Tom Kleindinst

Director Bob Gagosian presented several awards at the October 1998 Employee Recognition Ceremony.

1998 was designated by the United Nations as "The Year of the Ocean," and it provided both a backdrop and a spotlight for the Woods Hole Oceanographic Institution's numerous accomplishments.

The Institution's major achievements, of course, are advances in science and engineering and accompanying educational activities. We have a stunning research staff and student body whose dedication and scientific vision push the frontier of ocean exploration each day. An array of awards from the external oceanographic community received in 1998 attests to the quality of their efforts and their ability to compete with the best. (These awards are noted in the scientific department chairs' comments.)

We also received commendation this year from a more unusual place: No. 10 Downing Street, the address of British Prime Minister Tony Blair, who lauded the performance of our Deep Submergence Laboratory (DSL) in solving the riddle of what caused the 1980 sinking of *Derbyshire*, a 964-foot British bulk carrier with 44 people aboard. The answer relieved the anguish suffered by the families of the lost mariners and also pointed to ways to improve maritime safety. In a letter to President Clinton, Blair wrote: "This investigation was one of the greatest feats of underwater detective work ever undertaken…. The survey results have shown that the marine community can now investigate accidents even in the deepest oceans…. The outcome would not have been possible without the technology developed by the Woods Hole Oceanographic Institut[ion] who maintain the United States Deep Submergence Science Facility."

Our educational program also received a stellar review. As other academic institutions do, we periodically ask visiting committees, comprised of elite scientists and educators from other institutions, to give us an objective review of our departments and practices. We find their advice invaluable in planning for staffing and infrastructure to remain at the forefront of ocean sciences.

Such a visiting committee completed a review of the MIT/WHOI Joint Graduate Program in 1998, which marked the thirtieth anniversary of the program. We are grateful for the contributions of the review committee members, and what they concluded is a tribute to our faculty, students, and education staff: "The MIT/WHOI Joint Program is the top graduate program—or arguably one of the two top programs—in marine science in the world."

Newly minted oceanographers will be entering the field on the verge of an entirely new era. The strategy of mapping and sampling the oceans, which has served us well since World War II, is reaching its limits. We are shifting paradigms and creating the technology to make continuous, long-term observations of ocean processes and phenomena. Two important steps toward this goal were achieved last year as WHOI scientists led efforts to deploy the first permanent deep seafloor observatory and to plan for the establishment of a permanent coastal observatory off Martha's Vineyard.

Tom Kleindinst

Special recognition for John Hayes, right, in 1998 included election to the National Academy of Sciences. Here he discusses the operation of the National Ocean Sciences Accelerator Mass Spectrometry Facility with California Congressman Sam Farr, who visited WHOI in May 1998 to pursue hs long term interest in the oceans.

H2O, the Hawaii-2 Observatory, takes advantage of an abandoned 35-year-old AT&T trans-Pacific telephone cable to provide power and two-way communication to a 5,000-meter-deep seafloor observatory for an assortment of scientific instruments, such as devices to record earthquakes and listen for marine mammals. The Martha's Vineyard observatory will collect information 24 hours a day on the dynamic, but little-understood coastal processes that affect beach erosion, sand transport, weather conditions, waves, and coastal biological communities, as well as the interactions that occur where sea and air meet. Data from the observatory will be shared in real time with local officials, students, other scientists, and the public through the Internet.

WHOI scientists are also developing and building other kinds of observatories—instrument-packed arrays that can be moored in the oceans or that can float and drift for long periods throughout the oceans. These are the harbingers of technology that will allow us to "wire" the ocean—to receive continuous real-time information about it, much the way meteorologists now assemble data on atmospheric conditions.

We were also very pleased to obtain another type of "observatory," the Navy's deep submersible *Sea Cliff* with a diving capability of 6,100 meters. We are currently examining ways to combine the best of *Sea Cliff* with the 4,500-meter *Alvin*, which is now this nation's only deep-sea research submersible.

The "Year of the Ocean" offered many excellent opportunities for public outreach. We participated significantly in the National Oceans Conferences in Monterey, California, where I had the unexpected opportunity to brief President Bill Clinton, Vice President Al Gore, and Cabinet members on ocean issues. WHOI played a lead role in the US pavilion at Expo 98 in Lisbon, Portugal. We produced a video, "Discover Planet Ocean," that formed the centerpiece of the exhibit, as well as a display on the

Director's Comments

From left, Beecher Wooding, Seth Hitchings, Alan Chave, Skip Gleason, and Fred Duennebier (University of Hawaii) set up the junction box for the Hawaii-2 (H2O) observatory aboard *Thomas Thompson* (University of Washington).

Institution. During Expo 98's "US Day," I participated on a panel with the Secretaries of the Navy and Education, and also presented a keynote talk on the importance of the oceans to our future.

The PBS Visonaries series aired an excellent program on WHOI in 1998 and the Discovery Channel featured DSL's efforts in a documentary on the *Derbyshire* project. Our scientists continue their own outreach efforts, which range from one-on-one mentoring of young students preparing for science fair competitions to Internet interactions that have the potential to reach millions throughout the world. These are truly exciting times for communications, and I look forward to many more outreach successes—especially with the completion in early 2000 of a new addition to Fenno House, which will consolidate development, communications, and Director's office staffs under one roof. With an eye on space needs, we also initiated a campus-wide space planning effort in 1998, beginning with a review of scientific departments' needs. We will work over the next year toward assembling a 10- to 15-year campus space plan. Other infrastructure activity includes upgrading our docking facilities and telecommunication capabilities.

Our government-sponsored research income for 1998 was 7 percent ahead of budget, and prospects for ocean science funding appear brighter than they have for several years. The 1999 National Science Foundation budget is up 8.8 percent for research and related activities, and the Office of Naval Research basic research budget is up by 4 percent. In the National Science Foundation budget report, Congress noted the importance of ocean, earth, and atmospheric programs. This represents a turnaround in attitude and language from previous years.

We believe that our efforts in Washington, along with those of many others in the science community, are bearing fruit. We continue to intensify our work with Congress and with sponsoring agencies. Pam Hart, Executive Assistant to the Director, coordinates our Washington efforts, an important stewardship assignment that entails broadening the base of good working relationships there, analyzing events in light of their impact on the Institution, and educating key officials about the importance of the ocean for the future of the country.

For Congress and federal funding agencies, K-12 science education is an increasingly important priority. We proudly look forward to the release of the Turnstone Ocean Science Kits, books, and supplemental materials on ocean science for grades four through nine. These classroom materials are the result of a partnership between WHOI and two publishing groups, Turnstone Publishing and Steck-Vaughn, a division of Harcourt Brace & Company, and we believe that they will help attract students to science by communicating the thrill of discovery—through the oceans. These materials were scheduled to be premiered in the spring of 1999 at the National Science Teacher's Association meeting in Boston, where I was invited to be a keynote speaker. We also launched a partnership with BBH Exhibits, Inc. to build a 6,000-square-foot museum exhibit that highlights WHOI's role in the exploration of the "Extreme Deep." The exhibit is scheduled to debut at the Boston Museum of Science in the fall of 1999 and travel to venues across the nation over the next several years.

We closed the books on fund raising for 1998 at $8.5 million—a good year for Woods Hole and our best non-campaign year ever. These private funds encourage and support new science, engineering, and education initiatives in oceanography, such as the new Mentorship Program, designed to foster interaction between junior and senior scientists, which has been applauded by all the scientific staff. The new Stanley W. Watson Graduate Student Fellowships are beginning to support students in their first two years at WHOI—a critical financial and intellectual juncture in their careers. The new Mary Sears Senior Scientist Chair adds to our means for recognizing and rewarding excellence within the senior staff.

Significant funds are targeted to meet new requirements to match federal grants and contracts. This practice—once a luxury we *tried* to afford, but now a necessity we *have* to afford—puts funds to work to secure regional observatories, bid for important federal grants and contracts, and start up visionary scientific research programs. According to many scientific staff, this flexibility and license to "think outside the box" is what being—and staying—at the Woods Hole Oceanographic Institution is all about.

The "Year of the Ocean" was an excellent year for us. But every year is "a year of the ocean" for us at WHOI. We continually strive to penetrate the oceans' vastness and to learn how they work. A primary goal is to provide the scientific foundation for making wise decisions on how to protect, use, and manage the oceans, which sustain life, and the quality of life, on our planet.

—Robert B. Gagosian, Director

Comments from the Director of Research

In 1998, we signed a Memorandum of Agreement (MOA) with the National Oceanic and Atmospheric Administration (NOAA) to establish a formal partnership, the Cooperative Institute for Climate and Ocean Research (CICOR). WHOI and NOAA have collaborated for a number of years in such areas as long-term climate studies and fisheries research; the MOA reaffirms our common interests and provides a basis for consolidating established cooperative programs and common research interests.


Dave Gray

R/V *Knorr* will be among the US ships important to the work of the new National Oceanic and Atmospheric Administration/Woods Hole Oceanographic Institution Cooperative Institute for Climate and Ocean Research.

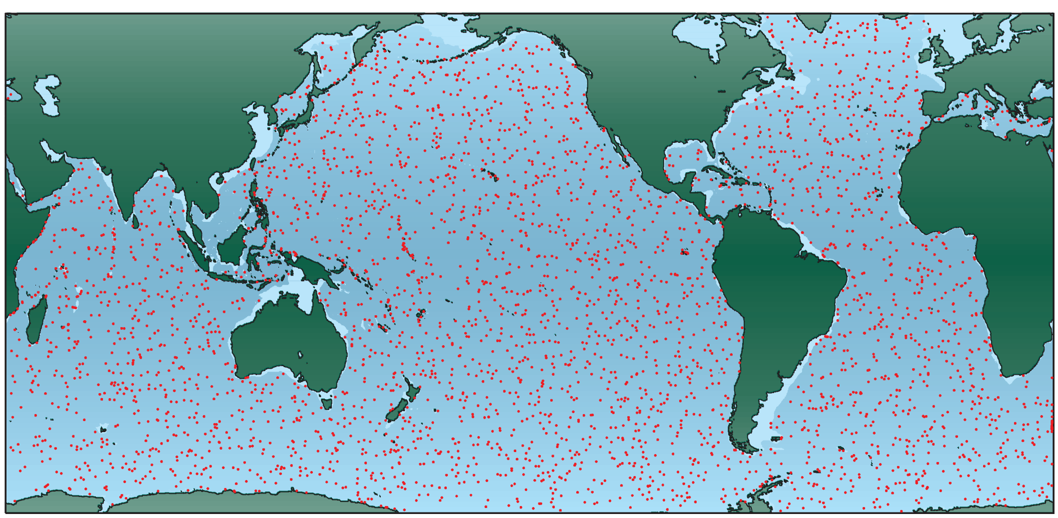
CICOR is structured to improve the long-term effectiveness of NOAA and academia through sponsored research organized around three broad themes. The coastal-ocean and near-shore processes theme includes scientific research on fundamental processes of biology, physical oceanography, and sediment and sand transport, as well as the effects of contaminants and the changing environment upon ecosystems and habitats for marine mammals, fish, and humans. This research is interdisciplinary in nature—finding solutions to the problems requires basic understanding of processes relevant to several fields. In addition, there will be an emphasis on the development of predictive capability, which requires a sustained effort to make meaningful observations of phenomena on scales comparable to the physical variability and to incorporate critical data into models. Making these observations on appropriate spatial and temporal scales requires new technology, so there will be a substantial focus on developing and exploiting acoustic technology, as well as recent advances in chemical and biological sensors.

CICOR's second theme is the ocean's role in climate and climate variability. Over the past 25 years, there has been growing recognition of the critical role of sub-basin-scale oceanographic processes in the dynamics of the overall climate system. The time scales on which these processes operate and interact range from seasonal to millennial and beyond. Sustained observational studies and process experiments can provide important information about relatively high frequency processes. Paloceanographers contribute information about longer frequency processes to promote understanding of oceanographic and climate variability on long time scales. Analysis of high resolution proxy records such as corals, ice cores, and sedimentary records can also be used to bridge the so-called spectral gap between the instrumental climate record and lower resolution geological records.

