their work integrates the social sciences, such as economics and law, with WHOI's basic strengths in the ocean sciences.

During 1995, a number of MPC research projects reflected the increasing emphasis on policy approaches that integrate natural resource management and environmental protection with economic efficiency and growth. These included such topics as management of fishing effort and estimation of optimal risk-sharing strategies for maritime oil transport. Other studies concentrated more narrowly on economic problems, such as allocation of resources to maritime safety or sources of economic risk and productivity change in marine sector industries.

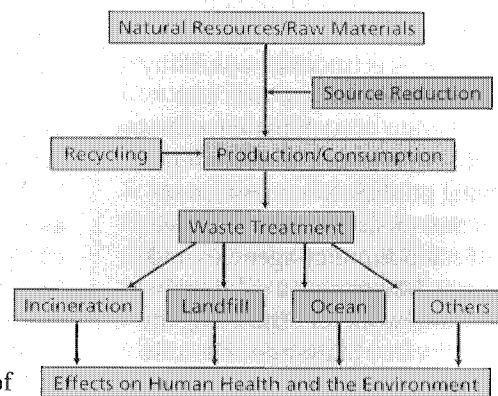
Several studies addressed the need to reconcile commercial fishing interests with public policy objectives to reduce incidental taking or “bycatch” of marine mammals and other nontarget species, to restore depleted fish stocks, or to promote effective coastal zone management. One project concentrated on the potential role of market-based approaches, such as “green” labeling and tradeable bycatch quotas, in reducing bycatch. The study concluded that the relevant bycatch problem must be carefully defined for each specific fishery on the basis of combined biological and economic multispecies models, and it cautioned that the selective removal of one species from an ecosystem is not necessarily an optimal policy from either an economic or an environmental standpoint.

MPC researchers also began a multidisciplinary study in 1995 to develop an integrated model to determine the optimal level of risk sharing between private marine oil transport interests and the public. Recent

changes in the US liability regime may precipitate an insurance crisis for oil carriers operating in US waters. Under the 1990 Oil Pollution Act, shipowners must assume that their liability for spills in US waters will be unlimited in most, if not all, cases. Insurers are disinclined to offer full-coverage insurance, however, and the coverage they do offer is expensive. Thus, the new liability regime is likely to discourage operation in the US by larger shippers seeking to avoid risk, and they may be replaced by smaller companies with limited assets, less ability to pay for oil spill damages, and less incentive to exercise precaution. MPC's integrated model will capture the tradeoffs between benefit from oil supply and associated environmental damage under various conditions, and the results will be

Waste Management

Source Reduction, Recycling, Multimedia Disposal



A comprehensive waste management strategy should incorporate both downstream multimedia (land, water, and air) disposal operations and upstream measures, such as source reduction and recycling. The social objective is to minimize the expected total cost of waste management, including internal cost (processing, transport, and disposal) and external cost (damage to human health and the environment). Scientific research generally leads to a reduction in the cost uncertainties surrounding one or more policy options, and the value of the research is the economic benefit (in this case, reduction in total waste management cost) associated with improved management resulting from the reduced uncertainty.

Centers & Other Programs

used to develop recommendations for an economically optimal liability limit and investment in safety measures by ship owners and operators.

Marine transit risk is also the subject of a multi-year MPC study launched in 1995 to model the probability of ship groundings and to develop a means of estimating its economic consequences. This investigation will provide information and analyses to help federal agencies prioritize investments in maritime safety. The first year's emphasis was on prioritizing areas of US waters for hydrographic resurveying by the National Oceanic and Atmospheric Administration. In subsequent years, the project team will concentrate on providing comparable guidance to the US Coast Guard on placement of navigation aids and to the Army Corps of Engineers on channel design and maintenance priorities.

These and other MPC projects illustrate how scientific research contributes to improved management and produces economic benefits by reducing uncertainty or risk. The quantification of such benefits can be difficult, but it is also important for justifying public investments in research and measuring the effectiveness of science policy agencies and programs. Developing a solid theoretical framework for estimating the economic value of marine scientific research is the goal of a one-year MPC study that uses as an example a proposed research program to investigate the environmental consequences of abyssal ocean waste disposal. This policy option is currently banned under federal law, on the grounds that it entails uncertain and potentially unacceptable risks to human health and the environment. Because the costs of land-based alternatives are rising rapidly as available capacity declines, the value of the proposed research may be substantial. The MPC project will develop estimates of this value and summarize the policy implications for the application of marine scientific research in a broad range of national policy issues.



From right, Craig Marquette, John Trowbridge, and Matt Gould deploy a mooring in the Hudson River estuary as Summer Student Fellow Jeff Freund looks on aboard R/V Mytilus. This deployment is part of a study of physical transport and turbulent mixing in the Hudson estuary.

Coastal Research Center

The Coastal Research Center fosters excellence in interdisciplinary research, especially in areas relevant to the management and protection of coastal resources. The Center encourages interaction among scientists based in different WHOI departments and also cultivates strong interinstitutional links. In the educational area, CRC cooperates with the Education Office to offer coastal traineeships for incoming MIT/WHOI Joint Program students, and a new international training program for Kazakhstan scientists has been established.

While CRC's limited financial resources are not adequate to fund entire research programs, they can serve as a catalyst for start-up, rapid response, student, or travel support—CRC cannot function as the main engine for research, but it can serve as a bow-thruster. Over the next few years, CRC funding will focus on several themes that build on previous Center research experience. These include:

- *New Technology for Measuring Spatial Gradients in the Coastal Ocean.* Immense spatial variability is a major characteristic of the coastal ocean's complexity, but whether studies focus on bottom sediments, zooplankton, or salinity, their spatial variability is

rarely resolved. Since traditional oceanographic instrumentation generally measures vertical variables, CRC is encouraging development of new instruments to measure horizontal variations. Examples include a program to measure turbulence from a remotely operated vehicle, sponsorship and matching funds for a Department of Defense proposal for instrumentation designed to resolve horizontal variability, and a successful proposal to the Defense University Research Instrumentation Program for studies of air-sea interactions and coastal mixing and optics.

- *Transport Processes at the Sediment-Water Interface.* This interface is perhaps the most important but least understood component of coastal systems with respect to environmental quality. Anthropogenic stresses such as eutrophication and chemical contamination appear initially and most intensely at the sediment-water interface. The physical and biogeochemical processes that influence the transport of material across this interface need to be better understood and quantitatively modeled before coastal managers can make economical and effective decisions. CRC will help to maintain WHOI's leadership role in this area of research.

- *Interdisciplinary, Predictive Modeling.* There is an urgent need for high-

quality, predictive, interdisciplinary modeling to address an ever-increasing number of coastal management questions. Methods are needed to aid and encourage cooperation between the scientists who best understand the natural systems being modeled and the engineering consultants who develop predictive models. A redirection of scientific talent is essential to help bring the level of available predictive tools to the point where they match the research community's understanding of natural system functioning.

• *Causes and Consequences of Changes in Coastal Marine Biodiversity.* Evaluating the scale and consequences of changes in marine biodiversity due to human activities, which are pervasive in coastal habitats, is seriously compromised by inadequate knowledge of the patterns and basic processes that control the diversity of life in the sea. Research in this thematic area focuses on identifying the natural or anthropogenic process responsible for changes in coastal biodiversity (such as organic enrichment, changes in freshwater runoff, and physical habitat alteration) and the consequences of these changes (such as altered food-chain relationships and changes in productivity or in harvestable fisheries).

Sea Grant Program

The WHOI Sea Grant Program supports research, education, and advisory projects to promote the wise use and understanding of ocean and coastal resources for the public benefit. It is part of the National Sea Grant College Program of the National Oceanic and Atmospheric Administration (NOAA), a network of 29 individual programs located in each of the coastal and Great Lakes states. The goal of the program is to foster cooperation among government, academia, and industry. WHOI Sea Grant-supported projects provide: 1) linkages between basic research and applied aspects of research and 2) communication between the scientific community and

groups that utilize information on the marine environment and its resources.

During 1995, the WHOI Sea Grant Program supported 16 concurrent research projects in addition to 26 new initiative awards for project development. The Woods Hole Program was successful in obtaining support for two projects in the national marine biotechnology competition in 1994 and four projects in the special enhancement competition in 1995. Many of the projects address local and regional needs, while others have national or even global implications. Some examples of currently funded projects include:

- boundary mixing in Massachusetts Bay,
- benthic processing of sewage nutrients in Massachusetts Bay,
- red tide bloom dynamics in Massachusetts Bay,
- detection and quantification of harmful algal species using molecular probes,
- development of species-specific immunofluorescent markers for larvae of benthic invertebrates,
- optimal risk sharing strategy for marine oil transport,
- molecular approaches for assessing contaminant effects in marine mammals, and
- effects of environmental contaminants on aquatic bird populations.

Transferring the results of research

and providing general marine-related information are important components of the WHOI Sea Grant Marine Advisory and Communications Programs. Both programs facilitate communication among users and managers of marine resources, including members of the fishing community, local officials, environmental regulatory agencies, and the general public. Two areas of particular interest in the marine advisory 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. Examples of providing information to a broad audience of users include: assembly of a *Directory of Cape and Islands Coastal Outreach Organizations*, management of an electronic network for information exchange among the directory organizations, and publishing a catalog of WHOI Sea Grant publications issued from 1971 to 1995. In addition, WHOI Sea Grant Communicator Tracey Crago was coauthor of the recently issued national Sea Grant publication *Marine Science Careers: A Sea Grant Guide to Ocean Opportunities*. It features question-and-answer profiles and photos of 38 marine scientists and other marine-related professionals to offer students insight and advice about a variety of career paths.



George Hampson, assisted by Dave Schlesinger, dives to collect benthic flux cores in Nantucket Harbor, part of an ecosystem-level study of the harbor's water quality, supported, in part, by WHOI Sea Grant. The cores are used to measure nutrients and changes in the sediment.

1995 Voyage Statistics

R/V ATLANTIS II

R/V OCEANUS

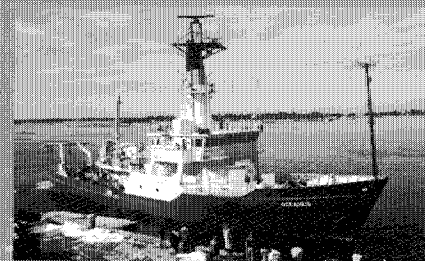


R/V Atlantis II & DSV Alvin

Total Nautical Miles in 1995—20,525,
Total Number of Alvin Dives—172

Atlantis II worked in both Atlantic and Pacific Oceans in 1995. The year began with a 15-dive investigation of the geological structures of major fault zones on the Mid-Atlantic Ridge near 24°N. This cruise was followed by 11 dives to hydrothermal vents at the Trans Atlantic Geotraverse site, including inspection of 17 holes drilled there by the Ocean Drilling Program. The ship transited the Panama Canal in March and proceeded to 9°N on the East Pacific Rise for 11 dives devoted to studies of how organisms interact with the environment when they colonize hydrothermal vent sites. The year's schedule included dives for long-term studies of temporal changes in deep-sea benthic boundary layer communities off the California coast and at sites of recent volcanic activity on the mid-ocean ridge. From June to October, *Atlantis II* made six trips to the Juan de Fuca Ridge off the coast of Oregon, where scientists from 15 institutions made 83 dives for extensive studies of hydrothermal vent biology, geology, and geochemistry. *Atlantis II* was host to the first deep-sea use of the Autonomous Benthic Explorer (ABE) during the Juan de Fuca work. (See ABE article on page 4.) During the last months of 1995, *Atlantis II* and *Alvin* worked in waters off California and Mexico.