Marine ecosystem processes analysis is CICOR's third broad theme. It encompasses a wide range of community and ecosystem level studies. Many of these investigations concern the interaction of biological composition and structure with physical, chemical, or geological characteristics of the environment. Research on the species composition, trophic structure, and evolutionary history of a variety of marine ecosystems has long been a central strength of WHOI. In more recent years, there has been greater emphasis on the processes of ecosystem function—fluxes of energy and materials, growth of individuals and populations, competitive and predatory interactions, succession of species and populations. CICOR's environmental studies will range from coastal estuaries and salt marshes to offshore shelf and bank regions, the oceanic water column, the abyssal seafloor, and the hydrothermal vents of ocean ridges.

Senior Scientist Bob Weller is CICOR's first director. Six principal investigators have already been funded through CICOR and more proposals are pending.

—*James Luyten, Senior Associate Director and Director of Research*


Jay shriver

CICOR will be a contributor to the international Argo Program, currently in the planning stages, intended to seed the world ocean with some 3,000 profiling floats (red dots) and approximate for the ocean the data gathering capabilities of the worldwide network of balloon-borne radiosondes that contribute to accurate three- to five-day weather forecasts.

The Applied Ocean Physics & Engineering (AOP&E) Department, with 156 staff members and 34 students, continues to make significant advances spanning diverse areas in ocean science, technology, and engineering research. In 1998, 44 principal investigators led 146 projects.

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

Several department members were promoted this year, including Al Bradley and Chris von Alt to Principal Engineer, Roger Stokey to Senior Engineer, Dudley Foster and Andy Bowen to Research Specialist, and John Kemp to Senior Engineering Assistant II. Dan Lynch of Dartmouth College was appointed Adjunct Scientist to complement the department's research in coastal circulation processes. Ann Henry completed a 27-year association with the Institution, retiring as Department Administrator, and she was succeeded by Tom Nemmers.

AOP&E staff recognized in 1998 for their accomplishments include John Colosi and Dennis McGillicuddy, who were both named Office of Naval Research Young Investigators, and Cheryl Ann Butman, who was awarded the Institution's Stanley W. Watson Chair. Senior Technical Staff awards went to Dan Frye and Barrie Walden for extraordinary accomplishments in engineering and instrument development as well as mentoring younger staff members. Andy Bowen, Jon Howland, Steve Lerner, and Dana Yoerger were commended in a letter from British Prime Minister Tony Blair to President Bill Clinton for their roles in the survey of the sunken bulk carrier *Derbyshire*. Lane Abrams received a 1998 Lucent Technologies Patent Recognition Award for work he did while employed by AT&T Bell Laboratories from 1986 to 1991, and Wade McGillis was named a fellow of the NOAA/University of Miami Cooperative Institute for Marine and Atmospheric Studies.

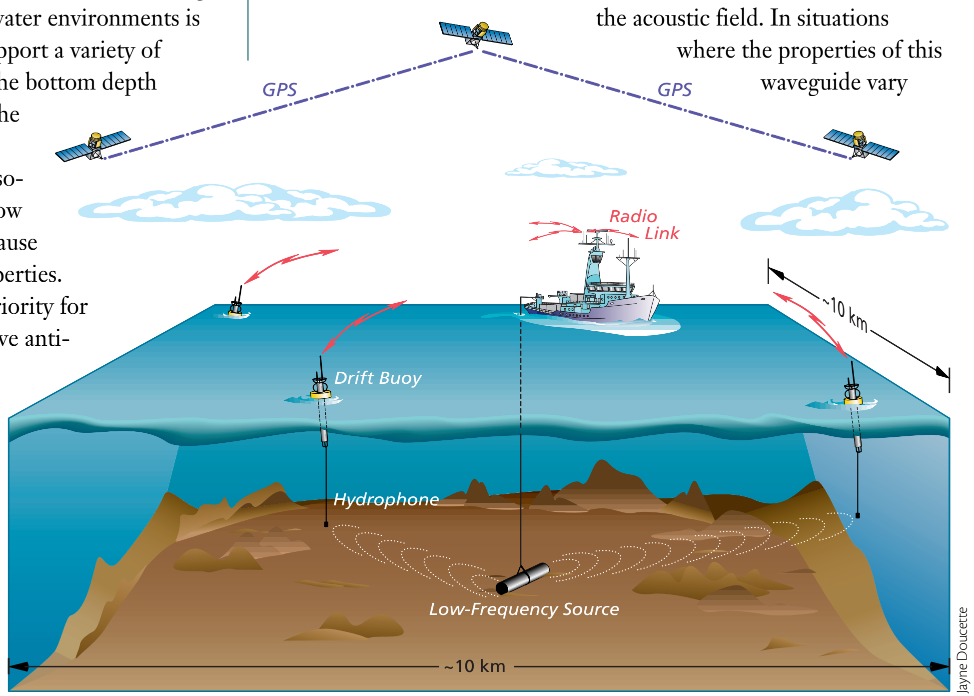
—*Timothy K. Stanton, Department Chair*

Modal Mapping in a Complex Shallow Water Environment

George V. Frisk, *Senior Scientist*

Sound propagation in shallow water is affected by a number of oceanographic features, such as fronts, internal waves, and surface gravity waves. However, the single most important factor influencing the complexity of the acoustic field in shallow water environments is the seabed, a multilayered structure that can support a variety of different wave types. The spatial variability of the bottom depth and subbottom composition is accentuated by the complicated geological processes that form the continental shelf and the coastal zone. High-resolution measurements of the sound field in shallow water are therefore of considerable interest because they can be used to infer these geoacoustic properties. Shallow water acoustics research is also a top priority for the modern Navy in its quest to conduct effective anti-submarine warfare in shallow water.

This complex shallow water environment is typically incorporated into our understanding of acoustic propagation through a method called "normal modes." In this approach, the sound field is described in terms of some number of natural modes of vibration whose properties are determined by the detailed nature of the sea surface, water column, and bottom. Specifically, the field is decomposed into a set of standing waves that are trapped between the surface and the seabed and are analogous to the modes of a vibrating string. Each mode also has a radially propagating component that allows the sound to travel outward, sometimes to long ranges. The combination of the surface, water column, and bottom thus form a waveguide for the acoustic field. In situations where the properties of this waveguide vary

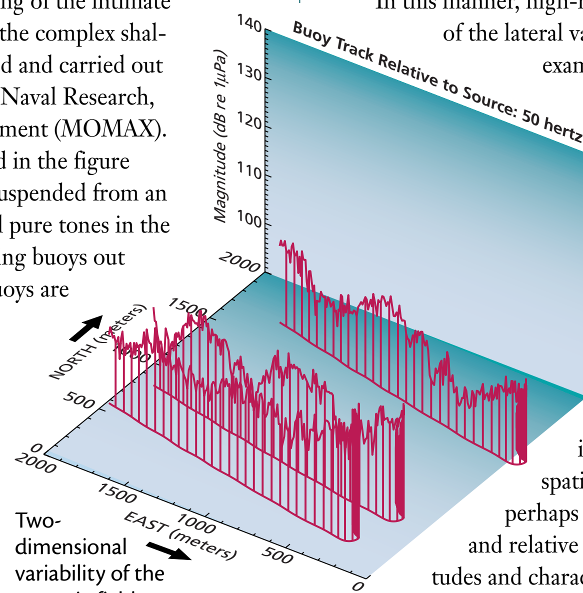


Experimental configuration for the Modal Mapping Experiment (MOMAX).

slowly with range, the modes adapt to the local environment and are described by a technique known as "adiabatic mode theory."

In an effort to increase our understanding of the intimate connection between the acoustic field and the complex shallow water environment, our group designed and carried out an experiment, sponsored by the Office of Naval Research, which is called the Modal Mapping Experiment (MOMAX). The experimental configuration is depicted in the figure opposite. A low-frequency sound source, suspended from an anchored or drifting ship, transmits several pure tones in the band 50 to 300 hertz to several freely drifting buoys out to ranges of about 10 kilometers. These buoys are similar to sonobuoys used by the Navy to detect submarines in that each one is equipped with a suspended hydrophone to receive the signals and a radio link to transmit the data back to the ship.

Unlike a typical sonobuoy, however, each MOMAX buoy also contains a Global Positioning System (GPS) antenna and receiver, and its position is also transmitted to the ship. These data, when combined with GPS positioning of the sound source, enable the creation of a local differential GPS network that provides sub-meter accuracy in determining the position of the buoys relative to the source.



Two-dimensional variability of the acoustic field magnitude measured on three MOMAX buoys at 50 hertz in 70 meters of water off the New Jersey coast.

Jayne Doucette

In this manner, high-resolution, two-dimensional measurements of the lateral variation in the sound field can be made. An example of the magnitude of the field measured on three buoys at 50 hertz in 70 meters of water off the New Jersey coast is shown in the figure at left and illustrates one type of "modal map" that can be generated. Because we also measure the low-frequency phase, the drifting buoys create two-dimensional, synthetic aperture horizontal arrays. These arrays can be steered to determine the strength of the sound field in different propagation directions, thereby providing information about the characteristic spatial frequencies of the normal modes and perhaps a method for inferring the source position and relative velocity. The evolution of the modal amplitudes and characteristic frequencies as a function of position provides another type of modal map that characterizes the waveguide. Knowledge of the modal evolution can ultimately be used to determine the three-dimensional acoustic properties of the seabed using inverse techniques.

Searching for the Ocean's Carbon Dioxide Sink

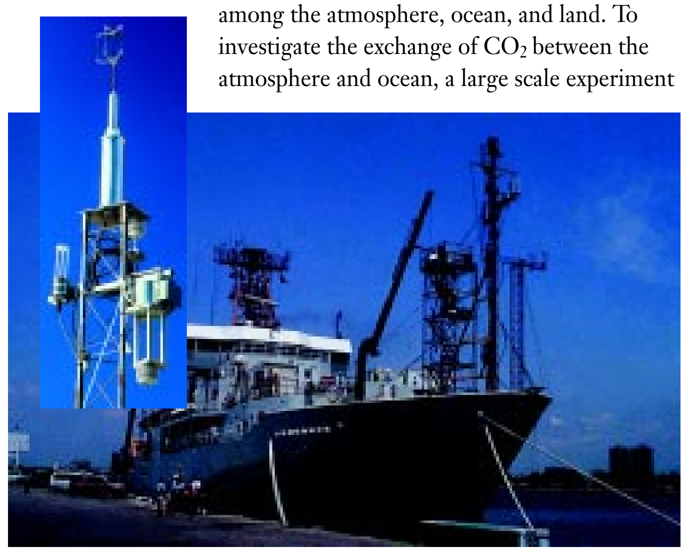
***Wade R. McGillis**, Assistant Scientist*
***James B. Edson**, Associate Scientist*

Carbon dioxide (CO_2) and water vapor are the most important gases affecting the earth's radiative balance. The radiative transfer properties of CO_2 permit short-wave radiation (sunlight) to pass through the atmosphere to warm the earth's surface, but traps long-wave (infrared) radiation emitted from the heated planet that would otherwise be lost to space. Thus, the presence of CO_2 in the atmosphere provides us with a significantly warmer planet than if the earth had a CO_2-free atmosphere.

Human activity, including the burning of carbon-rich fuels such as coal, natural gas, and oil, adds CO_2 to the atmosphere. For this reason, atmospheric CO_2 levels are now higher than they have been for over 200,000 years. CO_2 released by human activity cycles naturally through three major earth systems: the atmosphere, the ocean, and the terrestrial biosphere, with about half residing in the atmosphere. One of the crucial questions is how these systems will respond over time to the large accumulation of CO_2 in the atmosphere, and, in particular, how the oceans and land take up CO_2, thereby functioning as sinks for the increasing atmospheric component.

Depending on the time of year, different regions of the ocean can be sources or sinks for atmospheric CO_2. On average, it is estimated that the ocean as a whole currently acts as a sink, taking up about 2 gigatons per year of the approximately 5.5 gigatons of carbon produced by industrial and agricultural activity each year. However, there is significant uncertainty in this estimate.

To improve future predictions of atmospheric CO_2 levels, we must understand the mechanisms controlling the rate at which CO_2 cycles among the atmosphere, ocean, and land. To investigate the exchange of CO_2 between the atmosphere and ocean, a large scale experiment



Wade McGillis

Inset shows WHOI-developed meteorological tools that were part of the instrumentation mounted on a bow tower for the GasEx98 cruise aboard the NOAA research vessel *Ronald H. Brown.*

called GasEx98 was conducted in the North Atlantic in June 1998. This experiment included researchers from WHOI, the National Oceanic and Atmospheric Administration (NOAA), the Bermuda Biological Station for Research, the University of Miami, the University of Washington, Bigelow Laboratory, the Lamont-Doherty Earth Observatory, and Laboratoire d'Oceanographie Dynamique et de Climatologie.

WHOI's role in GasEx98 was to explore the feasibility of measuring air-sea CO_2 transfer directly, rather than relying on longer time scale measurements in the water column. This research was funded by the National Science Foundation. For one month, we studied a single warm-core eddy spun from the Gulf Stream and located at 46°6'N, 20°55'W. Because of an intense phytoplankton bloom in the sun-rich surface of the eddy, a large CO_2 sink was observed throughout the study period. During this time, we were then able to measure the air-sea flux (that is, the transfer rate of some quantity per unit area) of both CO_2 and dimethylsulfide (a tracer for CO_2) over a wide range of weather conditions that included two storms.

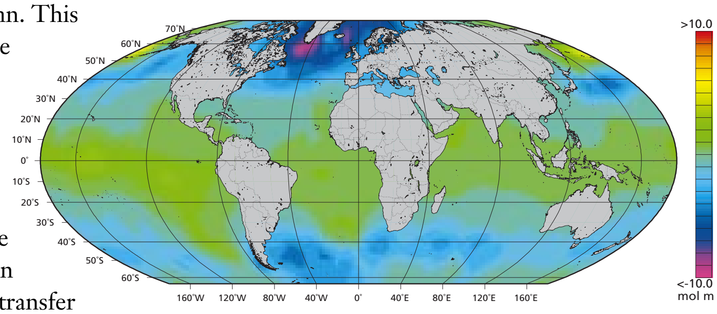
Almost all previous estimates of the CO_2 flux between air and sea have been made by indirect methods because it is very difficult to measure the air-sea CO_2 flux directly. During the GasEx98 experiment we were able, for the first time, to directly measure this CO_2 flux over the open ocean. This was accomplished by combining a technique known as the "direct covariance method" with improved instrumentation and additional techniques developed at WHOI.

The photo on page 5 shows some of the meteorological instruments we used on board the NOAA research vessel *Ronald H. Brown*. The flux of CO_2 into the ocean was quantified by measuring the vertical wind transport and the CO_2 concentrations simultaneously. So far, experiment results show that at low wind speeds our direct measurements agree with previous results found using indirect methods. At higher wind speeds, however, we found that the indirect methods underestimated CO_2 transfer velocities, and thus the total uptake of atmospheric CO_2 by the ocean.

Based on GasEx98 field results, we have developed a new parameterization to help predict global ocean CO_2 sources and sinks. Our work has unveiled a new relationship between wind speed and gas exchange, where gas exchange can be approximated as the wind speed cubed. This relationship shows a weaker correlation of gas transfer at low wind speeds and a significantly stronger dependence on high wind speeds than has been suggested by previous relationships.

This relationship can be theoretically explained by the retardation of gas transfer at low to intermediate winds by surfactants, soaplike substances that are ubiquitous in the world's oceans, and the enhancement of gas transfer at higher winds from bubble effects. The existence of a cubic relationship is also consistent with previous CO_2 estimates from bomb-produced carbon 14 methods. By applying our new relationship globally, using worldwide wind speeds and surface observations, the global annual CO_2 uptake can be estimated. The global figure shows that the ocean acts predominantly as a CO_2 sink in high latitudes and as a source in equatorial regions. This new formulation provides an estimate of global CO_2 uptake of around 2.2 gigatons of carbon per year, consistent with previous methods of estimation. This technique promises to provide extremely fine scale resolution of changes in air-sea gas flux behavior over time, which will aid in the determination of processes responsible for changes in ocean uptake of CO_2.

GasEx98 collaborators include John Dacey and Jonathan Ware (WHOI), as well as Jeffrey Hare (University of Colorado), Christopher Fairall (NOAA/ETL), and Rik Wanninkhof (NOAA/AOML).



Blue-to-red shading indicates wind-speed-driven elevated carbon dioxide uptake in high latitude ocean waters. GasEx98 research identified a new relationship between wind speed and air/sea gas exchange.

An Autonomous Workhorse for Oceanographic and Navy Needs

***Roger P. Stokey**, Senior Engineer*

REMUS (Remote Environmental Measuring UnitS) are small autonomous underwater vehicles (AUVs) developed by the seven engineers of the Oceanographic Systems Laboratory (OSL). Once launched, a REMUS vehicle is entirely on its own and makes whatever decisions are necessary to successfully navigate the course it has been given. Complex missions may have more than 100 different legs and require the vehicle to change instrument settings as it swims and changes depth, on its own for as long as 10 hours.

Tom Kleindinst

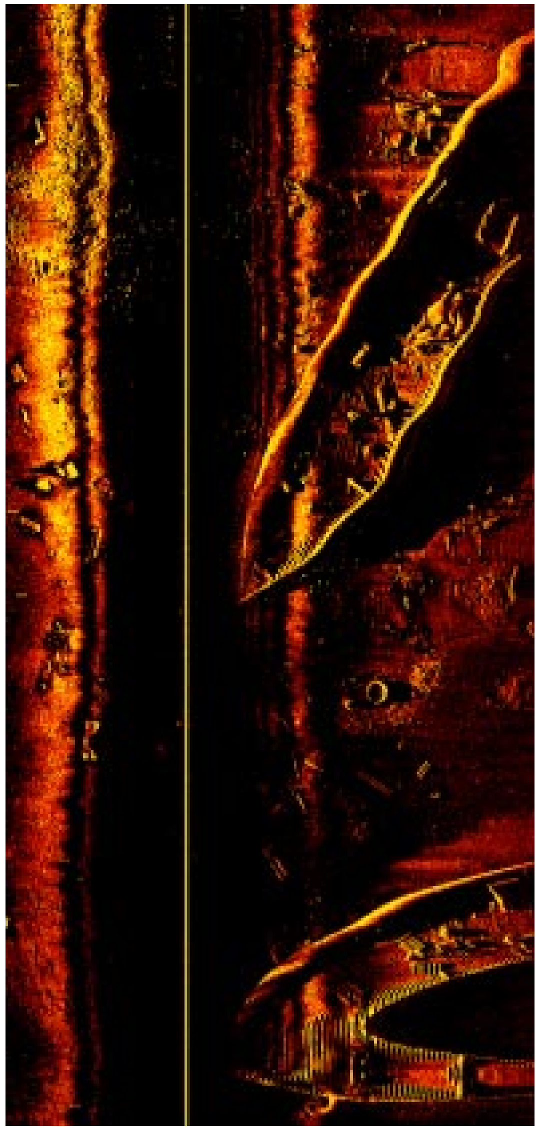
The 5-foot REMUS and its traveling case.

REMUS was born of the needs of scientists operating the Long-term Ecosystem Observatory (LEO-15). The observatory's two permanent data-collecting nodes, located 15 meters under water and 5 miles off the coast of New Jersey, have been transmitting data to the Internet via fiber-optic cable for over two years. They are helping scientists understand coastal oceanographic processes such as upwelling and recurrent hypoxia (low oxygen) events that result in significant shellfish mortalities and consequent economic losses. However, while these nodes provide 24-hour-a-day presence, they are spatially fixed. It was the need to gather data over a wider geographic scale in response to episodic events detected via satellite and the LEO-15 nodes that prompted development of a mobile platform that became REMUS. To date, REMUS has operated at LEO-15 during two month-long periods in the summers of 1997 and 1998, completing missions as long as 36 miles and traveling as far as 17 miles offshore, while its handlers stayed ashore, monitoring its progress. The current, conductivity, temperature, depth, and other data it gathers are enabling scientists to understand the life cycles of these events.

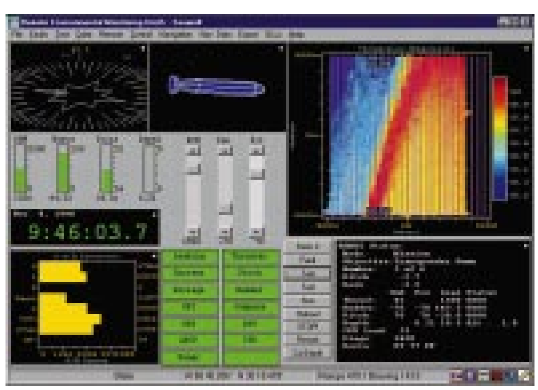
Our goal has always been to make AUV deployment routine. However, autonomous vehicles are complex craft: The vehicle itself presents a myriad of design challenges such as acoustic navigation and vehicle control in addition to requirements of the individual instruments. However, the biggest impediment to efficiency is *us*—when managing this level of complexity, operators are more prone to mistakes than the vehicle. Consequently, we have developed a user interface designed to advise operators when they are doing something foolish or have forgotten something, to indicate whether the vehicle, if launched, will be able to complete its mission, and to provide guidance in diagnosing and correcting the problem when something is wrong.

An AUV is an expensive instrument, so creating an environment that gives operators the confidence to launch the vehicle, watch it disappear, and know that it will come back is crucial. We have designed systems to assist operators in all stages of deployment: mission planning, launch, operational phase, vehicle recovery, and data processing, display, and export to other applications.

This last step has proven particularly important. The ability to rapidly assess data allows time for more of it to be analyzed. REMUS generates an extraordinary amount of information, not only from the traditional oceanographic sensors it carries, but also from its routine engineering data, which can produce



A REMUS side-scan sonar image shows liberty ships scuttled in the 1970s to create an artificial reef near Gulfport, Mississippi.



The REMUS user interface screen allows operators "quick-look" access to vehicle operations and instrument data. The plot at upper right shows an unexpected temperature front.

surprising results. For example, while inspecting the signal-to-noise ratios of the vehicle's acoustic navigation system, we observed that there was better performance in shallow water at longer ranges from the source than in deeper water closer to the source. This is as if a theatergoer could hear more clearly from the back of the house as opposed to close by the stage. We are only beginning to investigate this phenomenon.

REMUS success in the scientific arena piqued the interest of the military. In World War II, the first marines landing at Tarawa in the Gilbert Islands had to wade ashore through 700 yards of withering machinegun fire because the Higgins landing craft ran aground on reefs whose depths aerial reconnaissance could not reveal. (Higher tides on the second day of the landing allowed the Higgins craft closer access.) Detailed surveys back then required sending a large advance team to scout potential landing areas, to determine water depths, and to probe for mines. More than 50 years later, the approach is fundamentally unchanged.

In September 1997, OSL demonstrated REMUS's hydrographic capabilities to the Naval Oceanographic Office during trials sponsored by the Office of Naval Research in the Gulf of Mexico. These tests clearly showed that small AUVs were capable of creating detailed images of the seafloor using sidescan sonar, as well as providing valuable hydrographic information, all while accurately navigating a preprogrammed path. Development of the REMUS concept for Naval Special Warfare (the Navy SEALS) was subsequently initiated. In the future, REMUS will give the military a covert means of obtaining accurate bathymetry and the location of mine fields and other underwater obstructions.

Thus REMUS offers a new, highly efficient method of collecting data that yields valuable insights in the coastal regime and also provides a new military tool that has changed the way the military views autonomous underwater vehicles and advanced by several years the schedule for integrating them into the Navy fleet.

Biology Department research covers a wide range of organisms from viruses and bacteria to algae, zooplankton, whales, and birds. We use an equally broad array of methods and approaches, including molecular biology; video microscopy and flow cytometry; acoustic, video, and net sampling; behavioral observations; and mathematical modeling and analysis.