Chief scientists for 1995 were: J. Karson, Duke University (Voyage 132-I, 15 dives); D. Kadko, University of Miami, (132-II, 11 dives); L. Mullineaux (132-IV, 11 dives); K. Smith, Scripps Institution of Oceanography (132-VI, 10 dives); J. Delaney, University of Washington (132-VIII, 17 dives); R. Embley, NOAA/PMEL (132-IX, 13 dives); Maurice Tivey (132-X, 13 dives); M. Mottl, University of Hawaii (132-XI, 17 dives); H.E. Johnson, University of Washington (132-XII, 13 dives); J. Delaney, University of Washington (132-XIII, 10 dives); R. Chandler (132-XV, 3 dives); R. Batiza, University of Hawaii (132-XVII, 9 dives); R. Lutz, Rutgers University (132-XVIII, 19 dives); and C. Fisher, Pennsylvania State University (132-XIX, 11 dives).*



R/V Oceanus

Total Nautical Miles in 1995—27,637

Oceanus returned to service in January after a six-month layup that followed the ship's midlife refit and upgrade. Improvements to the ship included an expanded pilot house and increased laboratory space. Three cruises for the World Ocean Circulation Experiment took the ship to the western South Atlantic for mooring work in the program's Deep Ocean Experiment. Moving to the western North Atlantic, *Oceanus* supported studies of water particle motion in the Gulf Stream and a hydrographic study of the Deep Western Boundary Current. Early summer found the ship conducting seismic surveys for hydrocarbon hazard assessment at proposed Ocean Drilling Program sites and for the Office of Naval Research Strata Formation on Margins program. Late summer was devoted to a multiship operation with R/V *Endeavor* (University of Rhode Island) and R/V *Cape Hatteras* (Duke/University of North Carolina Oceanographic Consortium) for studies of the influence of internal wave fields on the properties of acoustic signals. Following September testing of instrumentation for tracer release studies off Martha's Vineyard, the ship was laid up for the remainder of the year.

Chief scientists for 1995 were: J. Valdes (Voyage 266-II); S. Worrlow (Voyage 266-III); G. Tupper (266-IV); T. Rossby, University of Rhode Island (267); R. Pickart (269); J. Austin, University of Texas, and G. Mountain, Lamont-Doherty Earth Observatory (270); S. Wolf, Naval Research Laboratory (271); N. Hogg (272); and I. Ledwell (273).*

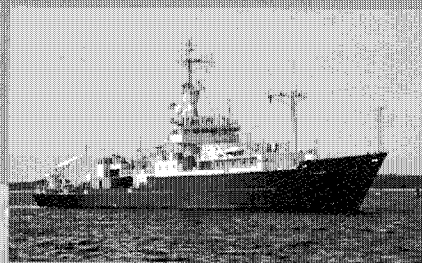
R/V Knorr

Total Nautical Miles in 1995—43,252

Knorr's 1995 schedule was entirely devoted to the Indian Ocean component of the World Ocean Circulation Experiment Hydrographic Programme. This work, which began in December 1994, encompassed 1,244 hydrographic stations in 367 days at sea. The ship covered more than 50,000 nautical miles for this project, while more than 400,000 water samples were drawn by scientists from 26 institutions and organizations representing 21 nations. Piers Chapman, Director of the US WOCE Office, wrote in a letter of thanks to the Institution, "I have had nothing but cooperation from everybody involved, and I have also heard nothing but praise from the various chief scientists [for] the way the officers and crew bent over backwards to ensure that everything aboard ran smoothly. I believe that the data we have gathered as a result of these cruises will provide a really impressive description of the large-scale oceanography of the region."

Chief scientists for 1995 were: M. McCartney (Voyage 145-V); A. Gordon, Lamont-Doherty Earth Observatory (145-VI); L. Talley, Scripps Institution of Oceanography (145-VI); W. Nowlin, Texas A&M University (145-VIII); J. Toole (145-IX); D. Olson, University of Miami (145-X); J. Morrison, North Carolina State University (145-XI); B. Walden (145-XII); N. Bray, Scripps Institution of Oceanography (145-XIII); G. Johnson, NOAA (145-XIVA); and B. Warren (145-XIVB).*

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



TOM REINHARDT

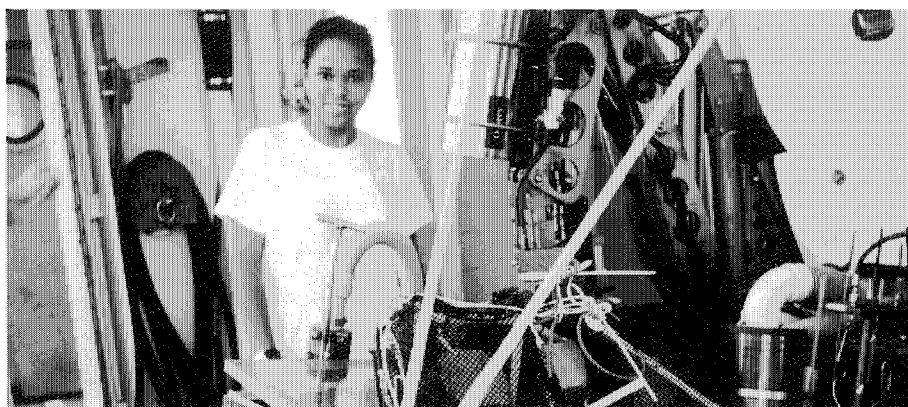
Dean's Comments

A cornerstone of the Institution's education programs is the *Massachusetts Institute of Technology-Woods Hole Oceanographic Institution Joint Program in Oceanography and Applied Ocean Sciences and Engineering* (the MIT-WHOI Joint Program). This year both WHOI and MIT undertook internal reviews of their respective portions of the Joint Program in preparation for an External Review scheduled for the 1996-1997 academic year. The WHOI Internal Review Committee was chaired by Bob Detrick, Education Coordinator for the Geology and Geophysics Department, and the MIT Committee was chaired by Jack Kerrebrock, Professor of Aeronautics and Astrophysics. Both reports reaffirmed the importance of the Joint Program to their respective institutions' education offerings and provided specific recommendations for maintaining the high quality of the program in a rapidly changing educational world.

Professor Sallie W. "Penny" Chisholm of the MIT Civil and Environmental Engineering and Biology Departments completed her second term as MIT Joint Program Director in July 1995. The Joint Program benefited immensely from her intellectual and personable leadership. Professor Marcia McNutt of the Earth, Atmospheric and Planetary Sciences Department has come onboard as the new Joint Program Director. I have enjoyed working with

Marcia in her capacity as chair of the Joint Committee for Marine Geology and Geophysics, and I look forward to continuing this association on the broader program. Marcia brings a wealth of scholarly, teaching, and advising experience to this position.

In the fall of 1995, there were 143 graduate students enrolled in the MIT-WHOI Joint Program and one student in the WHOI graduate pro-



Shannon Smith, a 1994 Summer Student Fellow with Lauren Mullineaux, accompanied her mentor aboard Atlantis II during a series of Alvin dives in December 1994 for hydrothermal vent work. Shannon, a Savannah State College student, was photographed on Atlantis II near Alvin's basket.

gram. We were pleased to award our first National Science Foundation Coastal Ocean Processes Traineeships this year to five incoming graduate students as the result of our participation in a national, peer-reviewed competition.

This is a period of challenge and dynamic change for all graduate education programs in sciences, engineering, and mathematics. We have taken a leadership role in organizing special sessions at national meetings to address these career issues and to share experiences with other graduate programs in ocean sciences and ocean engineering. One example was a special panel discussion, "Education in Ocean Sciences: Careers and Curricula," presented at The Oceanography Society meeting in April 1995.

Graduates of the MIT-WHOI Joint Program

chartered an *Alumni/Alumnae Association* in late 1994. Their elected representatives met in October 1995 to choose officers (see side bar opposite) and to plan several activities. These include a directory update, career guidance resources for Joint Program students, a home page on the World Wide Web, and fund raising for the Joint Program.

For the second year, we were

pleased to offer 18-month appointments (in contrast to 12 months prior to 1994) to *Postdoctoral Scholars* as a result of a generous endowment challenge grant from the Henry L. and Grace Dougherty Charitable Foundation and generous annual giving of the Devonshire Trust.

Twenty-five *Summer Student Fellowships* were awarded to 14 women and 11 men from a pool of 268 applications; two of these undergraduates were minorities. Ten of these Fellows were supported by a National Science Foundation Research Experience for Undergraduates Grant and fifteen by generous donors to WHOI Education Programs. The Fall 1995 issue of *Woods Hole Currents* provides an excellent in-depth view of the Summer Student Fellowship Program, which benefits both the students and WHOI science.

Four *Minority Traineeships* were awarded from an applicant group of twenty-two. We were fortunate for the second consecutive year to have financial support and advisor participation from our Woods Hole partners, the US Geological Survey and the National Marine Fisheries Service. We also participated in a national workshop on "Expanding Opportunities in Ocean Sciences: Strengthening the Links Between Historically Minority Serving College and University Undergraduates and Oceanic Graduate Study" at Hampton University in September.

The *Geophysical Fluid Dynamics*

Degree Statistics

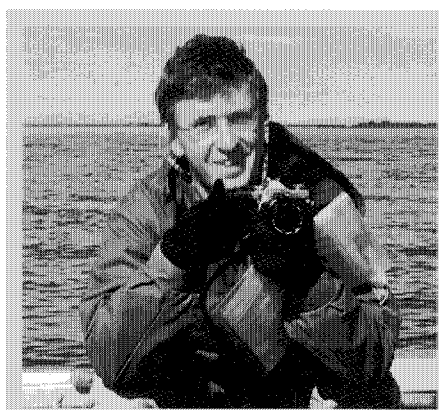
		1995	1968-95
WHOI	Ph.D.	—	3
MIT/WHOI	Ph.D.	19	302
MIT/WHOI	Sc.D.	—	28
MIT/WHOI	Engineer	4	53
MIT/WHOI	S.M.	8	69
Total Degrees Granted		31	455

Summer Study Program met for its 37th summer in Woods Hole to discuss "Rotating Convection" in the traditional eclectic mix of formal presentations and informal discussions on the Walsh Cottage porch.

Three teachers from southeastern Massachusetts completed their second, final summer in the *High School Teacher Summer Fellowship Program* that provides teachers with an opportunity to engage in ocean research projects and transition their experiences to their colleagues and into the classroom. A fourth teacher, George Hussey, of Falmouth High School, joined us for his third summer to participate in research and to assist us in evaluating the program and providing recommendations for future improvements.

Several WHOI Scientific and Technical Staff collaborated in 1995 to provide a course in Marine Environmental Quality at Massachusetts Maritime Academy (MMA) as part of the formal memorandum of understanding signed in 1992 by WHOI and MMA.

Although the education portion of



We were deeply saddened in June 1995 to learn of the tragic accidental death of MIT-WHOI Joint Program graduate student George P. "Gera" Panteleyev while leading a research expedition related to his master's degree research on the Ob River in Siberia. This photo was taken during earlier work there. Gera's enthusiastic approach to life and to the betterment of humankind enriched our lives, and he is greatly missed.

the Institution's mission is mainly in higher education, we are involved with selected local and regional K-12 education activities, often through the voluntary efforts of our staff and graduate students. We continued formal interaction with the Woods Hole Science and Technology Education Partnership and support of the Falmouth High School and Falmouth Acad-

emy Science Fairs by awarding scholarships and other prizes to the winners

Each year the staffs of the Information Office, Exhibit Center, Sea Grant Program, News Office, MBL-WHOI Library, and Education Office provide an amazing amount of information to thousands of inquiries from students, teachers, and others interested in the ocean sciences. To expand and augment these efforts, this year we began planning a partnership with New England Aquarium to combine the expertise, talents, and resources of both organizations to more efficiently provide the exciting knowledge of the oceans to a broad audience.

I mentioned above the *Woods Hole*



Dean John Farrington and Visiting Scholar Kathryn Sullivan, Chief Scientist of NOAA, saw the entering Joint Program class off on their summer cruise aboard Sea Education Association's sailing schooner Westward.

Association of the Alumni/Alumnae of the MIT-WHOI Joint Program

Officers and Committee Members

1995-1996 Term

Debra C. Colodner

B.S., Yale University, 1985
Ph.D., Chemical Oceanography, 1991

Michael S. Connor (Secretary)

B.S., Stanford University, 1974
Ph.D., Biological Oceanography, 1980

J. Robert Fricke

B.S., Vanderbilt University, 1974
M.S., Vanderbilt University, 1977
Ph.D., Oceanographic Engineering, 1991

Leslie K. Rosenfeld

B.S., University of Washington, 1978
Ph.D., Physical Oceanography, 1987

Christopher R. Tapscott (President)

B.A., Swarthmore College, 1972
Ph.D., Marine Geology & Geophysics, 1979

1995-1997 Term

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B.S., University of California, Berkeley, 1975
Ph.D., Physical Oceanography, 1980

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B.S., Trinity College, Ireland, 1984
MBA, Carnegie-Mellon University, 1993
Ph.D., Biological Oceanography, 1990

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B.S., Stanford University, 1978
Ph.D., Marine Geology & Geophysics, 1987

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B.A., Mount Holyoke, 1972
Ph.D., Chemical Oceanography, 1977

Susan Schultz Tapscott

B.S., Swarthmore College, 1972
O.E., Oceanographic Engineering, 1975

Liaison to the WHOI Corporation

Daniel H. Stuermer

B.A., University of California, Santa Barbara, 1970
Ph.D., Chemical Oceanography, 1975

Currents article about the Summer Student Fellowship Program. A quotation in that article captures for me the essence of an educational experience associated with Woods Hole Oceanographic Institution. Richard Signell, a 1982 Summer Student Fellow and 1989 MIT-WHOI Joint Program graduate, now at the US Geological Survey, Woods Hole, said, "The excitement of the Woods Hole scientific community is really contagious. The summer seminars, the people you meet, are outstanding. Everyone is intoxicated with the science."