In 1998 the department had 25 scientific staff, along with 7 Scientists Emeritus, 2 Oceanographers Emeritus, 15 Postdoctoral Scholars, Fellows, and Investigators, 14 technical staff, 33 Joint Program students, and 29 other support staff. During the year, the Scientific Staff pursued over 150 separate research projects, publishing about 69 scientific papers. We continue to show great strength in many subdisciplines such as ecology and physiology of bacteria and protozoa, bio-optical studies of phytoplankton, advanced optical and acoustic techniques for zooplankton distribution and behavior, and the ecology, behavior, and development of invertebrate larvae. Other areas of interest include mathematical analysis and computer modeling of life history, population dynamics and physical-biological interactions, toxicological and molecular research on how pollution affects marine organisms, and acoustical, anatomical, and behavioral studies of whales and dolphins.

In the face of ever tighter Federal support for basic research in biological oceanography, our scientists have turned to increasingly diverse sources of support and new kinds of partnerships. We submitted a total of 100 proposals to all sources, and received full or partial funding for 46 percent of them, for a total of more than $5 million in sponsored research in 1998. Leadership and participation by our staff in large national and international programs remains strong, including Joint Global Ocean Flux Study research in the Atlantic and Southern Oceans, the International Ridge Inter-Disciplinary Global Experiments and Larvae at Ridge Vents programs for hydrothermal vents, the Ecology and Oceanography of Harmful Algal Blooms program, and the US Global Ecosystems Dynamics Northwest Atlantic Program on Georges Bank, which is headquartered in the WHOI Biology Department.

The department and the entire community were saddened by the death in September of Holger Jannasch, a world-renowned pioneer in deep-sea microbiology. Holger participated fully in an *Alvin* cruise in May, and continued working through much of the summer with his characteristic passion, thoroughness, and charm. He received the Bergey Award from the Bergey's Manual Trust in 1998 for long-term distinguished achievement in bacterial taxonomy.

We were fortunate to be able to appoint two new Assistant Scientists in 1998, Andreas Teske, working on bacteria from hydrothermal vents, and Ken Halanych, who applies molecular and classical techniques to problems of evolution and phylogeny in benthic invertebrates. During 1998, Jesús Pineda was promoted to Associate Scientist and Mark Dennett to Research Specialist. Retired Senior Scientist and former Department Chair Joel Goldman was appointed Scientist Emeritus, and George Hampson became the Department's second Oceanographer Emeritus. Senior Scientist David Caron was awarded the first Mary Sears Chair for Excellence in Oceanography, and Research Specialist Carl Wirsen received a WHOI Senior Technical Staff Award for his work in deep-sea microbiology.

—Laurence P. Madin, Department Chair

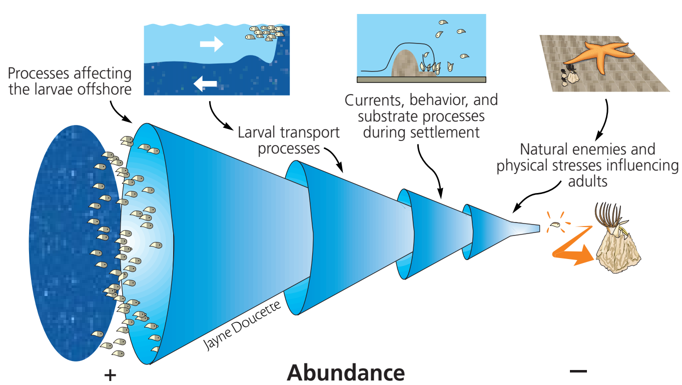
Larval Transport By Internal Tidal Bores

***Jesús Pineda**, Associate Scientist*

New generations of bottom-dwelling coastal marine animals face a complication on their way to establishing new colonies. The early life stages of such organisms as clams, mussels, shrimp, and barnacles live suspended in the water, drifting at the mercy of ocean currents in a "larval phase" that generally lasts a few weeks. At the end of it, the larvae must find a suitable habitat where they can grow into adults and complete their life cycles.

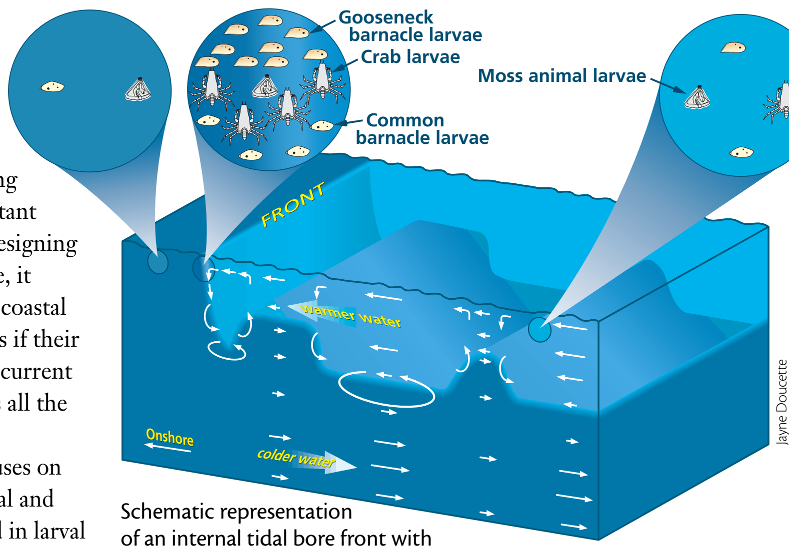
Because ocean currents disperse the larvae far from their birthplaces, they may find themselves several miles offshore in deep water just when they are ready to settle in the shallow coastal water—a waste of larvae because they will not survive in this situation.

After several weeks suspended in the ocean, the probability of a larva returning to its birthplace must be minimal, and the abundance of the colonizers at a given site is uncoupled from the living conditions of the adults. A site with no natural enemies and rich in food may be vacant because currents do not bring larvae, or, on the other hand, a sub-optimal habitat with scarce food may contain a large number of organisms if currents bring many larvae. Knowledge of



Processes that influence the population abundance of coastal bottom-dwelling organisms, with a barnacle as example. The number of larvae is larger than the number of adults, as each adult produces a myriad of larvae. Larvae are often found offshore, and before they can settle successfully at the coast, several conditions must be fulfilled. In each case, the proportion of larvae moving to the next set of processes is smaller. Small changes in the proportion of larvae that pass from one step to the next can produce large population changes.

ocean currents that return the larvae to coastal habitats is therefore key to understanding the maintenance and dynamics of coastal species. Understanding larval transport is also important for managing fisheries and designing marine reserves. For example, it would be futile to preserve a coastal site that contains many adults if their larvae are all wasted because current circulation at that site carries all the larvae offshore.



Schematic representation of an internal tidal bore front with observed circulation. Larvae of two species of barnacle and crabs accumulate at the front, but larvae of a moss animal (bryozoan) do not. All larvae occur offshore of the front, while most larvae found shoreward of the front belong to the bryozoan and one species of barnacle.

Much of my research focuses on studying the various biological and physical phenomena involved in larval transport by internal tidal bores. When waves traveling at the surface of the ocean approach the beach, they "feel the bottom," break, and produce a surge of surf running upslope. Internal (subsurface) waves, which are also ubiquitous, but slower and much larger than surface waves, also break when they shoal, producing internal surf. Rather than propagating along the air-sea interface, internal waves propagate along the interfaces of layers of water of different temperature and salinity that are found in most oceans. These internal tidal bores or breaking internal waves often occur about every 12.4 or 24 hours.

Recent observations in California show that when internal tidal bores occur, parcels of water that may be several miles long and extend from the beach to about 2 miles offshore are fully replaced by offshore waters once or twice a day. This dramatic exchange of water brings larvae of coastal species shoreward and occurs in two phases. First, the large internal tidal bore transports vast masses of colder water found at depth towards the shore, displacing the nearshore warmer water offshore. A few hours later, in the second phase, the heavier cold water recedes offshore, and is replaced by warmer offshore surface water. A front or line in the sea parallel to the shoreline marks the boundary between cold and warm water and leads the surface water in the second phase, with several other lines or slicks following shortly. The lines are created by currents that concentrate surface buoyant material, and, in the case of a front, the line contains a large concentration of floating debris, surf grass, and several species of larvae. Observations of these fronts revealed both striking patterns of circulation, capable of concentrating buoyant material, and frontal accumulation of some species of larvae but not of others.

With funding from the National Science Foundation and WHOI's Rinehart Coastal Research Center, we are pursuing many questions related to internal tidal bores. They range from the effects of El Niño on this mechanism to its variability along the shore in sites separated by several tens of miles to the fine mechanics of the process of frontal accumulation (the latter in collaboration with Karl Helfrich of the Physical Oceanography Department) and the reasons why only some types of larvae accumulate in the fronts while others do not. Further study should also elucidate the physical effects and ecological consequences of internal tidal bores, a process with profound yet largely unexplored implications for coastal communities.

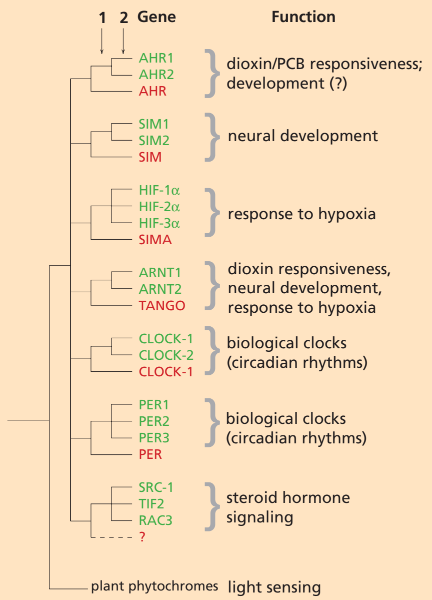
For more information, visit http://mathecol.whoi.edu/~pineda/

Evolution of Pathways for Chemical Sensing, Response, & Adaptation

Mark E. Hahn, Associate Scientist

All cells continuously sense their environment, looking for clues to changes in environmental conditions (such as light intensity and oxygen concentration) or chemical signals from other cells (such as hormones). These chemical and physical signals are detected by specific receptor proteins that initiate biochemical changes in the cell to "turn on" some response, such as gene transcription leading to protein synthesis. Scientists increasingly recognize that synthetic and natural chemicals present in the marine environment can interfere with signaling pathways, resulting in undesirable effects on cellular or organismal function (toxicity). Research at WHOI and elsewhere seeks to understand how these foreign chemicals disrupt physiological signaling pathways. In this research, the toxic chemicals also serve as valuable "molecular probes," helping to reveal the normal functioning of the pathways.

In my laboratory, we use comparative studies of a variety of organisms to unravel the evolutionary history of the biochemical pathways through which animals detect and respond and adapt to chemical exposure. In addition to providing a basic understanding of chemical-biological interactions, this information helps us predict the sensitivity of particular groups of organisms to specific classes of chemicals. We focus on the class of halogenated aromatic hydrocarbons that includes the chemical "dioxin" (2,3,7,8-tetrachlorodibenzo-*p*-dioxin) and certain polychlorinated biphenyls (PCBs). We are using dioxins and related chemicals to investigate the comparative biochemistry and evolutionary history of a family of signaling proteins—the PAS protein family—and their roles in environmental sensing. The PAS family includes proteins involved in such processes as neural development, the



Phylogenetic tree of the PAS family of genes involved in environmental sensing and responses. The tree, which illustrates the evolutionary relationships among these genes, was inferred by phylogenetic analysis of amino acid sequences of the corresponding proteins. PAS genes that occur singly in invertebrate animals are shown in red. PAS genes occurring as multiple forms in mammals, fish, or other vertebrate animals are shown in green. Phytochromes are plant PAS proteins involved in light sensing. Arrow 1 indicates the position of the vertebrate/invertebrate divergence. Arrow 2 indicates the gene duplications occurring early in the vertebrate lineage that gave rise to the multiple forms of PAS genes in vertebrates.

Fritz Heide

control of biological clocks, and adaptive responses to hypoxia (lack of oxygen), changes in light intensity, and the presence of small molecules such as dioxin.

Dioxin has gained a reputation as the most toxic synthetic chemical known, in part because it is so persistent, both in the environment and in cells. The extreme toxicity of dioxin is also a result of its strong and specific interaction with a receptor protein known as the aryl hydrocarbon receptor (AHR). Unlike the situation for most receptors, we do not know the normal function of the AHR. We do know that the presence of this receptor in an organism or cell confers sensitivity to dioxins and dioxinlike compounds.