—John W. Farrington

Senior Scientist, Associate Director for Education, and Dean

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Guy Nichols, right, shown with Corporation President Jim Clark, was honored at the May 1995 Annual Meeting upon his retirement after 10 years as Chairman of the WHOI Board of Trustees. Nichols received the Cecil Green Award and several gifts, including this model of the Institution's first ship, Atlantis.

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Frank Snyder, second from left, who succeeded Guy Nichols as Chairman of the Board, discusses marine affairs with Joe Coburn, left, Dick Pittenger, and Dave Casiles during a tour of R/V Oceanus.

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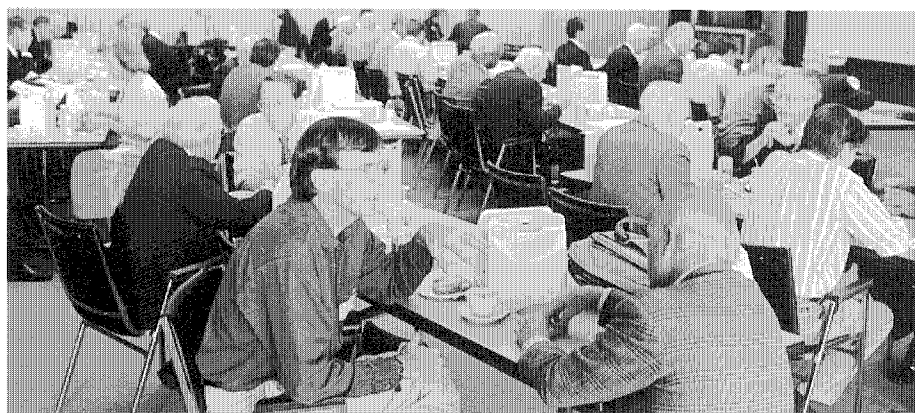
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Corporation Members and Trustees shared luncheon conversation with their "Scientist Partners" during October's Autumn Meeting activities. Henry Kendall, third from right, talks with partner George Frisk, and, at center, Walter Smith meets his new partner, Breck Owens.

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During October laboratory tours for Corporation members, Jonathan Howland describes Deep Submergence Laboratory work for Nick Bancroft, center, and John Stewart.

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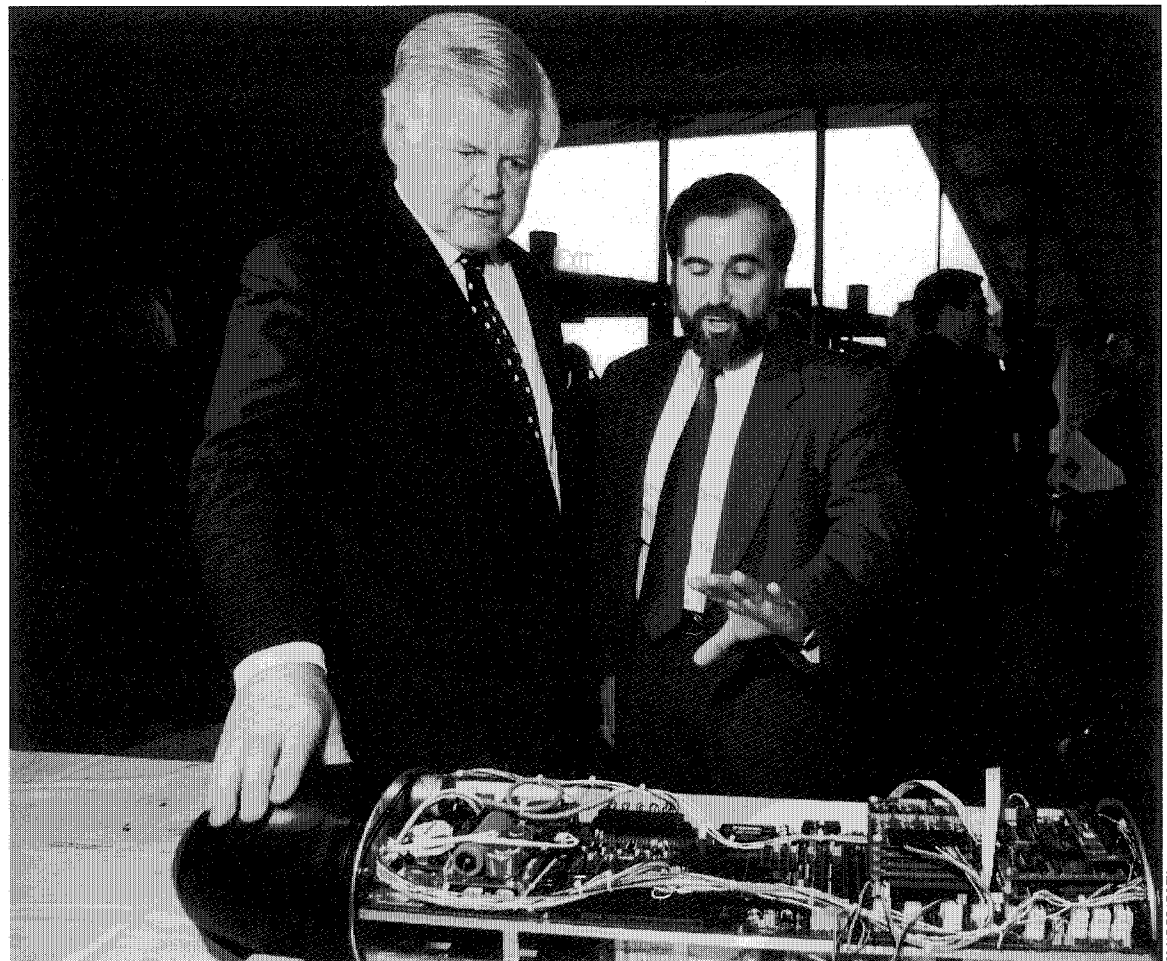
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In Memorium

The Institution greatly acknowledges the service and support of those members who passed away in 1995.

Thomas A. Fulham
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Stanley W. Watson



Director Bob Gagosian explains the operation of a REMUS (Remote Environmental Monitoring UnitS) vehicle to Massachusetts Senator Edward Kennedy at a Southeastern Massachusetts economic summit designed to enhance economic development, job creation, marine sciences, and support and growth of traditional industries in the area. The summit was held in November 1995 at the University of Massachusetts at Dartmouth.

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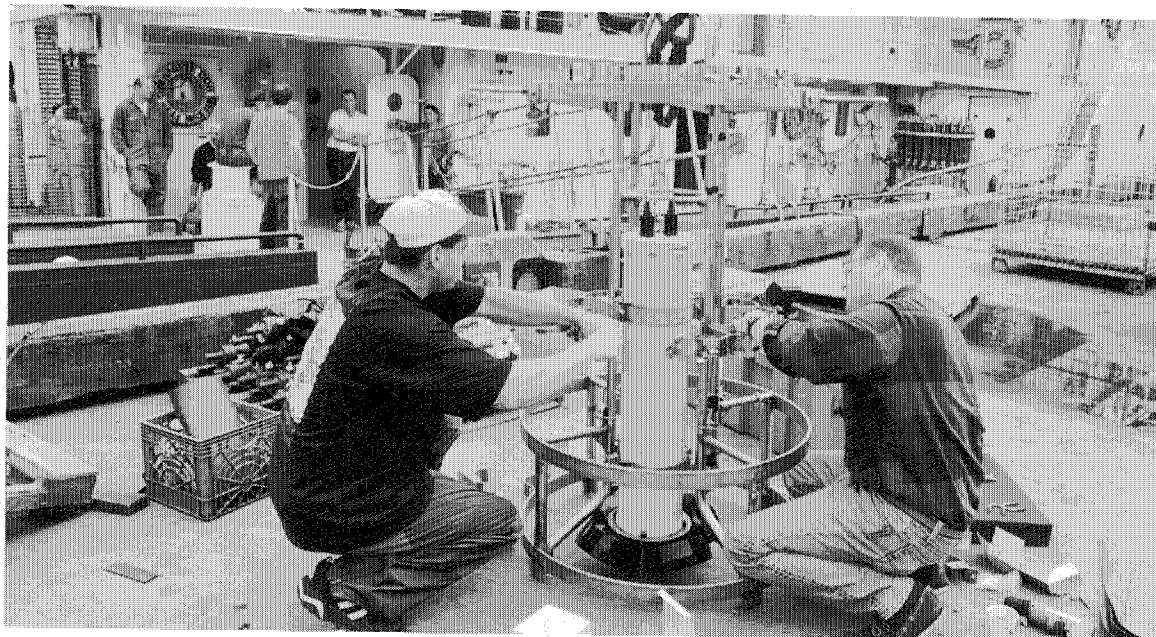
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George Tupper, right, and Jason McKay prepare an acoustic doppler profiler/CTD system for an R/V Oceanus summer 1995 deep western boundary current cruise.

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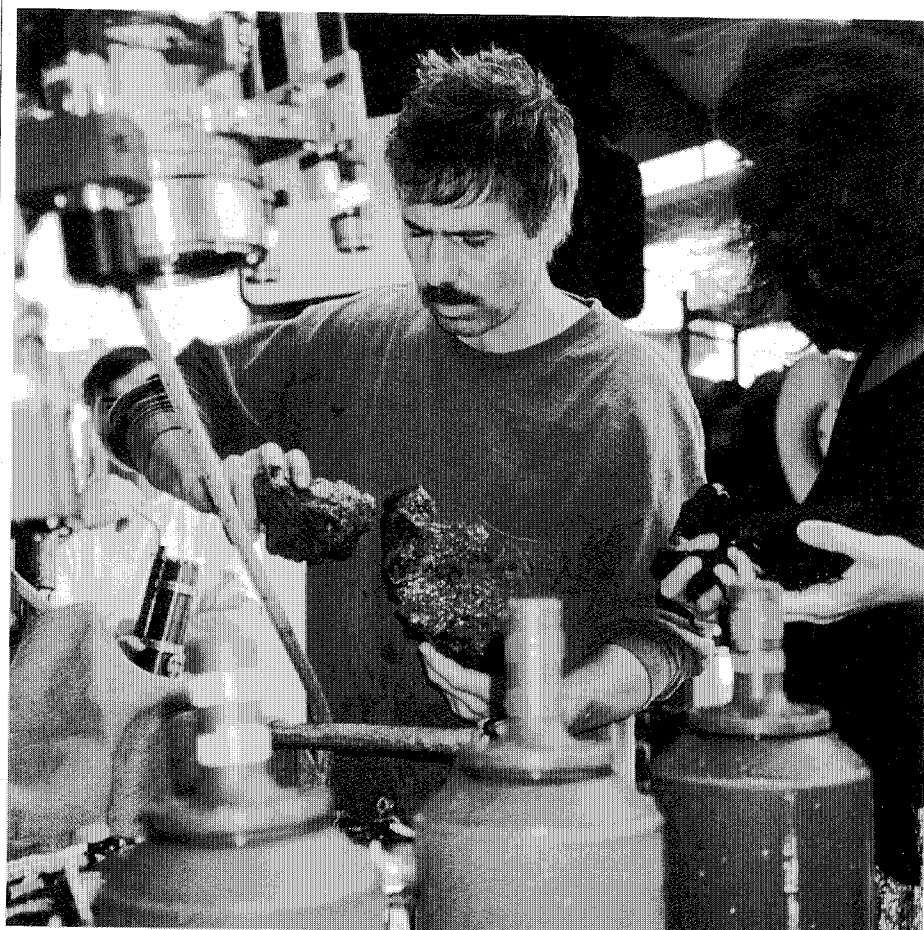
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Earl M. Young
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Aboard Atlantis II, Dan Fornari and Rachel Haymon (University of California, Santa Barbara) examine sulphide and chimney samples collected with Alvin on the East Pacific Rise in November 1995.

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Julio Candela
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Scientist Emeritus Betty Bunce, right, a geophysicist, was honored as the second Woman Pioneer in Oceanography at a Women's Committee celebration in March 1995. She chats with the first Woman Pioneer, Scientist Emeritus Mary Sears, a biologist, who was honored in 1994.

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Interim Center Direc-
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William R. Clarke



Neal Driscoll, right, and Dave Twichell (US Geological Survey) subsample sediments collected by a box corer during Block Island Sound work described in a science article on page 10.

Sheila A. Clifford
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Cynthia T. Gallo
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R/V Knorr made several exotic port calls during World Ocean Circulation Experiment work in the Indian Ocean, including this one in Port Louis, Mauritius.

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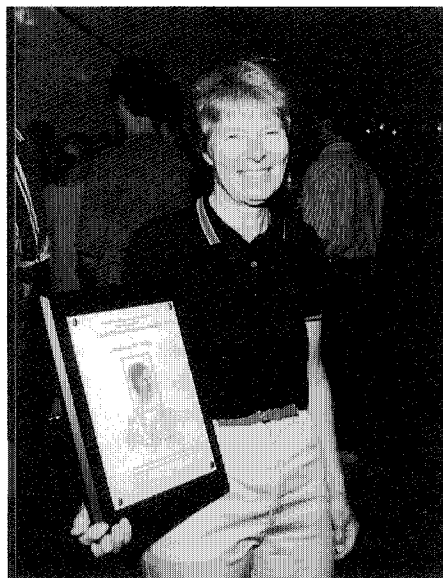
Administrative Staff

Nancy E. Barry
 Human Resources
 Administrator



Employee awards for 1995 were presented at a fall recognition ceremony. In the top photo, Larry Costello, left, and Dave Simoneau accept the Penzance Award on behalf of the Buoy Engineering and Rigging Shops for exceptional performance, WHOI spirit, and contributions to the personal and professional lives of Institution staff.

Associate Dean and Registrar Jake Peirson, above left, was honored with the Vetlesen Award for a variety of exceptional contributions to the WHOI community over a long period of time, and Freddy Valois, right, received the Linda Morse-Porteous Award for leadership, mentoring, dedication to work, and involvement in the WHOI community.



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George P. Silva
Andrew E. Sokolowski
Steven P. Solbo
William F. Sparks
Robert G. Spenle
Mark L. St. Pierre
Jeffrey M. Stolp
John K. Sweet, Jr.
Wayne A. Sylvia
William R. Tavares, Jr.
Anne M. Taylor
Michael A. Thatcher
Kevin D. Thompson
Anne Toal
Philip M. Treadwell
Carlos Velez
Arthur W. Volstad
Michelle Wadsworth
Herman Wagner
Dylan Weidman
Robert Wichterman
Michael W. Williams
Harry D. Wilson
Kathleen D. Wilson
Robert J. Wilson
Bonnie L. Woodward
Carl O. Wood
Jennifer Wysocki
Torii M. Young

1995 Retirees

Alfred T. Bouchard
Neil L. Brown
John M. Gassert
Nancy A. Hayward
Donald E. Koelsch
Donald F. LeBlanc
George H. Power
Richard F. Simpkin
Frederica W. Valois

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

Doctor of Philosophy

Keith D. Alverson

BS, Princeton University
Special Field: Physical Oceanography
Dissertation: Topographic Preconditioning of Open Ocean Convection

Edward P. Dever

BS, Texas A&M University
MS, Texas A&M
Special Field: Physical Oceanography
Dissertation: Subtidal Cross-Shelf Circulation on the Northern California Shelf

Michele D. DuRand

BA, Carleton College
Special Field: Biological Oceanography
Dissertation: Phytoplankton Growth and Diel Variations in Beam Attenuation through Individual Cell Analysis

Jeffrey A. Dusenberry

BS, Northwestern University
CE, Massachusetts Institute of Technology
Special Field: Biological Oceanography
Dissertation: Picophytoplankton Photo-acclimation and Mixing in the Surface Oceans

Ari W. Epstein

AB, Harvard University
Special Field: Physical Oceanography
Dissertation: Physical Processes and Zooplankton Distribution in the Great South Channel: Observational and Numerical Studies

Sarah T. Gille

BS, Yale University
Special Field: Physical Oceanography
Dissertation: Dynamics of the Antarctic Circumpolar Current: Evidence for Topographic Effects from Altimeter Data and Numerical Model Output

James R. Gunson

BS, University of Western Australia
SM, MIT/WHOI Joint Program
Special Field: Physical Oceanography
Dissertation: Estimating Open Ocean Boundary Conditions: Sensitivity Studies

Alan J. Kuo

BA, Harvard University
Special Field: Biological Oceanography
Dissertation: Mutant Analysis of Luminescence and Autoinduction in a Marine Bacterium

Jennifer G. Lee

BS, Yale University
Special Field: Chemical Oceanography
Dissertation: Cadmium: a Toxin and a Nutrient for Marine Phytoplankton

Sang Mook Lee

BS, Seoul National University
MS, Seoul National University
Special Field: Marine Geology and Geophysics
Dissertation: Tectonics of the East Pacific Rise: Studies of Faulting Characteristics, Magnetic and Gravity Anomalies

Alison M. Macdonald

BA, Bryn Mawr College
SM, MIT/WHOI Joint Program
Special Field: Physical Oceanography
Dissertation: Oceanic Fluxes of Mass, Heat and Freshwater: A Global Estimate and Perspective

David A. Mann

BS, Cornell University
Special Field: Biological Oceanography
Dissertation: Bioacoustics and Reproductive Ecology of the Damselfish *Dascyllus albisella*

Maria Mercedes Pascual-Dunlap

Licenciatura, University of Buenos Aires
SM, New Mexico State University
Special Field: Biological Oceanography
Dissertation: Some Nonlinear Problems in Plankton Ecology

Gopalkrishna Rajagopal

BS, India Institute of Technology
MS, University of Florida
Special Field: Oceanographic Engineering
Dissertation: Optimal Mode Localization in Disordered, Periodic Structures

Hanumant Singh

BS, George Mason University
Special Field: Oceanographic Engineering
Dissertation: An Entropic Framework for AUV Sensor Modelling

Fredrik T. Thwaites

SB, Massachusetts Institute of Technology
SM, Massachusetts Institute of Technology
Special Field: Oceanographic Engineering
Dissertation: Development of an Acoustic Vorticity Meter to Measure Shear in Ocean-Boundary Layers

Christopher R. Weidman

BS, State University of New York at Oneonta
Special Field: Marine Geology and Geophysics
Dissertation: Development and Application of the Mollusc *Arctica islandica* as a Paleoceanographic Tool for the North Atlantic Ocean

Renee D. White

BA, Wesleyan University
Special Field: Biological Oceanography
Dissertation: Tetrachlorobiphenyl Metabolism, Toxicity, and Regulation of Cytochrome P450 Expression in a Marine Teleost Fish

Huai-Min Zhang

BS, Peking University
MS, Academia Sinica
SM, MIT/WHOI Joint Program
Special Field: Physical Oceanography
Dissertation: Application of an Inverse Model in the Community Modeling Effort Results

Master of Science and Ocean Engineer

Henry A. Laible

BS, OE, United States Naval Academy
Special Field: Oceanographic Engineering
Dissertation: Wave Scattering from Cylindrical Fluid Inclusions in an Elastic Medium and Determination of Effective Medium Properties

Dan Li

BS, University of Science and Technology of China
Special Field: Oceanographic Engineering
Dissertation: Low-Frequency Bottom Back-scattering Data Analysis Using Multiple Constraints Beamforming

Master of Science

Leo E. Chiasson, Jr.

BSE, Boston University
Special Field: Oceanographic Engineering
Dissertation: Radiated Noise from a Three Dimensional Truss

Lei Fu

BS, Peking University
MS, Academia Sinica
Special Field: Oceanographic Engineering
Dissertation: Amplitude Fluctuation Effects in Shallow Water Acoustic Scattering by Internal Waves

Gwyneth E. Hufford

BS, Pennsylvania State University
Special Field: Physical Oceanography
Dissertation: Parameterization of Convection in a Rotating Stratified Ocean: Comparison of Numerical and Laboratory Experiments with Theory

Thomas W. Singleton

BS, United States Naval Academy
Special Field: Oceanographic Engineering
Dissertation: The Steps in the Development of an Atmospheric Vorticity Meter

Miles A. Sundermeyer

BA, University of California, Santa Cruz
Special Field: Physical Oceanography
Dissertation: Mixing in the North Atlantic Tracer Release Experiment: Observations and Numerical Simulations of Lagrangian Particles and Passive Tracer

Eric C.-M. Won

BA, Columbia University
Special Field: Physical Oceanography
Dissertation: Sensitivity of a General Circulation Inverse Model to Sub-Grid Scale Parametrization Coefficients

Ocean Engineer

Helen Huang

BS, University of Science and Technology of China
SM, MIT/WHOI Joint Program
Special Field: Oceanographic Engineering
Comparative Experimental Study of Control Theoretic and Connectionist Controllers for Nonlinear Systems

Brian J. Sperry

BSE, University of Iowa
SM, MIT/WHOI Joint Program
Special Field: Oceanographic Engineering
Modal Analysis of Vertical Array Receptions for the Heard Island Feasibility Test

MIT/WHOI Joint Program

1995-96 Fall Term

Robert P. Ackert, Jr.
University of Maine
University of Maine,
M.S.

Jess F. Adkins
Haverford College

J. Ewann Agenbroad
University of
Washington

Einat Aharonov
Tel-Aviv University,
Israel

Susan E. Alderman
Mt. Holyoke College

Lihini I. Aluwihare
Mt. Holyoke College

Linda A.

Amaral Zettler
Brown University

Jamie M. Anderson
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San Diego
MIT/WHOI Joint
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Brian K. Arbic
University of
Michigan

Michael S. Atkins
University of California,
Santa Cruz

Jay A. Austin
California Polytechnic
Institute, San Luis
Obispo

Katherine A. Barbeau
Long Island
University

Shannon M. Bard
Stanford University
Université de Nantes,
France

Kyle M. Becker
Boston University
Pennsylvania State
University, M.S.

Natalia Y. Beliakova
Moscow State University,
Russia

Susan M. Bello
Michigan State
University

Bryan C. Benitez-Nelson
University of
Washington

Claudia R. Benitez-Nelson
University of
Washington

Jeffrey N. Berry
Pacific Lutheran
University

Vikas Bhushan
University of Toronto,
Canada
University of British
Columbia, Canada,
M.S.

Katie R. Boissonneau
University of Massachusetts,
Dartmouth

Melissa M. Bowen
Stanford University
Stanford University,
M.S.

John R. Buck
Massachusetts Institute
of Technology
MIT/WHOI Joint
Program, S.M., E.E.

Erik A. Burian
United States Naval
Academy

Sean M. Callahan
Princeton University

Susan J. Carter
Harvard University

Michael Y. Chechelnitsky
Chechelnitsky
Program, S.M.

Maureen E. Clayton
Eckerd College

Laura M. Connors
Roanoke College

Rebecca A. Coverdale
Dartmouth College
Humboldt State
University, M.A.

Max Deffenbaugh
Princeton University
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Diane E. DiMassa
Massachusetts Institute
of Technology
Massachusetts Institute
of Technology,
S.M., M.E.

Yuriy V. Dudko
Moscow Physical
Technical Institution,
Russia

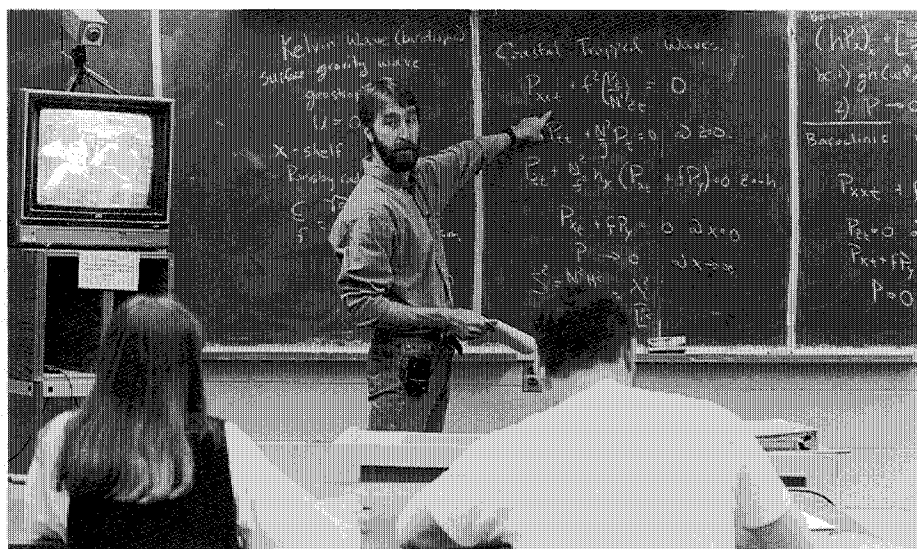
Henrietta N. Edmonds
Yale University

Christopher A. Edwards
Haverford College

Trym H. Eggen
Norwegian Institute of
Technology, Norway

Deana L. Erdner
Carnegie Mellon
University

Javier G. Escartin
University of
Barcelona, Spain
Perpignan University,
France, Maitrise



Steve Lentz presents a "Dynamics of Shelf Circulation" course lecture to students in a Woods Hole classroom and at MIT (on monitor) via a microwave link.