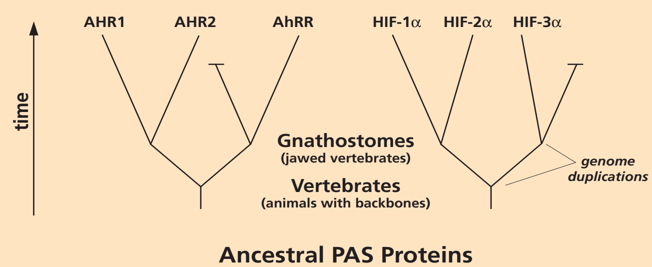
With funding from the National Institute of Environmental Health Sciences and the Oliver S. and Jennie R. Donaldson Charitable Trust, we are examining the evolutionary origin of the PAS gene family, the AHR, and dioxin responsiveness in animals. Our studies focus on living representatives of the earliest evolving groups of vertebrate animals (those with backbones): bony fish, cartilaginous fish, and jawless fish. Recently, we identified AHR genes and determined the sequence of the proteins they encode in the bony fish called mummichog (or killifish), the cartilaginous dogfish and skate, and the jawless sea lamprey, a descendent of the earliest vertebrate animals. These findings indicate that the AHR has existed in its present form for at least 450 million years and may serve an important function in vertebrate animals.

Our studies of the mummichog AHR have a second purpose: to understand the molecular basis of dioxin resistance we have found in a population of these fish inhabiting New Bedford Harbor, MA, a federal Superfund site that is highly contaminated with PCBs and other dioxinlike compounds. In the course of these studies we discovered a second form of the AHR (AHR2) in mummichogs. Both AHR forms are able to interact with dioxins, suggesting that both are functional. We hypothesize that changes in the function of either or both AHR forms in the New Bedford fish could explain the dioxin resistance of this population. We are testing this hypothesis in studies supported by the Superfund Basic Research Program.

This novel AHR form is not unique to mummichogs. We have now found an AHR2 in other fish, including cartilaginous fish such as dogfish, and we are searching for it in other vertebrate animals, including humans. The widespread occurrence of this second AHR in fish suggests that the mechanism of dioxin action may be quite complicated.

To understand how the two AHR proteins are related to each other and to other members of the PAS protein family, and how this family evolved, we conducted a phylogenetic analysis using the amino acid sequences of all known PAS proteins. (In phylogenetic analyses, computer programs attempt to reconstruct the evolutionary history of species or genes by grouping them based on their similarity. That inferred history can be displayed as an evolutionary tree.) The results of this analysis showed a common pattern of evolution. Most PAS proteins (and the genes that encode them) exist as single forms in invertebrate animals. However, in fish, mammals, and other vertebrates, each PAS protein exists in multiple forms. The generation of these multiple forms can be traced back to the earliest vertebrate groups, in which two rounds of extensive gene duplication occurred. This "duplication and divergence" within gene families is a common theme within the vertebrate lineage, and is thought to be responsible for some of the complex anatomical, physiological, and biochemical traits that exist in this group.

Our findings on the phylogenetic distribution of the AHR suggest that the biochemical machinery underlying dioxin responsiveness first evolved in early vertebrates. This knowledge can be used to predict which species or animal groups may be most sensitive to these chemicals. Ultimately, it may provide clues to the origin and normal function of the dioxin receptor and suggest ways in which dioxins interfere with this function to cause toxicity in marine animals, as well as in humans.



Hypothetical scheme illustrating the gene duplications that led to the expansion and diversification of the PAS gene family early in vertebrate evolution. AHR1 is the aryl hydrocarbon receptor involved in the response to dioxins. AHR2 is a novel form of this receptor in fish, first identified in the author's laboratory. AhRR is an AHR-related gene that inhibits the response to dioxins. The HIF genes encode proteins that mediate the adaptive response of cells to low oxygen (hypoxia).

Fritz Heide

View of the Surface Heat Exchange of the Arctic Ocean (SHEBA) ice camp from the bridge of *Des Groseilliers* in May 1998, prior to the onset of the melt season. The biology labs, located in the blue containers directly off the bow of the ship, included water baths to conduct experiments at ambient temperatures, a winch equipped with 3,500 meters of Kevlar cable, a 4-foot-square hydro hole in the ice for sampling, and space for microscope work and chemical analyses. Though on this date a large lead separated the biology labs and the ship from the rest of the ice camp, the lead subsequently closed, reuniting the camp.

Ice Camp Research Examines Zooplankton Adaptation

Carin J. Ashjian, Assistant Scientist

Extreme Arctic environmental variations—from winter's total darkness, extreme cold, and complete ice cover to summer's milder temperatures, partial ice melt, and penetration of light to the upper water column—profoundly influence the biology of far northern seas. These conditions also limit biologists' ability to study marine life adaptations to Arctic conditions.

The perception of the Arctic Ocean as largely a biological desert was called into question by measurements taken in 1994 during a cruise across the Arctic Ocean aboard US Coast Guard vessel *Polar Sea*. Their work documented zooplankton biomass eight to ten times greater than previously observed. Recently, the National Science Foundation (NSF) provided a group of marine biologists an unprecedented opportunity for further examination of Arctic Ocean biology during extended periods at an ice camp established in conjunction with the NSF/Office of Naval Research-funded Surface Heat Exchange of the Arctic Ocean (SHEBA) project. The Canadian Coast Guard ship *Des Groseilliers* was frozen into the ice pack from October 1997 to October 1998 to serve as base for SHEBA investigators. Surrounding tents, huts, and containers provided on-ice laboratory space and instrument support.

An example of an adult female of the large Arctic copepod *Calanus hyperboreus.*

SHEBA allowed us to conduct a year-long study of abundances and vertical distributions and migration patterns (both seasonal and daily) of zooplankton populations and vital rates of four target copepod species (*Calanus glacialis*, *Calanus hyperboreus*, *Metridia longa*, and *Oithona species*) in the upper 500 meters of the Arctic Ocean. Because of the difficult access to the Arctic Ocean, there have been few studies conducted over an annual cycle.

My immediate collaborators were Robert Campbell (University of Rhode Island) and Charles Flagg (Brookhaven National Laboratory). Significant col-

Canadian Coast Guard vessel *Des Groseilliers,* viewed from the on-ice biology lab, in May 1998.

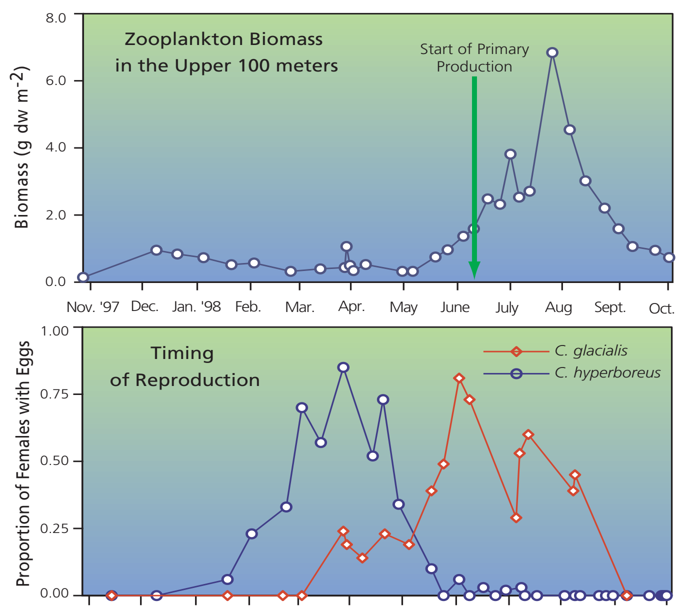
laboration with many other US and Canadian investigators was critical to the project's success. We spent approximately 14 weeks working at the facility, traveling to the ice camp four times (in October 1997 and February-March, May, and June-August 1998). Our objectives were to determine whether Arctic Ocean zooplankton are more productive than previously believed, whether populations of the dominant Arctic Ocean copepod species originate from in situ reproduction or immigrate from marginal shelf regions, and whether dominant copepod species undergo both diel (timed to the daily light cycle) and seasonal vertical migration.

We used nets to collect live samples and assess population density and acoustic Doppler profilers to examine daily and seasonal changes in vertical distribution from backscatter profiles, and we conducted experiments to determine the timing and magnitude of egg production, assess growth, and measure respiration rates, RNA/DNA ratio (an indicator of the vital rates of copepods), and changes in carbon content of selected copepod species. Our group conducted some of the first growth experiments ever attempted with Arctic Ocean copepods.

Much of our research focused on the key processes of the biomass-dominant Arctic ocean copepods *Calanus glacialis* and *Calanus hyperboreus*. These animals tolerate the Arctic winter darkness and absence of food with a sort of hibernation adaptation in which much of the population overwinters at depths of 200 meters or greater, utilizing stored lipid (fat) reserves and functioning at a much reduced metabolic rate, and migrate seasonally into the upper portion of the water column to feed during the summer.

Our preliminary results are exciting. We demonstrated that active reproduction of these copepod species was occurring in the Arctic Ocean; whether recruitment was sufficient to permit populations to be self-sustaining remains to be determined after consideration of population abundances. The timing of reproduction for the two *Calanus* species differed, with *Calanus hyperboreus* beginning reproduction in February, at depth, and *Calanus glacialis* initiating reproduction later in the year while in the upper water column. Diel vertical migration was evident in backscatter intensities from acoustic Doppler current profilers; the persistence of this phenomenon and whether it existed during periods of complete daylight is presently being analyzed. Total zooplankton standing stock during the summer was of the same order of magnitude or greater than that observed in 1994, confirming our hypothesis that zooplankton biomass in the Arctic Ocean is of greater magnitude than previously believed.

At SHEBA, biologists obtained a data set of unprecedented quality and extent that will help us gain a better understanding of the functioning of the Arctic ecosystem and the cycling and regeneration of carbon in this region. The Arctic Ocean is potentially of import to global climate and carbon cycles, and our work supports a revised paradigm regarding the production of the Arctic Ocean.



Some preliminary Arctic biology results. *Upper Panel*: Zooplankton biomass in the upper 100 meters of the water column. Note elevation of biomass during summer months as a result both of seasonal upwards migration of *Calanus* populations and in situ production. Onset of water column primary production also is noted. *Lower Panel*: Timing of reproduction for the copepod species *Calanus glacialis* and *C. hyperboreus*. Note that *Calanus hyperboreus* reproduces prior to the productive season while *Calanus glacialis* times its reproduction to coincide with primary production.

Three new appointments were made to the G&G resident Scientific Staff in 1998. Susan Humphris, a 1977 graduate of the MIT/WHOI Joint Program in Oceanography, was appointed as a Senior Scientist. Susan, who studies the petrology and geochemistry of deep-sea hydrothermal vent systems, previously served as the Dean of the Sea Education Association and, more recently, as a member of the WHOI Technical Staff. She just completed a two-year tenure as the Chair of the JOIDES Science Committee (SCICOM) for the Ocean Drilling Program while the committee's office was located at WHOI. Karen Bice, a recent Ph.D. from Penn State University who works with numerical modes of the climate system to study earth climate history, joined the paleoceanography research group as an Assistant Scientist. Jerry McManus was named Assistant Scientist upon completion of an 18-month appointment as a WHOI Postdoctoral Scholar. Jerry studies the climate history of the earth as it is revealed in deep-sea sediments. With the departure of two Assistant Scientists, Tracy Gregg and Yang Shen, the resident Scientific Staff stands at 32.

The department submitted 129 research proposals during 1998, mostly to federal agencies. There were 58 active awards during 1998 for a total of $12.7 million in funding. This research resulted in more than 82 scientific publications in peer-reviewed journals. As part of our diverse research programs, the department participated in 23 research cruises. Senior Scientist Alan Chave led one noteworthy cruise, to establish one of the first seafloor observatories, using an abandoned telephone cable that connected Hawaii with the continental United States. The WHOI team developed a junction box to serve as the interface between the cable and seafloor instrumentation. In collaboration with researchers from the University of Hawaii, a permanent seafloor seismometer was deployed at the site. Other research at sea included Research Associate John Collins's deployment of a broadband seismometer as part of the Ocean Seismic Network pilot experiment in the Pacific, and Associate Scientist Delia Oppo's sediment coring cruise off the southeast Brazil margin.