Albert S. Fischer
Massachusetts Institute
of Technology

Derek A. Fong
Stanford University
Stanford University,
M.S.

Carrie T. Friedman
University of California,
Berkeley

J. Steve Fries
Carnegie Mellon
University

Elizabeth D. Garland
Florida Institute of
Technology

Jennifer E. Georgen
University of Virginia,
Charlottesville

Karina Y. H. Gin
University of
Melbourne, Australia

Jason I. Gobat
Colorado School
of Mines
University of California,
San Diego, M.S.

Daniel R. Goldner
Harvard University

Jason C. Goodman
Carleton College

Robert J. Greaves
Boston University
Stanford University,
M.S.

Orjan M. Gustafsson
Slippery Rock
University

Benjamin T. Gutierrez
College of William
and Mary

Jill K. Hahn
Harvard University
Boston University, M.A.

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

Stephanie A. Harrington
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Washington

Carolyn L. Harris
Wellesley College

Constance A. Hart
College of St.
Catherine

Deborah R. Hassler
University of Kansas
University of Georgia,
M.S.

Robert H. Headrick
Oklahoma State
University
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Program, S.M., O.E.

Eli V. Hestermann
Purdue University

Mark F. Hill
University of Massachusetts,
Boston
University of Massachusetts,
Boston, M.S.

E. Maria Hood
Texas A&M University

Emilie E. Hooft
University of Toronto,
Canada

Michael J. Horowitz
Oberlin College

Allegra Hosford
Brown University

William R.N. Howell, Jr.
Tulane University

Youngsook Huh
Korea University,
Korea
Korea University,
Korea, M.S.

Stefan A. Hussenoeder
St. Louis University

Garrett T. Ito
Colorado College

Gary E. Jaroslow
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Amherst

Steven R. Jayne
Massachusetts Institute
of Technology

Brenda A. Jensen
Eckerd College

Kelsey A. Jordahl
Eckerd College

Igor V. Kamenkovich
Moscow Institute of
Physics and Technology,
Russia

Rafael Katzman
Tel-Aviv University,
Israel
Tel-Aviv University,
Israel, M.S.

Timothy C. Kenna
Vassar College
University of Rhode
Island, M.S.

Daniel B. Kilfoyle
Massachusetts Institute
of Technology
Massachusetts Institute
of Technology, S.M.
University of California,
San Diego, M.S.

Stacy L. Kim
University of California,
Los Angeles
Moss Landing, M.S.

James H. Knowles
University of Idaho
University of New
Hampshire

Kenneth T. Koga
Rensselaer Polytechnic
Institute

Jun Korenaga
University of Tokyo,
Japan
University of Tokyo,
Japan, M.Sc.

Elizabeth Kujawinski
Massachusetts Institute
of Technology

Joseph H. LaCasce
Bowdoin College
Johns Hopkins University,
M.A.

Kirsten L. Laarkamp
Pennsylvania State
University

Phillip J. LeBas
Auburn University

Kwok-Lin Lee
Chinese Culture
University, Republic
of China
National Taiwan
University, Republic
of China, M.S.

Craig V. Lewis
Stanford University

Dan Li
University of Science
and Technology of
China, Peoples
Republic of China
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EE Lin Lim
Smith College

Oleg N. Limeshko
Moscow Institute of
Physics and Technology,
Russia

Fellows, Students, & Visitors

Christopher A. Linder
United States Naval
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Daniel Lizarralde
Virginia Polytechnic
Institute
Texas A&M Univer-
sity, M.S.

Laura S. Magde
University of Califor-
nia, Berkeley

Elizabeth L. Mann
Bowdoin College

Thomas Marchitto
Yale University

Linda V. Martin
University of Water-
loo, Canada

Sean P. McKenna
Rensselaer Polytech-
nic Institute

Patrick J. Miller
Georgetown University

Elizabeth C. Minor
College of
William & Mary

Archie T. Morrison III
Harvard University

Bingjian Ni
Peking University,
Peoples Republic of
China
Peking University,
Peoples Republic of
China, S.M.

Douglas P. Nowacek
Ohio Wesleyan Uni-
versity

Marjorie F. Oleksiak
Massachusetts Insti-
tute of Technology

Vladimir I. Osychny
Moscow State Univer-
sity, Russia

George P. Panteleyev
Moscow State Univer-
sity, Russia

Young-Gyu Park
Seoul National
University, Korea
Seoul National
University, Korea, S.M.

Ann Pearson
Oberlin College

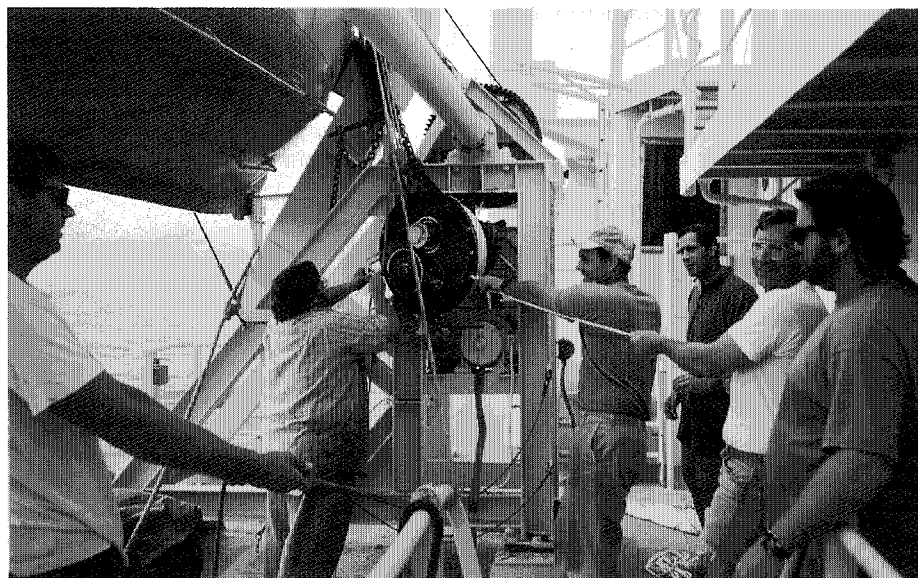
Nicole Poulton
Virginia Polytechnic
Institute

François W. Primeau
University of Water-
loo, Canada
University of Alberta,
Canada, M.S.

James M. Pringle
Dartmouth College

Brian S. Racine
Millersville University

Deborah M. Redish
Stanford University



Atlantis II personnel repair lifeboat falls. From left, they are Ray Burke, Phil Treadwell, Mike Schmitt, Mike Feeney, Charley Charpentier, and John Cawley.

Bonnie J. Ripley
Occidental College

Paul E. Robbins
Oberlin College

Gabrielle Rocap
Massachusetts Insti-
tute of Technology
Massachusetts Insti-
tute of Technology,
S.M.

Alberto E. Saal
Universidad
Nacional de Cordoba,
Spain, Ph.D.
Massachusetts Insti-
tute of Technology,
S.M.

Julian P. Sachs
Williams College

Makoto Saito
Oberlin College

Paulo Salles
National Autono-
mous University of
Mexico

Gorka A. Sancho
Universidad
Autonoma Madrid,
Spain

Mary Ann Schlegel
University of Vermont
University of Vermont,
M.S.

**Jennifer Joy
Schleizinger**
Boston College

Mario R. Sengco
Long Island Univer-
sity, Southampton

William J. Shaw
Princeton University

Li Shu
The Cooper Union
The Cooper Union,
M.E.

Sharon R. Siegel
Columbia College

Daniel M. Sigman
Stanford University

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

Mikhail A. Solovev
Moscow State
University, Russia

Brian J. Sperry
University of Iowa
MIT/WHOI Joint
Program, S.M.

Louis C. St. Laurent
University of Rhode
Island

Dana R. Stuart
University of
Michigan
University of
Michigan, M.S.

Miles A. Sundermeyer
University of Califor-
nia, Santa Cruz

Xiaou Tang
University of Science
and Technology of
China
University of Roches-
ter, M.S.

Gaspar Taroncher
Oldenburg
Universidad
Autonoma Madrid,
Spain

Alvin Tarrell
University of
Nebraska, Lincoln

Rebecca E. Thomas
Duke University

Brian H. Tracey
Kalamazoo College
MIT/WHOI Joint
Program, S.M.

Peter A. Traykovski
Duke University
MIT/WHOI Joint
Program, S.M.

Kathleen E. Wage
University of Tennes-
see at Knoxville
MIT/WHOI Joint
Program, S.M.

Richard M. Wardle
University of York,
England

Joseph D. Warren
Harvey Mudd College

Helen F. Webb
Worcester Polytechnic
Institute

Sandra R. Werner
Dartmouth College
Technical University
of Aachen, Germany,
M.S.

Suzanne W. Wetzel
Princeton University

Frank M. Weyer
Stevens Institute of
Technology
California Institute of
Technology, M.S.

Sheri N. White
Purdue University

William J. Williams
Cambridge Univer-
sity, Jesus College,
England

Xiaoyun Zang
Nanjing Institute of

Meteorology, Peoples
Republic of China
Institute of Atmo-
spheric Physics,
Peoples Republic of
China, M.S.

Jubao Zhang
University of Science
and Technology of
China, Peoples
Republic of China
Chinese Academy of
Science, Peoples
Republic of China,
M.S.

Woods Hole Program 1995-1996 Fall Term

Amy Samuels
University of Califor-
nia, Davis
University of Califor-
nia, Davis, M.S.

Postdoctoral Scholars/ Fellows Awarded

**Myriam Andree
Barbeau**
George D. Grice
Postdoctoral Scholar,
Dalhousie University,
Canada

Onno Bokhove
J. Seward Johnson
Postdoctoral Scholar,
University of Toronto,
Canada

Minhan Dai
Henry L. and Grace
Doherty Postdoctoral
Scholar, Xiamen
University, China

David Darby
J. Seward Johnson
Postdoctoral Scholar,
University of Glasgow,
Scotland

Tracy K. P. Gregg
NSF RIDGE
Postdoctoral Fellow,
Arizona State
University

**Alexander E.
Krupitsky**
J. Seward Johnson
Postdoctoral Scholar,
Columbia University

Dennis J. McGillicuddy
J. Seward Johnson
Postdoctoral Scholar,
Harvard University

Sharon Kay Papiernik
Environmental
Organic Geochemistry
Postdoctoral Scholar,
University of
Nebraska

Ingo Andreas Pecher
USGS/WHOI
Postdoctoral Scholar,
University of Kiel,
Germany

Craig Peter Sayers
J. Seward Johnson
Postdoctoral Scholar,
University of
Pennsylvania

Jeff Shimeta
Devonshire Associates
Postdoctoral Scholar,
University of
Washington

Kenneth W. W. Sims
J. Seward Johnson
Postdoctoral Scholar,
University of Califor-
nia, Berkeley

George Voulgaris
Andrew W. Mellon
Coastal Processes
Postdoctoral Scholar
University of South-
ampton, England