This was an excellent year for awards in the department, led by the remarkable recognition of Senior Scientist John Hayes's research career. John was awarded the Treibs Medal of the Geochemistry Society and elected both to the National Academy of Sciences and as a Fellow of the American Academy of Arts and Sciences. Scientist Emeritus Dick von Herzen received the 1998 Maurice Ewing Medal of the American Geophysical Union, and Associate Scientist Debbie Smith was named the Green Foundation for Earth Sciences Scholar at Scripps Institution of Oceanography, where she spent three months visiting in early 1998. In addition, Senior Scientist Brian Tucholke and Associate Scientist Jian Lin were honored by the Office of Naval Research (ONR) when their paper on slow spreading ridges was named as one of the most significant papers supported by ONR, in celebration of ONR's 50th anniversary.

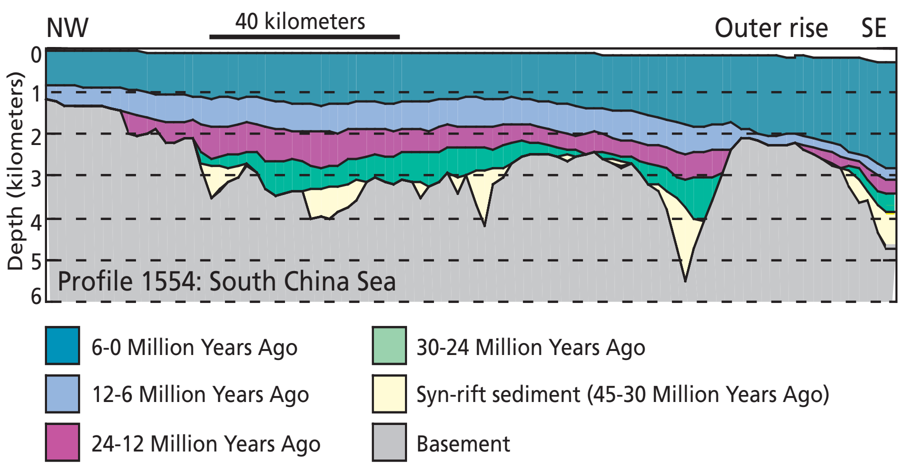
—William B. Curry, Department Chair

Investigating Continental Breakup in the South China Sea

***Peter Clift**, Assistant Scientist*

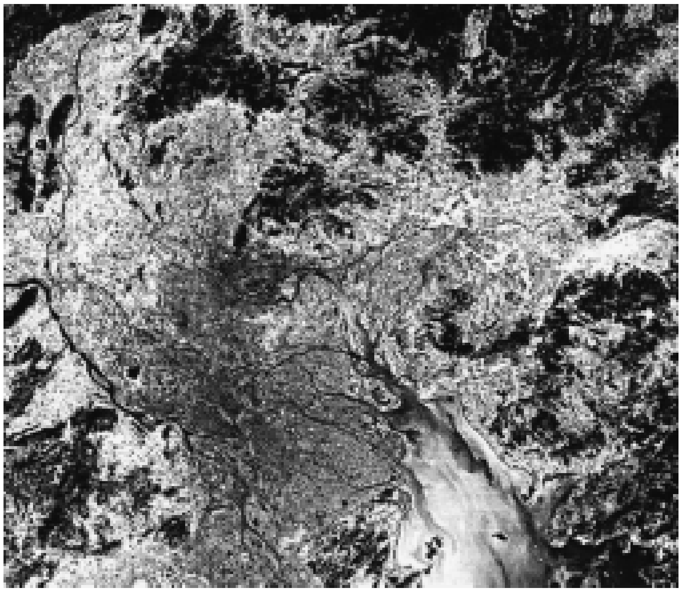
Studies of plate tectonics over the last 30 years show that modern ocean basins formed as a result of the rifting and breakup of large continental masses, culminating in the initiation of seafloor spreading. Although this spreading process is now quite well understood, the events that led up it are only poorly documented. The rifted margins of the Atlantic, for example, are blanketed by sediments that locally exceed 12 kilometers thick, making it difficult to study sediments deposited early in the process of continental separation. This gap in understanding of the plate tectonic model is significant not only academically but also economically because there is the prospect of significant mineral reserves, most notably petroleum, on the continental shelf and slope.

With funding from the Office of Naval Research and the National Science Foundation, Associate Scientist Jian Lin and I are examining the nature of continental breakup during formation of the South China Sea. This area is ideal for such work because it dates only to about 30 million years ago, compared to some 120 million years ago for the central Atlantic, and, consequently, the early sediments are not deeply buried. We use both academic data sources from the deeper part of the continental slope and petroleum industry seismic and drilling data, released to us by BP Exploration plc and the Chinese National Offshore Oil Company in order to determine how the continental crust extends prior to seafloor spreading.



Interpreted cross section through the South China continental shelf. Note the deep sediment-filled basins caused by extension.

Competing models suggest that the continental crust behaves in one of two ways when placed in tension. One possibility is that the crust and upper mantle may deform in a plastic fashion, much like a bar of toffee bends, with the same amount of extension at different depths, albeit more brittle at shallow levels and more ductile at great depth. Alternatively, the crust may be torn apart along shallow-dipping fault surfaces, like those first recognized in the Basin and Range of the western US, resulting in more shallow extension in one place and deeper extension in another. The end product of this style of extension is that opposing continental margins are not mirror images, but rather some show more crustal extension and others more mantle extension. The density and buoyancy differences between crust and mantle allow us to resolve competing models by studying vertical continental shelf motions recorded in sediments that underlie the modern slope.



Landsat image of the Pearl River mouth, source of most of the sediment on the margin. Sediment is eroded from China and East Tibet.

On the South China continental shelf we have found that upper crustal extension is small, while mantle extension is large. Intriguing evidence suggests that the lower crust may extend even more than the mantle, behaving as a soft ductile layer during extension. This implies that neither of the two extension models may apply to the continental margins. Final resolution of the problem involves ongoing work on the opposing continental margins, off Borneo and Palawan. We will determine if the lower crust missing from under South China is present on the opposite side of the basin or if the two margins behave in similar fashions. If this latter scenario is confirmed, this work will demonstrate that the transition from continental extension to seafloor spreading is not simply an extension of processes that generate continental sedimentary basins, but a whole new regime of crustal deformation.

Can the Southern Ocean Biological Pump Regulate Earth's Climate?

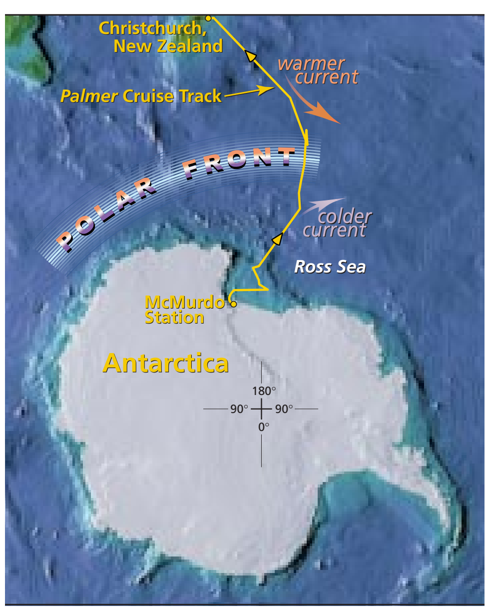
***Susumu Honjo**, Senior Scientist*

Extensive use of fossil fuels has increased levels of carbon dioxide (CO_2) in the atmosphere by more than 30 percent since the Industrial Revolution. The buildup of this heat-trapping gas threatens to cause a "greenhouse effect" that could raise global temperatures. Recent climate abnormalities are partially the result of this rapid accumulation of atmospheric CO_2.

But not all the CO_2 sent into the atmosphere by smokestacks and exhaust pipes remains there. Some is absorbed by the ocean, land plants, and soil. These could provide "sinks" for the excess CO_2 that might alleviate any potential greenhouse effect.

The excess CO_2 may be large enough to change the world's climate, but it is still small compared to all the carbon stored over billions of years throughout the earth system. Thus tracking precisely where industrial gases end up is like searching for a needle in a haystack. Despite ardent efforts by scientists, the best estimates to determine the fate of CO_2 remain unclear.

Deep and vast, the oceans could provide the most effective "sink." Colder seawater absorbs CO_2 directly, but the primary mechanism by which the ocean takes up CO_2 is the "biological pump." It starts when marine plankton in sun-drenched surface waters convert dissolved CO_2 via photosynthesis into organic matter containing carbon. When the plankton are consumed or die, carbon-containing particles sink to great ocean depths. This process not only supports ecosystems throughout the water column, it also results in the removal of CO_2 from the air and its transport to the abyss. The ocean's carbon cycle involves physics, chemistry, and biology, and is one of the most complex systems operating on Earth.



Jayne Doucette

The NSF-supported US-Joint Ocean Flux Study (JGOFS) is a major interdisciplinary program designed to improve understanding of the carbon cycle in the world ocean. Since the 1980s, US and international scientists have collaborated to study this important cycle in several critical regions, including the North Atlantic, the equatorial Pacific, and the Arabian Sea. WHOI has participated in all of these programs to measure the rate at which the biological pump process removes carbon from the upper ocean for very long-term storage in the deep ocean.

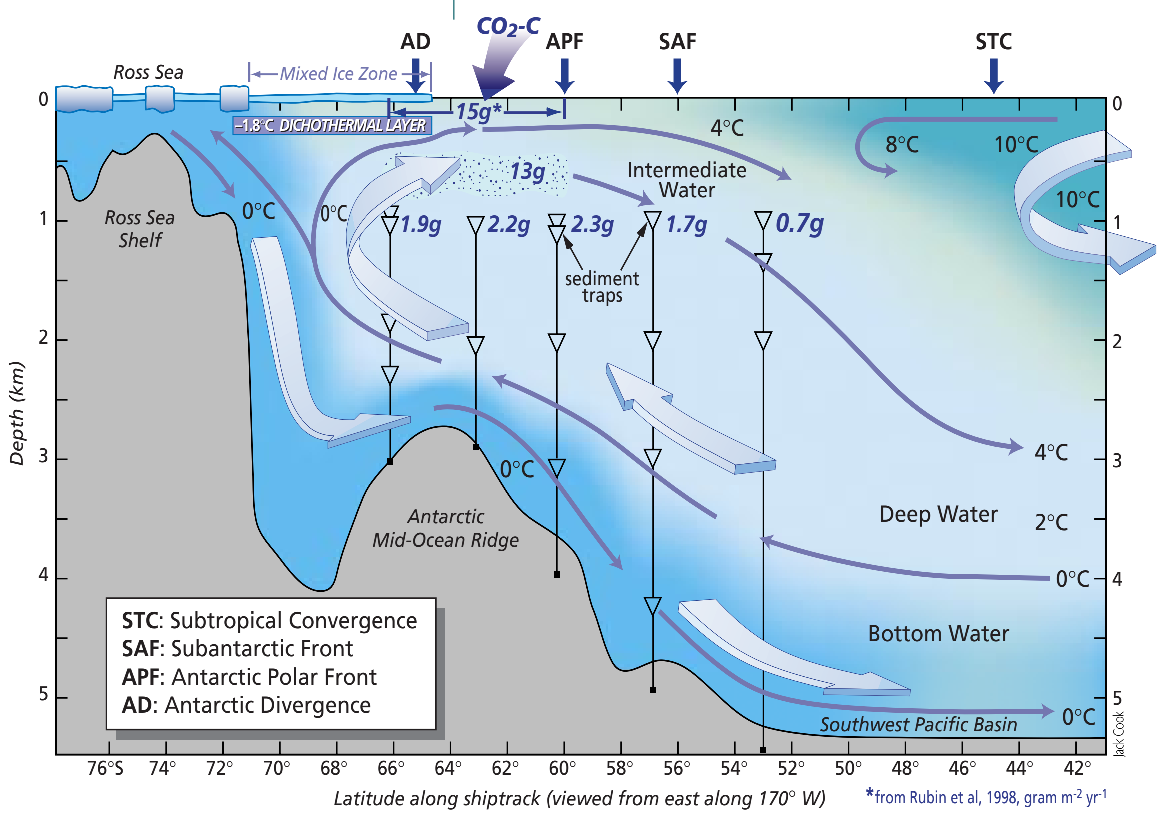
The last JGOFS ocean program, the Antarctic Environmental Southern Ocean Process Study (AESOPS), was mounted in the southern ocean around Antarctica, with WHOI scientists and a team from Oregon State University participating. From February to April 1988, we worked aboard RVIB *Nathaniel B. Palmer*, NSF's state-of-the-art research icebreaker, to recover an array of seven large moorings set to catch the rain of carbon particles that fall through the southern ocean. The moorings were set along longitude 170°W, from the Ross Sea to a point south of New Zealand. This *Palmer* cruise completed 15 years of US-JGOFS cruises studying ocean processes. [*Editor's Note:* Author Sus Honjo served as chief scientist for both the first US-JGOFS cruise aboard R/V *Atlantis II* from Madeira to Iceland in 1989 and this last JGOFS cruise in Antarctica.]