Marine Policy Senior Research Fellow

Daniel Curran

Marine Policy Research Fellow

Maria Borgia
Boston University

Summer Student Fellows

Thomas T. Ballantine
Princeton University

Anna E. Chefter
Massachusetts Institute of Technology

Stephanie Hamilton Concelman
University of Georgia, Athens

Paula Aileen Dygert
Boston University

Margaret Saxby Edie
University of Washington

Jeffrey Alan Freund
Stanford University

Erica Beth Goldman
Yale University

David Kenneth Hall
University of Washington

Benjamin Scott Halpern
Carleton College

Leslie Hopewell Hebb
University of Denver

Passant V. Karunaratne
Lafayette College

Brenda Michelle Kutcher
University of California, Irvine

Yvette Sue Maestas
Wellesley College

Tracey Ann McDonnell
Hood College

Juliet A. Nichols
Barnard College

James W. Partan
Cambridge University, England

Samanthi A. Perera
Mount Holyoke

Paul Christian Ripple
Northern Michigan University

Emily G. Severance
University of Maryland

John D. Tolli
San Diego State University

Ana L. Unruh
Trinity University

Graham J. Veitch
Cambridge University, England

Cheryl Lynn Waters
Duke University

Karen Marie Worminghaus
DePauw University

Brian S. Wysor
Southampton College

Minority Trainees

Mary Elizabeth Bryant
Northeast Missouri State University

Malibea Ivette Burguillo
George Washington University

Eva Santana
University of Delaware

Dale Warren Young
Virginia State University

Geophysical Fluid Dynamics Participants

James L. Anderson
Stevens Institute of Technology

Neil J. Balmforth
University of Texas

Pavel Berloff
Florida State University

Paola Cessi
University of California, San Diego

Eric P. Chassignet
University of Miami

Eric A. D'Asaro
Applied Physics Laboratory, Seattle

Diego del-Castillo Negrete
University of California, San Diego

Stephan Fauve
Ecole Normale Supérieure de Lyon, France

Joseph H. Fernando
Arizona State University

Glenn R. Flierl
Massachusetts Institute of Technology

Rupert Ford
University of California, San Diego

Anand Gnanadesikan
Woods Hole Oceanographic Institution

Thomas Haine
Massachusetts Institute of Technology

Joseph L. Hammack
Warriors Mark, Pennsylvania

Diane M. Henderson
Pennsylvania State University

Jackson R. Herring
National Center for Atmospheric Research

Simon Hood
University of Liverpool, England

Louis N. Howard
Florida State University

Keith A. Julien
National Center for Atmospheric Research

Joseph B. Keller
Stanford University

Robert M. Kerr
National Center for Atmospheric Research

Oliver Kerr
City University, London, England

Richard Kerswell
University of Newcastle, England

Edgar Knobloch
University of California, Berkeley

Ruby E. Krishnamurti
Florida State University

Sonya A. Legg
University of California, Los Angeles

Amala Mahadevan
University of Chicago

Willem V.R. Malkus
Massachusetts Institute of Technology

John C. Marshall
Massachusetts Institute of Technology

Steven P. Meachem
Florida State University

Olivier J. Metais
LEGOS, France

Philip J. Morrison
University of Texas

Young-Gyu Park
MIT/WHOI Joint Program in Oceanography

Brendan B. Plapp
Cornell University

Claes G. Rooth
University of Miami



Summer employees Glenn McDonald and Naomi Fraenkel prepare Sandy Williams's quadrapod to be deployed off Manhattan Island for studies of turbulence and mixing in the Hudson River estuary.

Fellows, Students, & Visitors

Thomas Rossby
University of
Rhode Island

Richard L. Salmon
University of Califor-
nia, San Diego

Engelbert L. Schuckling
New York University

Uwe Send
Kiel University,
Germany

Edward A. Spiegel
Columbia University

Andrew Stamp
University of
Washington

Victor Steinberg
Weizmann Institute
of Science, Israel

Melvin E. Stern
Florida State
University

Reuben K. Thieberger
Columbia University

George Veronis
Yale University

Martin Visbeck
Massachusetts Insti-
tute of Technology

Joseph A. Werne
National Center for
Atmospheric Research

John Whitehead
Woods Hole Oceano-
graphic Institution

Andy Woods
Cambridge Univer-
sity, England

Rodney Worthing
Massachusetts Insti-
tute of Technology

William R. Young
University of Califor-
nia, San Diego

Geophysical Fluid Dynamics Summer Semi- nar Fellows

Jonathan M. Aurnou
Johns Hopkins
University

Helene Theresa Banks
University of
Southampton,
England

Paul John Dellar
Cambridge Univer-
sity, England

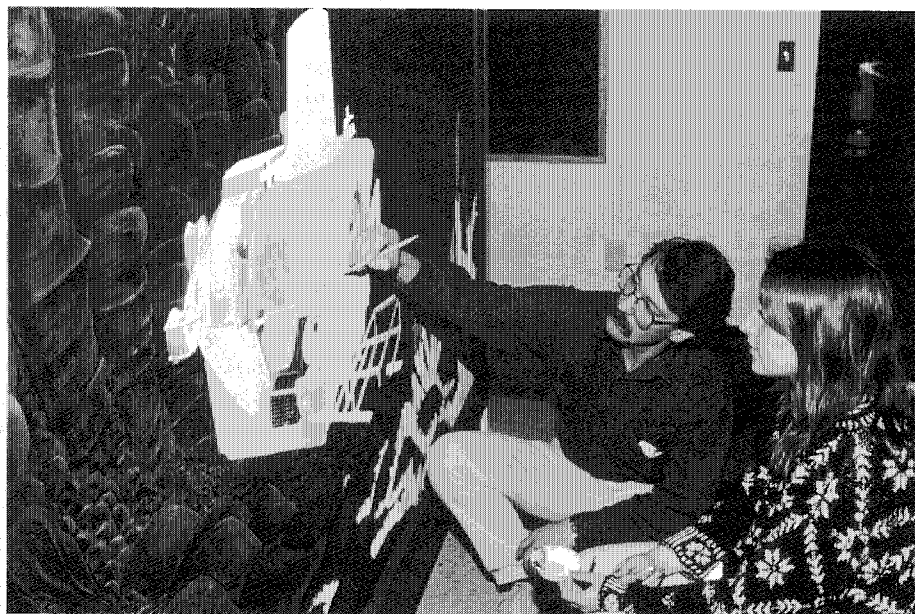
Oleg Eugene Esenkov
University of Miami,
Rosenstiel School of
Marine and Atmo-
spheric Science

Thomas James Noyes
University of Califor-
nia, San Diego

Vakhtang Putkaradze
Niels Bohr Institute,
Denmark

Fiammetta Straneo
University of
Washington

**Stephen Anthony
Zatman**
Harvard University



WHOI Illustrator Paul Oberlander worked with six Falmouth High School art students to create a 25-foot-long mural for the Exhibit Center. Here he and Jessica Hauser work out details for a rendering of the submersible Alvin.

H. Burr Steinbach Visiting Scholars

John Hayes
Indiana University

Walter Munk
Scripps Institution of
Oceanography

Sylvia A. Earle
Deep Ocean Explora-
tion and Research, Inc.

David M. Lane
Heriot-Watt Univer-
sity, Scotland

Peter B. Rhines
University of
Washington

Don L. Anderson
California Institute of
Technology

Guest Students

Fred A. Ackerman
Massachusetts Insti-
tute of Technology

Kimberly Amaral
University of Massa-
chusetts, Dartmouth

Niclas P. Bjornstad
University of
Göteborg, Sweden

Doug Bruce
Bowdoin College

Brenda Burkhalter
Boston University

Kathleen E. Campbell
Rumson-Fair
Haven H.S.

Giancarlo Cetrulo
University of Califor-
nia, Santa Barbara

Dreux Chappell
The Brearley School

Shoshana Coates
Cambridge Univer-
sity, England

Eric Cocco
Bronxville H.S.

David E. Cole
Syracuse University

**Stephanie Hamilton
Concelman**
University of Georgia,
Athens

Forbes L. Darby
Connecticut College

Christopher Ford
Bronxville H.S.

Andrew M. Freed
Utah State University

Cara E. Fritz
Amherst College

Ikuko Fujii
University of Tokyo

James S. Gerber
Brown University

Joshua D. Goldberg
University of Califor-
nia, San Diego

Caroline M. Granger
Smith College

Robert G. Granucci
Falmouth H.S.

Meghan A. Jendrysik
Massachusetts Insti-
tute of Technology

Tatyana Klibanov
Lafayette College

Patricia Ann Lee
Colby College

Ian Ogden Malin
Tabor Academy

Michael S. Morss
Stonehill College

Yea-Ling Ong
Lafayette College

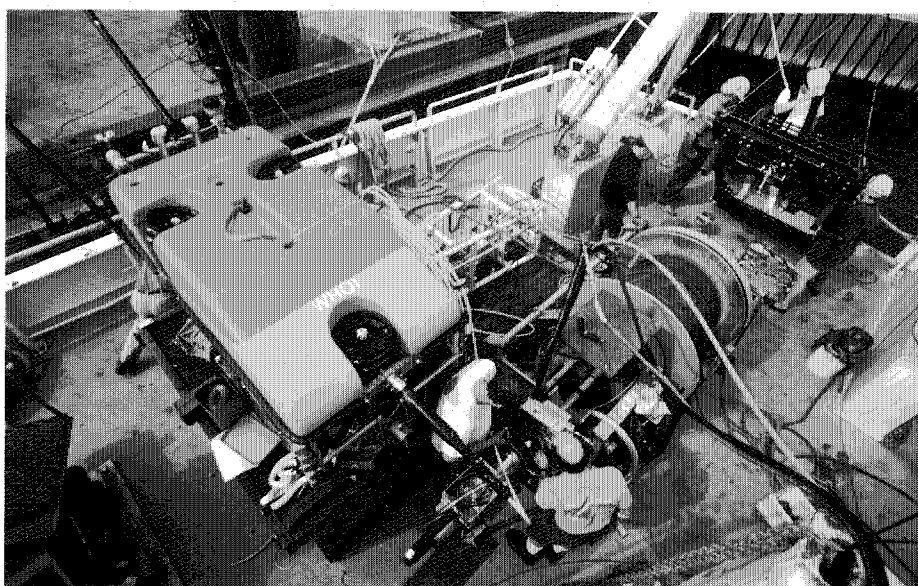
Jewel M. Parham
Fort Valley State
College

Kathrin Pisarew
University of Bremen,
Germany

William Robertson
Skidmore College

Laurel Schaidler
Massachusetts Insti-
tute of Technology

Sarah Swift
University of Rhode
Island



Will Sellers, left, and Phil Alatalo set up Cabell Davis's and Scott Gallagher's video plankton recorder for its first work with the robotic vehicle Jason aboard R/V Endeavor (University of Rhode Island). Endeavor crew members work with a multiple opening/closing net system at right.

Jacqueline Thomas
University of
Washington

Rebecca Trotsky-Sirr
South High

Christian Wells
Vanderbilt University

Bradley White
Michigan State
University

Jonathan Wylie
Birmingham
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Marshall Swartz lowers a conductivity/temperature/depth sensor into a calibration bath in Clark Laboratory South.

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Table 1
Sources of
Research Funding

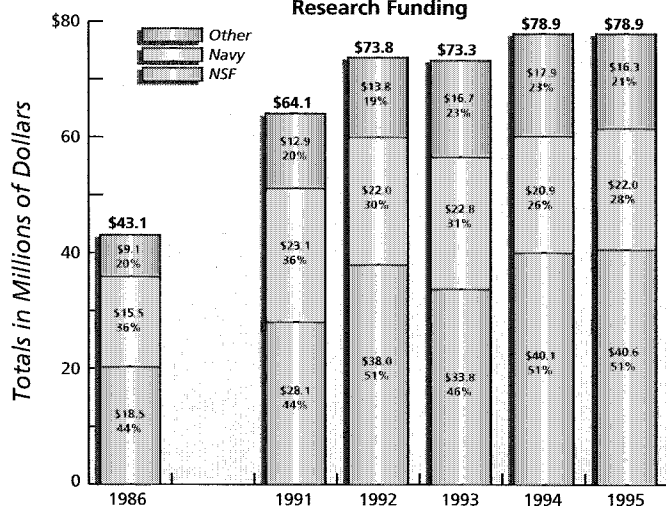


Table 2
Gifts and Grants from Private Sources
(excluding pledges)

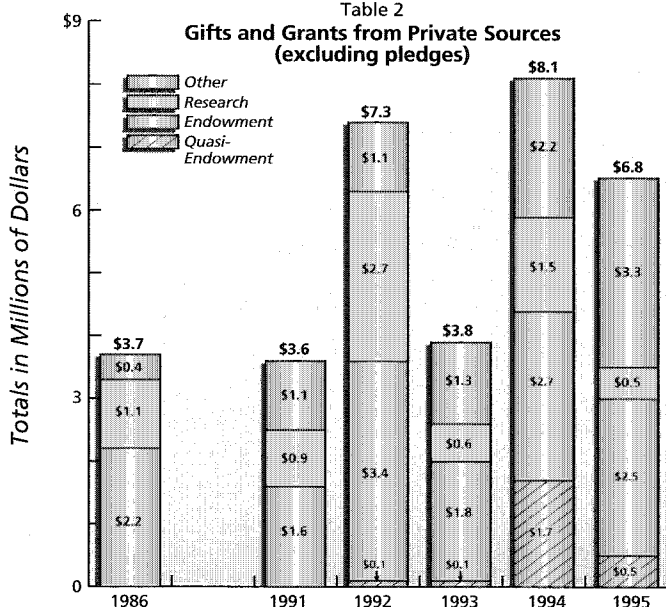
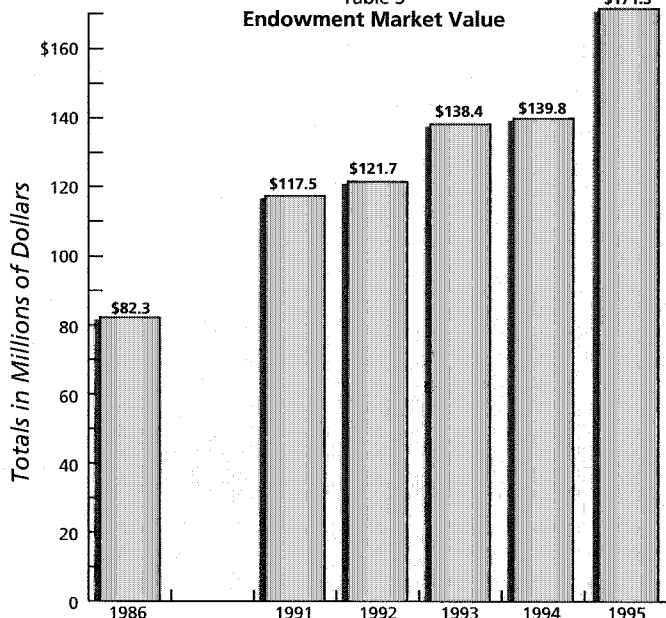


Table 3
Endowment Market Value



The Woods Hole Oceanographic Institution experienced many changes in its financial areas during the calendar year 1995. A new Chief Financial Officer was installed in early October, a new administrative financial system was implemented in December, and new financial statements were adopted in response to a pronouncement from the Financial Accounting Standards Board.

It is a pleasure to report that the Institution's financial position remains strong. The Institution is current with all government audits and continues to strengthen the financial staff in order to ensure that WHOI remains in compliance with regulations. The endowment grew 23%, ending the year with a market value of \$171.3 million. Private fundraising continues to be successful, adding over \$6 million in 1995. Government sponsored research funding remained flat from 1994 levels, despite the prediction of declining funding levels. Overhead expenses were below budget for the year, resulting in the Institution having fully recovered its overhead expenses in the current year. This full overhead recovery is indicative of management's close attention to overhead spending levels.

Management is committed to monitoring and controlling overhead spending. In 1995, overhead spending was 4% below budget. Further overhead spending reductions were made in the 1996 budget in order to ensure the competitiveness of the Institution's funding proposals.

Sponsored research continues to be the primary source of revenue for the Institution, representing more than 82% of the total operating revenue for the year. (See Table 1 for an overview of the sources of research revenue for the Institution.)

In 1995, gifts and grants from private sources were \$6.8 million, compared to \$8.1 million in 1994 and \$3.8 million in 1993. (See Table 2.) Outstanding pledges at the end of 1995 were \$4.7 million, compared to \$2.6 million at the end of 1994 and \$2.1 million at the end of 1993. (Note: For financial statement purposes, only unconditional pledges over \$10,000 are booked as revenue.) The Capital Campaign had raised almost \$42 million by the end of 1995.

Since it is still expected that government funding of ocean sciences research will decline in the coming years, the Institution is intensifying its efforts in the areas of strategic planning and identification of alternative sources of funding. It is the goal of management to position the Institution so that opportunities for alternative sources of funding can be taken advantage of as government sources diminish.

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 and Administration

BALANCE SHEET as of December 31, 1995 and 1994

	1995	1994			
Assets:					
Cash and cash equivalents	\$ 21,798,524	\$ 17,334,292			
Accrued interest and dividends	792,039	1,119,351			
Reimbursable costs and fees:					
Billed	5,241,352	3,685,844			
Unbilled	1,442,220	1,902,002			
Other receivables	565,693	768,505			
Pledges receivable	4,746,722	2,100,064			
Inventory	630,208	598,348			
Deferred charges and prepaid expenses	1,146,129	1,048,355			
Deferred fixed rate variances	(989,384)	474,346			
Investments	167,449,483	133,702,747			
Other current assets	826,200	-			
 Total current assets	 203,649,186	 162,733,854			
 Property, plant and equipment:					
Land, buildings and improvements	43,122,971	41,591,075			
Vessels and dock facilities	8,916,264	8,911,543			
Laboratory and other equipment	10,081,754	8,918,901			
Work in process	10,264	408,171			
	62,131,253	59,829,690			
Accumulated depreciation	(32,910,055)	(30,302,689)			
 Net property, plant and equipment	 29,221,198	 29,527,001			
 Remainder trusts	 951,173	 162,378			
 Total assets	 \$233,821,557	 \$192,423,233			
 Liabilities:					
Accounts payable and other liabilities	8,508,284	4,315,083			
Accrued payroll and related liabilities	4,478,099	4,778,953			
Accrued supplemental retirement benefits	5,480,325	4,567,104			
Deferred revenue and refundable advances (research)	7,151,900	3,893,203			
 Total liabilities	 25,618,608	 17,554,343			
	Unrestricted	Temporarily Restricted	Permanently Restricted		
Net assets:					
Undesignated	\$ 938,608	\$ 6,105,217		7,043,825	3,432,660
Designated	2,062,581			2,062,581	2,965,496
Plant and facilities	30,621,946	34,207		30,656,153	30,756,929
Education	337,878	2,298,679		2,636,557	2,452,410
Endowment and similar funds	39,573,843	102,435,131	\$23,794,859	165,803,833	135,261,395
Total net assets	\$73,534,856	\$110,873,234	\$23,794,859	208,202,949	174,868,890
 Total liabilities and net assets					
				\$233,821,557	\$192,423,233

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

STATEMENT OF CASH FLOWS for the years ended December 31, 1995 and 1994

	1995	1994
Cash flows from operating activities:		
Total change in net assets	\$ 33,334,059	\$ 4,657,045
Adjustments to reconcile increase in net assets to net cash provided by operating activities:		
Depreciation	2,833,288	2,591,513
Net realized and unrealized (gain) loss on investments	(27,572,686)	3,104,211
(Increase) decrease in:		
Accrued interest and dividends	327,312	(517,303)
Reimbursable costs and fees:		
Billed	(1,555,508)	(821,385)
Unbilled	459,782	329,678
Other receivables	202,812	(164,504)
Pledges receivable	(2,646,658)	(2,100,064)
Inventories	(31,860)	4,368
Deferred charges and prepaid expenses	(97,774)	(79,098)
Deferred fixed rate variances	1,463,730	1,011,179
Other current assets	(826,200)	-
Remainder trusts	(788,795)	(162,378)
Increase (decrease) in:		
Accounts payable and other liabilities	4,193,202	(4,048,620)
Accrued payroll and related liabilities	(300,854)	360,813
Deferred revenue	3,258,697	(24,707)
Accrued supplemental retirement benefits	913,221	113,124
Net cash provided by operating activities	13,165,768	4,253,872
Cash flows from investing activities:		
Capital expenditures:		
Additions to property and equipment	(2,527,485)	(5,101,464)
Disposals of property and equipment	225,922	-
Endowment:		
Proceeds from the sale of investments	109,287,744	100,606,647
Purchase of investments	(115,687,717)	(114,247,785)
Net cash (used) by investing activities	(8,701,536)	(18,742,602)
Net increase (decrease) in cash and cash equivalents	4,464,232	(14,488,730)
Cash and cash equivalents, beginning	17,334,292	31,823,022
Cash and cash equivalents, ending	\$ 21,798,524	\$ 17,334,292

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

Financial Statements

STATEMENT OF ACTIVITIES for the years ended December 31, 1995 and 1994

	Unrestricted	Temporarily Restricted	Permanently Restricted	1995	1994
Operating:					
Revenues:					
Fees	\$ 589,396			\$ 589,396	\$ 626,565
Sponsored research:					
Government		\$ 71,894,988		71,894,988	71,998,821
Non-government		7,022,791		7,022,791	6,883,351
Assets released from restriction	78,917,779	(78,917,779)		-	-
Education:					
Tuition	2,547,731			2,547,731	2,489,657
Endowment income		3,139,361		3,139,361	2,973,100
Gifts and transfers		464,538		464,538	172,203
Education funds availed of	2,617,865	(2,617,865)		-	-
Investment interest and dividends	1,483,010			1,483,010	1,403,630
Contributions and gifts	1,447,188	4,059,529	\$ 2,601,026	8,107,743	8,033,434
Rental income	639,806			639,806	592,477
Communications and publications	241,003			241,003	171,141
Other	64,483			64,483	91,659
Total revenues	<u>88,548,261</u>	<u>5,045,563</u>	<u>2,601,026</u>	<u>96,194,850</u>	<u>95,436,038</u>
Expenses:					
Sponsored research:					
National Science Foundation	40,580,767			40,580,767	40,051,468
United States Navy	21,946,891			21,946,891	20,857,577
Subcontracts	3,581,893			3,581,893	5,200,398
Advanced Research Projects Agency	3,202,289			3,202,289	4,739,541
National Oceanic and Atmospheric Administration	2,333,449			2,333,449	2,561,451
Department of Energy	1,747,905			1,747,905	1,526,853
United States Geological Survey	400,521			400,521	644,878
Other	5,124,064			5,124,064	3,300,006
Education:					
Faculty expense	1,946,069			1,946,069	1,786,319
Student expense	1,006,342			1,006,342	1,127,173
Postdoctoral programs	367,642			367,642	334,006
Other	571,678			571,678	548,723
Development	1,086,948			1,086,948	1,493,667
Rental expenses	355,667			355,667	336,128
Communications and publications	711,052			711,052	627,610
Un-sponsored programs	992,272			992,272	769,741
Other expenses	2,575,365			2,575,365	1,668,472
Total expenses	<u>88,530,814</u>	<u>-</u>	<u>-</u>	<u>88,530,814</u>	<u>87,574,011</u>
Change in net assets from operating activities	<u>17,447</u>	<u>5,045,563</u>	<u>2,601,026</u>	<u>7,664,036</u>	<u>7,862,027</u>
Nonoperating:					
Income:					
Ship overhaul	2,635			2,635	1,331,328
Net realized gain (loss) on investments	1,019,174	5,090,932		6,110,106	3,006,905
Net unrealized gain (loss) on investments	3,579,984	17,882,596		21,462,580	(6,111,116)
Expenses:					
Nonoperating research and education expense	1,801,887			1,801,887	-
Ship overhaul	2,635			2,635	1,331,328
Other nonoperating expenses	26,549	74,227		100,776	100,771
Change in net assets from nonoperating activities	<u>2,770,722</u>	<u>22,899,301</u>	<u>-</u>	<u>25,670,023</u>	<u>(3,204,982)</u>
Total change in net assets	<u>2,788,169</u>	<u>27,944,864</u>	<u>2,601,026</u>	<u>33,334,059</u>	<u>4,657,045</u>
Net assets at beginning of year	<u>70,746,687</u>	<u>82,928,370</u>	<u>21,193,833</u>	<u>174,868,890</u>	<u>170,211,845</u>
Net assets at end of year	<u>\$ 73,534,856</u>	<u>\$ 110,873,234</u>	<u>\$ 23,794,859</u>	<u>\$208,202,949</u>	<u>\$174,868,890</u>

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 balance sheets of Woods Hole Oceanographic Institution as of December 31, 1995 and 1994 and the related statements of activities and cash flows for the years then ended. These financial statements are the responsibility of the Institution's management. Our responsibility is to express an opinion on these financial statements based on our audits.

We conducted our audits 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 audits provide 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, 1995 and 1994, and the changes in its net assets and its cash flows for the years then ended, in conformity with generally accepted accounting principles.