The 1998 AESOPS voyage produced very exciting and useful results. The southern ocean had long been regarded as the marine equivalent of a desert, but we have learned from this investigation that the biological pump there is vigorously working at transferring CO_2 from the air to the deep ocean sink. This active biological pump is probably the most efficient one known. It operates within the Antarctic Polar Front Zone (APFZ), an oceanic boundary where warmer waters moving south meet cold Antarctic waters. The APFZ encircles Antarctica and is twice as large as the Mediterranean Sea. The primary operators of the biological pump are plant plankton called diatoms, which use both organic carbon and silicate (SiO_2) to make their shells. These diatoms overwhelmed the more commonly found coccolithophorids that secrete calcium carbonate ($CaCO_3$) for their shells. Thus, the diatom-rich APFZ appears to constitute a biogeochemical province independent of the rest of the world ocean.

To our surprise, we also dispelled the notion that $CaCO_3$ was not produced extensively in the southern ocean, as was previously believed. Unlike in any other ocean, $CaCO_3$ *was* produced in the southern ocean by pteropods, small planktonic snails. We also found another factor that significantly affected the flux of carbon through the water colum: very strong stratification of water layers in the mixed ice zone (such as the dichothermal layer with –1.8°C temperatures).

Perhaps the most exciting outcome of our AESOPS cruise was a better method to pursue the trail of carbon in the southern ocean—knowledge that can be applied to the rest of the world ocean. While Stephaney Rubin and other scientists at the Lamont-Doherty Earth Observatory measured the net amount of CO_2 withdrawn from the atmosphere to the surface ocean, Sus Honjo, Fred Sayles, and other WHOI scientists measured the amount of carbon molecules settling through the water column and sinking to the seafloor (see Fred Sayles's article on page 17). We then established a relationship between the rates of CO_2/carbon sequestered at the euphotic layer and the fluxes of carbon particles in water column and at the seafloor. This has given us a more comprehensive picture of the biological pump in the southern ocean, which our preliminary calculations show is indeed a major sink of atmospheric CO_2 on this planet.

This important advance in understanding the ocean's carbon cycle will allow us to make more reliable determinations of the fate of fossil CO_2 and its effects on the global environment.



1997–1998 research indicated where and how carbon dioxide (CO_2) may be stored in the highly productive southern ocean by the "biological pump." Carbon molecules in CO_2 are sequestered by photosynthesis to the euphotic layer of the Antarctic Polar Frontal Zone along 170˚W at the rate of 15 grams per square meter per year. However, only about 1.9 to 2.3 grams of that total settles as particles at depths of 1 kilometer. These carbon particles keep sinking without dissolving into CO_2 and settle on the deep seafloor, which acts as a "sink" for excess CO_2, a greenhouse gas. The remaining 13 grams of carbon is consumed by zooplankton and bacteria and reconverted to dissolved CO_2. In contrast to most oceans, a large amount of dissolved CO_2 may be stored in cold intermediate water layers of the southern ocean, thus serving as another type of CO_2 sink.

At the end of 1998, the Department of Marine Chemistry and Geochemistry (MC&G) consisted of 18 scientific staff, 19 technical staff, 17 graded and administrative staff, and 11 people with postdoctoral appointments, all working on a total of well over 100 funded research projects. In addition, there were 14 MIT/WHOI Joint Program students, more than half of them in residence at Woods Hole.

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

In 1998 there were a number of personnel changes: Dan Repeta was promoted to Senior Scientist, Meg Tivey and Tim Eglinton were promoted to Associate Scientist with Tenure, Maureen Conte was promoted to Associate Scientist, and Eric Hintsa was appointed Assistant Scientist. The department bid farewell and best wishes to Bill Jenkins who took a position at the University of Southampton (UK). Ken Buesseler returned to the department after a two-year absence to serve as a National Science Foundation program manager.

Several prestigious awards came to members of the department during the year. Senior Scientist Fred Sayles was elected a Fellow of the American Geophysical Union. Tim Eglinton was given best paper award, and Silvio Pantoya best student paper award, by the Organic Geochemistry Division of the Geochemical Society, and Joint Program student Ann Pearson received an Outstanding Student Paper award at the 1998 spring meeting of the American Geophysical Union.

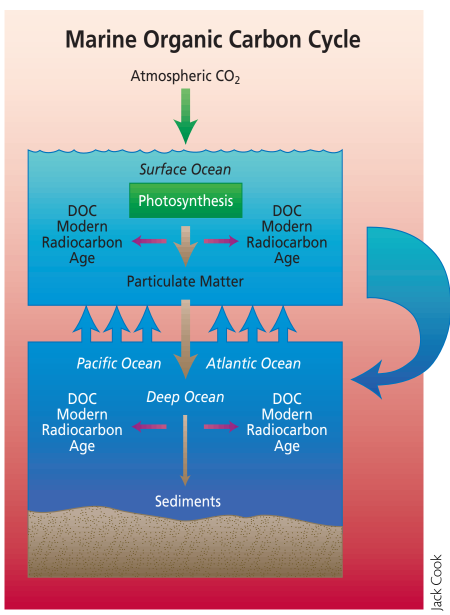
—Mark D. Kurz, Department Chair
(as of March 1999)

Tracking Dissolved Carbon from Surface to Deep Ocean

***Daniel J. Repeta**, Senior Scientist*

Organic carbon is the currency of marine life. Each year, marine phytoplankton living in the sunlit layer of the ocean fix about 60 billion tons of carbon dioxide into organic carbon through the process of photosynthesis. This organic carbon is consumed by herbivorous grazers and bacteria and respired back to carbon dioxide. The cycling of carbon between carbon dioxide and organic carbon in the ocean shares many features with the more familiar carbon cycle on land. Annually, marine and land plants each fix about the same amount of carbon dioxide into organic matter, and the mass of carbon stored on land and in the sea is also about the same.

There are, however, important differences as well. Most terrestrial organic matter is stored in plants, which live on average for several decades. In the sea, photosynthesis is carried out by microalgae, which live for only a few days. The standing stock of algal carbon is relatively small, and only about 3 to 5 percent of the total organic carbon in seawater is in phytoplankton and other living biomass. The remaining 95 to 97 percent of marine organic carbon is nonliving organic matter that is dissolved in the seawater.



Jack Cook

Atmospheric carbon dioxide is fixed by marine plants into organic carbon and largely cycled in the upper ocean. A small amount of carbon is exported to the deep sea by sinking particles, thought to dissolve at depth. This process may inject new carbon, which would sustain bacteria, into the deep sea. Radiocarbon measurements on specific fractions of deep sea dissolved organic carbon will help to quantify this cycle.

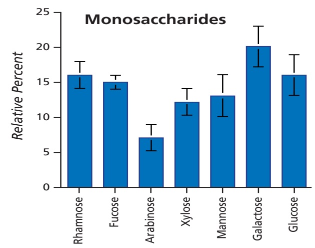
For decades, marine chemists have puzzled over the problem of dissolved organic matter (DOM). Though DOM is one of Earth's major storage reservoirs of carbon, we do not know its source, why it accumulates in seawater, or how it is ultimately removed from the ocean. Much of the problem rests in our inability to sample and characterize DOM. Although the DOM inventory is very large, its concentration in seawater is very low, and isolating it from seawater in the presence of high salt concentrations has proved to be a formidable challenge.

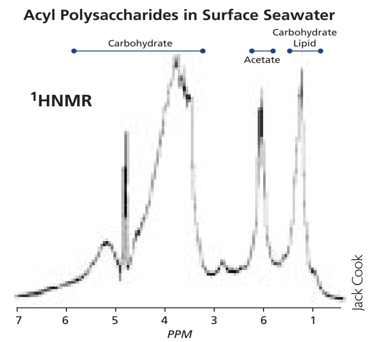
Using techniques developed for the biotechnology industry, Joint Program student Lihini Aluwihare, Postdoctoral Fellow Silvio Pantoja, and I have been working to characterize DOM chemically in seawater and to study its production and fate. When we began our project, it was widely believed that marine DOM was the soluble waste product of the global carbon cycle: Organic matter added to seawater from rivers, marine photosynthesis, and grazing would react with sunlight and particles and be converted into structurally complex and biologically inert macromolecules. From this perspective, DOM was thought to be a very complex mixture of organic compounds with no well-defined chemical characteristics.

However, as we began to chemically characterize DOM, two features immediately became apparent. First, DOM is compositionally simple, made up largely of carbohydrates and acetate, and second, this composition does not vary from place to place in the ocean (figure opposite)—wherever we sampled DOM, its composition was the same. These observations suggested that DOM might have a direct biological source. To test this hypothesis, we analyzed the DOM from cultures of marine algae, and in many cases we were able to isolate DOM very similar in chemical characteristics to seawater DOM. For reasons we do not yet understand, this organic matter, which we call acylpolysaccharide (APS), is resistant to microbial degradation and therefore accumulates in seawater.

What is perhaps even more surprising is that most APS resides in the deep sea, far removed from its source in the euphotic zone. Two mechanisms could supply deep sea APS. Acylpolysaccharides could survive degradation in the surface ocean and be transported into the abyss as deep water forms at high latitudes. Alternatively, APS could be supplied by rapidly sinking large particles that dissolve as they settle to the seafloor. It is the dissolution of large sinking particles that particularly intrigues us. This mechanism may inject into the deep sea fresh organic matter that supports bacterial activity and other deep sea biological processes. It may further provide a route by which carbon fixed in the upper ocean could be rapidly removed and stored in the deep sea.

The two mechanisms for adding APS to the deep sea can be distinguished by their radiocarbon content. If APS is added during water mass formation, we expect it to have the same radiocarbon age as dissolved carbon dioxide. We also expect a significant radiocarbon age





Jack Cook

The nuclear magnetic resonance spectrum of high molecular weight dissolved organic matter in seawater (above). The spectrum suggests a relatively simple chemical composition of carbohydrates, acetate, and lipid. The spectrum is consistent with a direct biological source for DOM. Detailed analysis of the carbohydrate component reveals an unusually complex mixture of simple sugars (above right), which may provide some protection from microbiological degradation.

difference, about 1,000 years, between the deep Atlantic and Pacific Oceans; this is the period of time it takes for deep seawater to move between the two basins. If APS is injected by large particles, then it should have a modern radiocarbon age equal to surface water carbon dioxide, and there should be no age difference between the deep Atlantic and Pacific basins. Radiocarbon analysis of APS is a difficult undertaking, and it will be several years before our study is complete.

However, preliminary results from APS collected in the deep Pacific Ocean show it does indeed have a modern radiocarbon age equal to surface water carbon dioxide. If this result is confirmed by future analyses, it suggests there is an important, previously unknown pathway in the ocean carbon cycle that directly links organic matter production in the upper ocean with carbon accumulation and removal in the deep ocean.