As discussed in Note B to the financial statements, the Woods Hole Oceanographic Institution adopted the provisions of Statement of Financial Accounting Standards No. 116, *Accounting for Contributions Received and Contributions Made*, and No. 117, *Financial Statements of Not-for-Profit Organizations*, in 1995, effective January 1, 1994. Accordingly, the Institution restated its previously issued 1994 financial statements to conform to these new accounting standards.

Coppen & Lybrand C.P.C.

Boston, Massachusetts
March 29, 1996

NOTES TO FINANCIAL STATEMENTS

A. Background:

Woods Hole Oceanographic Institution (the "Institution") is a not-for-profit research and educational institution located in Woods Hole, Massachusetts. The Institution was founded in 1930.

B. Summary of Significant Accounting Policies:

Basis of Presentation

In 1995 the Institution adopted 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*. The Institution adopted these statements effective January 1, 1994 and prospectively restated its originally reported 1994 financial statements to conform to the new standards. 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 accompanying financial statements, which are presented on the accrual basis of accounting, 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 following table shows the grouping of fund balances formerly presented in the Institution's financial statements and the current asset classification:

Fund Group	Net Asset Class
Current unrestricted funds	Unrestricted
Current restricted funds	Restricted or temporarily restricted
Current designated funds	Unrestricted
Current other funds	Unrestricted
Endowment funds	Unrestricted, temporarily or permanently restricted
Quasi-endowment funds	Unrestricted
Invested in plant	Unrestricted
Unexpended plant funds	Unrestricted or temporarily restricted

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 appro-

priates 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.

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 of assets other than cash are recorded at their estimated fair value. Contributions to be received after one year are discounted at the appropriate rate commensurate with the risks involved. Amortization of the discount is recorded as additional contribution revenue in accordance with the donor-imposed restrictions, if any, on the contributions. 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. Endowment income and gains of the Institution's unrestricted investments over the amount appropriated under the Institution's spending plan are reported as nonoperating revenue.

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.

Included in cash at December 31, 1995 and 1994 is \$2,999,081 and \$2,447,884, respectively, representing advances received from the United States Navy. Such amounts are restricted in use to certain vessel refit and other research programs.

Financial Statements

Interest earned on unspent funds reverts to the federal government. Cash and cash equivalents also include uninvested amounts from each classification of net assets (i.e., 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. 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.

Contracts and Grants

Revenues earned on contracts and grants for research are recognized as related costs are incurred. The Institution has negotiated with the federal government fixed rates for the recovery of certain indirect costs. 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.

Investment Income Utilization

Investment of the Institution's endowment fund is based on a total return policy. The Institution distributes to individual funds an amount of investment income earned by each of the fund's proportionate share of investments in the endowment fund (interest and dividends) based on a percentage of the prior three year's endowment market values. During periods when investment income exceeds the distribution, such excess income is added to a stabilization account. Conversely, when investment income is less than the distribution such deficit is funded by accumulated excess income or accumulated net realized and unrealized gains of the stabilization account.

The Institution has interpreted relevant state law as generally permitting the spending of gains on endowment funds over a stipulated period of time. The Board of Trustees has appropriated all of the income and a specified percentage of the net appreciation 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 \$5,947,126 and \$5,544,549 for the years ending December 31, 1995 and 1994, respectively, and is classified in operating revenues (research, education, and operations).

Gifts

Unconditional gifts are recognized as revenue when pledged (as temporarily restricted assets until received) and restricted gifts are recognized as revenue as they are expended for their stated purposes.

Noncash gifts are generally recorded at market value on the date of the gift, 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.

Property and equipment

Property, plant and equipment assets 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 plant assets purchased by the Institution in the amounts of \$2,732,512 and \$2,490,742 in 1995 and 1994, respectively, has been charged to operating activities. Depreciation on certain government-funded facilities (*Atlantis* and *Atlantis II*, the Laboratory for Marine Science and the dock facility) amounting to \$100,776 and \$100,771 in 1995 and 1994, respectively, has been charged to nonoperating as these assets are owned by the Government. Title to the research vessels *Atlantis* and *Atlantis II* are contingent upon their continued use for oceanographic research.

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, 1995 and 1994, 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.

C. Investments:

The cost and market value of investments held at December 31, 1995 and 1994 are as follows:

	1995		1994	
	Cost	Market	Cost	Market
U.S. Government and government agencies	\$ 17,952,260	\$ 18,822,499	\$ 11,340,797	\$ 10,578,329
Corporate bonds	8,793,317	9,223,161	9,875,143	9,304,581
International bond funds	8,900,476	9,483,318	10,434,662	9,767,574
Other bonds	403,589	403,698	3,053,778	3,126,836
Common stock	90,301,231	125,887,735	80,648,097	97,707,523
Other	4,521,478	3,629,072	3,980,188	3,217,904
Total investments	<u>\$130,872,351</u>	<u>\$167,449,483</u>	<u>\$119,332,665</u>	<u>\$133,702,747</u>

D. Investment Units:

The value of an investment unit at December 31, 1995 and 1994 was \$3.0058 and \$2.4524, respectively. The investment income per unit for 1995 and 1994 was \$.0731 and \$.0684, respectively.

	1995	1994
Unit value, beginning of year	\$ 2.4524	\$ 2.5085
Unit value, end of year	3.0058	2.4524
Net change for the year	.5534	(.0561)
Investment income per unit for the year	.0731	.0684
Total return per unit	<u>\$.6265</u>	<u>\$.0123</u>

E. Investment Income:

Investment income consisted of the following:

	1995	1994
Interest and dividends	\$ 4,718,661	\$ 4,309,024
Investment management costs	(513,706)	(423,783)
Net investment income	<u>\$ 4,204,955</u>	<u>\$ 3,885,241</u>

F. Net Assets Released from Restrictions:

Net assets released from temporary donor restrictions by incurring expenses satisfying the restricted purposes or by occurrence of events specified by the donors are as follows:

	1995	1994
Purpose restrictions:		
Research	\$ 78,917,779	\$ 78,882,172
Education	2,617,865	2,656,456
	<u>\$ 81,535,644</u>	<u>\$ 81,538,628</u>

G. Pledges Receivable:

Pledges receivable consisted of the following at December 31:

	1995	1994
Unconditional promises expected to be collected in:		
Less than one year	\$ 3,259,601	\$ 1,593,743
One year to five years	1,487,121	506,321
	<u>\$ 4,746,722</u>	<u>\$ 2,100,064</u>

Pledges due in a period greater than one year have been recorded at their present value based on discounted cash flow.

H. Retirement Plans:

The Institution maintains a noncontributory defined benefit pension plan covering substantially all employees of the Institution. The Institution also maintains a supplemental benefit plan covering 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 consisted of the following for 1995:

	Defined Benefit Plan	Supplemental Benefit Plan	Total
Service cost	\$ 3,159,730	\$ 113,980	\$ 3,273,710
Interest cost	5,969,453	235,064	6,204,517
Actual return on plan assets	(23,204,114)	(133,530)	(23,337,644)
Net amortization and deferral	14,045,345	(167,973)	13,877,372
Net pension (income) expense	\$ (29,586)	\$ 47,541	\$ 17,955

Below is a reconciliation of the funded status of the plans at December 31, 1995:

	Defined Benefit Plan	Supplemental Benefit Plan	Total
Actuarial present value of obligation:			
Vested benefit obligations	\$ (72,176,819)	\$ (1,209,192)	\$ 73,386,011
Nonvested benefits	(2,158,353)	(1,315,882)	(3,474,235)
Accumulated benefit obligation	(74,335,172)	(2,525,074)	(76,860,246)
Projected benefit obligation	(88,288,733)	(3,352,720)	(91,641,453)
Fair value of plan assets (primarily invested in common stocks and fixed income securities)	119,652,747	-	119,652,747
Plan assets in excess of the projected benefit obligation	31,364,014	(3,352,720)	28,011,294
Unrecognized net transition (asset) obligation	(3,877,573)	772,778	(3,104,795)
Unrecognized prior service costs	371,804	-	371,804
Unrecognized net gain	(27,664,978)	(1,023,733)	(28,688,711)
Prepaid pension cost	\$ 193,267	\$ (3,603,675)	\$ (3,410,408)

The plan assets listed above are held in the Woods Hole Oceanographic Retirement Trust at December 31, 1995. In addition, the Institution has accrued a liability sufficient to fund future supplemental plan benefits earned at December 31, 1995.

The discount rate and rate of increase in future compensation used to determine the projected benefit obligation as of December 31, 1995 were 7.25% and 4.5%, respectively. The expected return on plan assets was 9.6%.

I. Other Post Retirement Benefits:

In addition to providing pension 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 with certain time in service limitations.

In December 1990, the Financial Accounting Standards Board issued Statement of Financial Accounting Standards No. 106, "Employer's Accounting for Postretirement Benefits Other than Pensions" ("SFAS 106"). SFAS 106 requires companies to accrue the cost of postretirement health care within the employees' active service periods. In 1993, the Institution adopted SFAS 106. SFAS 106 allows either immediate recognition of the obligation for postretirement benefit or the delayed recognition method. The Institution elected the delayed recognition method and is recognizing the accumulated postretirement benefit obligation over 20 years.

Net periodic postretirement benefit cost consisted of the following for 1995:

Service cost	\$ 339,499
Interest cost	1,154,746
Actual return on plan assets	(390,738)
Net amortization and deferrals	331,430
Net periodic postretirement benefit cost	\$1,434,937

The Institution has a Voluntary Employees' Beneficiary Association Trust (the "Trust") that will be used 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 Plan. During the year ended December 31, 1995 the Institution paid \$1,600,000 in retiree health benefits on behalf of the Trust. The following table sets forth the funded status of the Plan as of December 31, 1995:

Financial status of plan:

Accumulated postretirement benefit obligation:	
Retirees	\$ (9,696,157)
Fully eligible, active plan participants	(3,306,170)
Other active plan participants	(4,250,558)
Total obligation	(17,252,885)
Plan assets at fair value	7,202,520
Unrecognized net transition obligation	14,510,339
Unrecognized prior service cost	(6,318,924)
Unrecognized loss	3,490,472
Accrued postretirement benefit asset	\$ 1,631,522

The assumed discount rate is 7.25%. The expected long-term rate of return on plan assets used in determining the net periodic postretirement benefits cost was 8.25% in 1995. The rate of increase in the per capita costs of covered health care benefits is assumed to be 7.0% in 1995 and 5.5% in future years.

If the health care cost trend rate assumptions were increased by 1%, the accumulated postretirement benefit obligation, as of December 31, 1995, would be increased by approximately \$2,318,516; the effect of this change on the sum of the service cost and interest cost components of net periodic postretirement benefit cost for 1995 would be an increase of approximately \$259,467.

J. Restatement of Prior-Year Financial Information:

As discussed in Note B, in 1995 the Institution adopted SFAS 116 and 117 effective January 1, 1994, and restated the previously reported 1994 financial information to conform to the newly adopted accounting principles. The effect of the standards and other changes on the January 1, 1994, previously reported fund balances is as follows:

	1995	1994
January 1 fund balances, as previously reported	\$ 181,229,133	\$178,720,568
Less:		
Reclassifications of refundable U.S. Government to deferred revenue	(3,893,203)	(4,054,743)
Reclassification of supplemental restricted reserve to liability	(4,567,104)	(4,453,980)
Add:		
Pledges receivable booked in 1994 on adoption of SFAS 116 as of January 1, 1994	2,100,064	-
January 1 net assets as restated	\$174,868,890	\$170,211,845

K. Tax Status:

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.

L. Contingencies:

The Institution receives funding or reimbursement from federal government agencies for sponsored research under government grants and contracts. These grants and contracts provide for reimbursement of indirect costs based on rates negotiated with the Office of Naval Research (ONR), the Institution's cognizant agency. The Institution's indirect cost reimbursements have been based on fixed rates with carryforward of under or over recoveries. The Defense Contract Audit Agency (DCAA) is responsible for auditing both direct and indirect charges to grants and contracts on behalf of the ONR. In 1995, the Institution and the ONR agreed to a settlement of certain disputed items for the years 1987 to 1993. In the settlement each party agreed to consolidate actual 1987-1993 and estimated 1994 carryforward amounts and liquidate the net carryforward balances as part of the 1995 fixed rates. In addition, the 1995 fixed rates included the impact of certain unallowable costs from years 1987-1993. Currently 1994 and 1995 remain open subject to final negotiation. The Institution believes that the resolution of the open years will not have a material impact on its financial position.