Studying Seafloor Chemistry Down Under—Way Down Under

***Frederick L. Sayles**, Senior Scientist*

The waters around Antarctica, commonly called the “southern ocean” by oceanographers, constitute nearly 20 percent of the global ocean. This area is of particular interest because, perhaps more than in any other major oceanographic system, processes regulating carbon fluxes are susceptible to perturbation by global warming. Despite its central and sensitive role in the ocean-atmosphere system, the southern ocean is one of the least studied areas of the world ocean. This is largely due to its remoteness and its well deserved reputation as the roughest ocean in the world. However, its importance in global climate has led to increased efforts to study it.

In February 1998, we participated in the Antarctic Environment and Southern Ocean Process Study (AESOPS), a large interdisciplinary National Science Foundation research effort that seeks to define southern ocean carbon fluxes within the context of the global carbon cycle. Our goal was to study reactions occurring on the seafloor and in the sediments as they affect the preservation and recycling of biogenic debris settling into the deep ocean. Our research on reaction and burial of material on the seafloor was closely coupled to studies

Joanne Goudreau

Scientists and crew land the WHIMP aboard NSF’s research vessel/icebreaker *Nathaniel B. Palmer* during a rare calm day in the southern ocean.

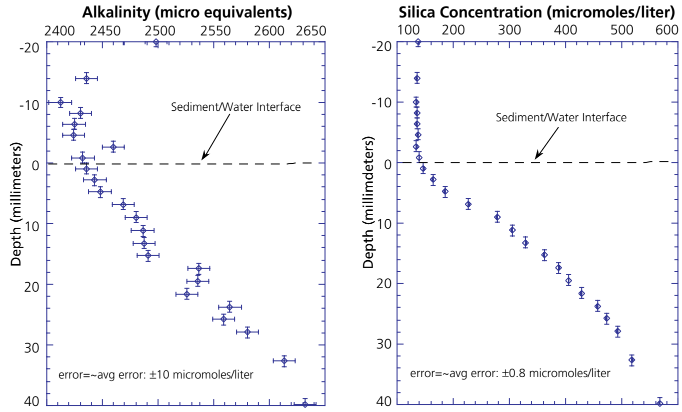
Joanne Goudreau

Fred Sayles, right, and Larry Costello, prepare a stripped WHIMP for loading aboard *Palmer* from the ice pier at McMurdo Station. The AESOPS group found that summer in Antarctica brings both 24 hours of "sun" and daily snow.

of vertical sediment fluxes led by Sus Honjo (WHOI—see article on page 14) and Jack Dymond (Oregon State). By linking these studies, we can construct a mass balance of material supplied to the seafloor (sediment fluxes), material reacting on the seafloor (and hence recycled back into the ocean), and material being incorporated into the sediments and buried (and thus isolated from the ocean-atmosphere system for hundreds of millions of years).

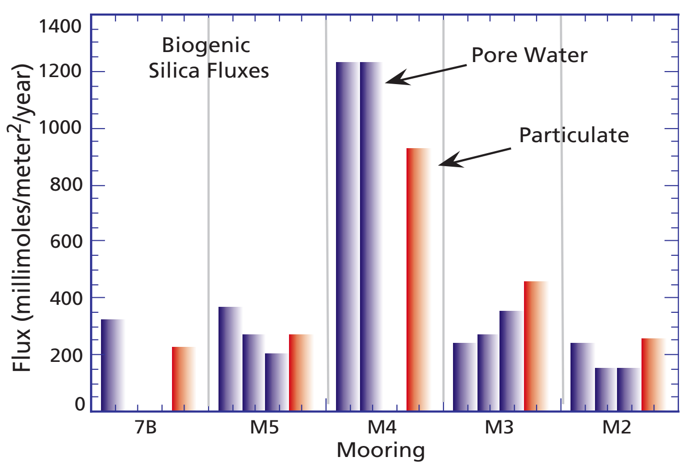
The materials of particular interest to us include biogenic silica, alkalinity and total carbon dioxide, and the nutrient nitrate. Silica is essential for the growth of *siliceous* organisms in the surface waters and is released on the seafloor by the dissolution of their skeletons. Alkalinity and total carbon dioxide measurements permit us to determine and separate the recycling of organic carbon and carbonate (inorganic carbon) derived from calcium carbonate, the skeletal material of *calcareous* plankton "raining" to the seafloor. Nitrate, essential for the growth of all organisms in the surface waters, originates in the breakdown of particulate organic material. The partitioning between recycling and burial of these compounds determines the fertility of the waters when they later upwell from the deep ocean on time scales of hundreds of years.

We focus on pore waters (water between solid grains of sediment) just below the water/sediment interface because they accumulate products of recycling reactions. Most of these reactions occur in the upper 10 centimeters of sediment, including important ones with a depth scale of only 1 or 2 centimeters. Additional reactions that can occur in sediments being transferred thousands of meters to the surface ocean during recovery may drastically alter the concentration of materials of interest, so it is necessary to collect our pore water samples on the seafloor. We also need short, undisturbed, upper-sediment cores in order to determine burial rates for calcium carbonate, organic carbon, and other components and products of the deep sea system.



Data sets like these, which show the concentration-depth relationships for alkalinity (a key carbon component) and silica (from dissolution of the skeletons of the dominant Antarctic plankton), provide the basis for studying the recycling of materials at the seafloor. Dissolution rates are derived from the chemical gradients at the sediment/water interface.

In order to collect these samples, we use a tripod sampler known as WHIMP (Woods Hole Interstitial Marine Probe). It has evolved over many years, ironically growing larger and larger as our studies of reactions indicated the need to sample closer and closer to the seawater/sediment interface. It is now a 2,500-pound, 10-foot-tall instrument (see photos) designed to make millimeter-scale measurements! Launching and retrieving it in rough southern ocean seas was indeed a challenge.



Dissolution rate estimates like those in the figure at the top of the page for each station visited are compared with the delivery rate for particulate silica to the seafloor as measured in Sus Honjo's sediment traps to yield conclusions about the origin of the southern ocean's siliceous sediments. The 7B sediment trap was in the Ross Sea, and M2 was the northernmost mooring of the transect.

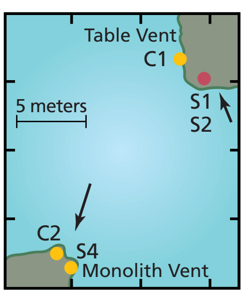
We are in the first stages of interpreting the southern ocean data. Using our estimates of fluxes across the sediment-water interface derived from profiles such as the figure opposite top (silica content of pore waters), we can make an initial comparison between recycling rates and the particulate delivery rates determined with sediment traps. The figure opposite below compares the two fluxes for biogenic silica. The data suggest that the two fluxes are nearly in balance, that is, the particulate rain of silica is effectively recycled, and there is little accumulation. This is somewhat surprising in that the sediments of much of the southern ocean are largely (80 to 90 percent) biogenic silica. Numerous previous explanations of the high silica content called upon an unusually high preservation (burial) rate. Our data run directly counter to this and require little present day accumulation. Either conditions have changed over the past few thousand years, or the dominance of silica reflects a dearth of other components and the slow accumulation of a small fraction of the sedimenting silica. A first look at other AESOPS cruise data indicates that, unlike other biogenic components and other areas of the world ocean, a large fraction of the organic carbon reaching the southern ocean seafloor is rapidly recycled at the sediment-water interface, which requires reaction rates much higher than those observed elsewhere.

During 1999, we expect to refine these initial estimates and to place quantitative constraints on the roles of recycling and burial in this important ocean.

Time-Series Measurements At Seafloor Vent Sites

Margaret Kingston Tivey, Associate Scientist

Seafloor hydrothermal vents located along Earth's mid-ocean ridges are the surface manifestation of dynamic hydrologic systems operating within the upper few kilometers of very young oceanic crust. Temperatures of venting fluids range from near ambient (about 2°C) to greater than 350°C, and the fluids are acidic and metal- and sulfide-rich as well as magnesium- and sulfate-poor relative to seawater. These hydrothermal systems play key roles in global heat budgets, geochemical balances, and modification of the physical and chemical properties of young ocean crust. They are also responsible for forming modern-day equivalents of economically valuable massive sulfide deposits, and, with the presence of steep thermal and chemical gradients, for providing suitable environments for chemosynthetically based ecosystems.

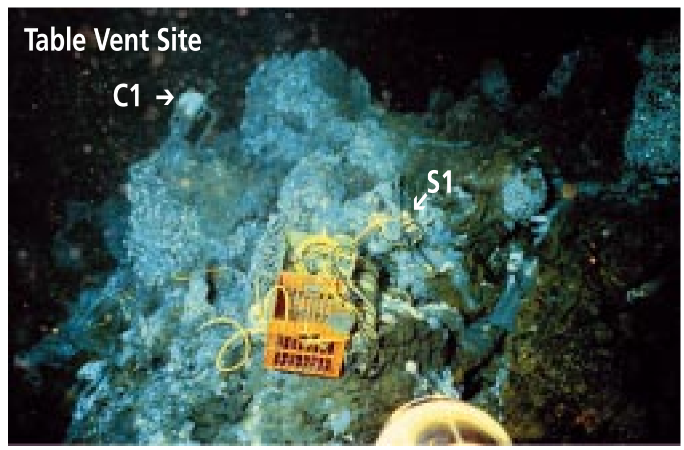


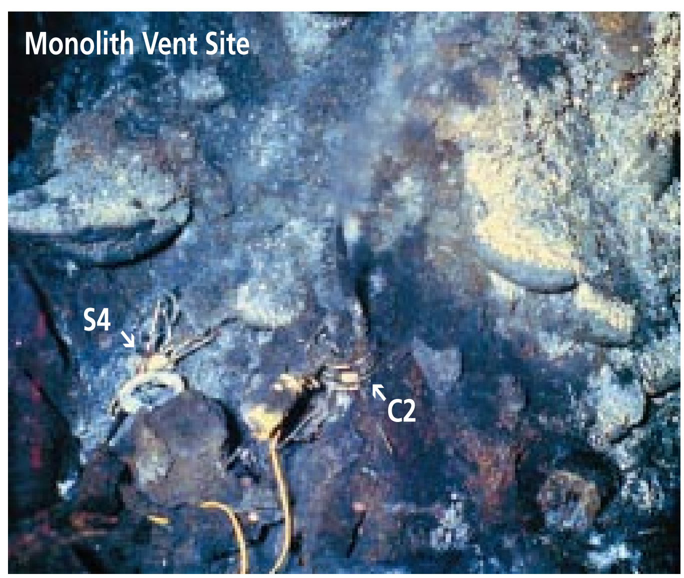
Jack Cook

Relative location of Table and Monolith vent sites. Arrows indicate the direction in which the photographs were taken just prior to recovery of the instruments in June 1995.

In recent years considerable effort has been devoted to exploring the dynamic nature of these systems through in situ long-term monitoring of vent phenomena. A major observatory effort, to be carried out on the Endeavour segment of the Juan de Fuca Ridge and funded by the National Science Foundation's RIDGE (Ridge Inter-Disciplinary Global Experiments) Program, is planned for the year 2000. In preparation for this observatory effort, vent scientists are developing instruments to monitor temperature, fluid flow rates, and aspects of fluid chemistry in the hostile low pH, high pressure, high temperature environments common to vent sites.

With funds from NSF, I have been working with Al Bradley of the AOP&E Department to develop instruments capable of monitoring temperature in both focused, high-temperature and diffuse, low-temperature hydrothermal fluids. We deployed two instruments for testing at the Monolith and Table Vents on the

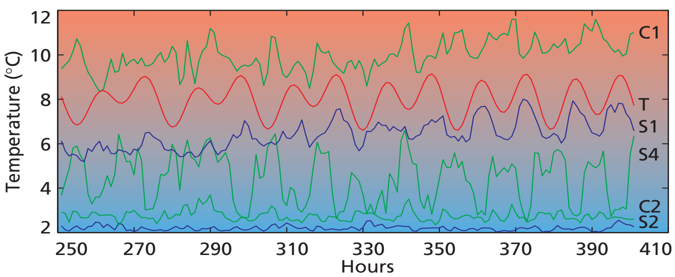




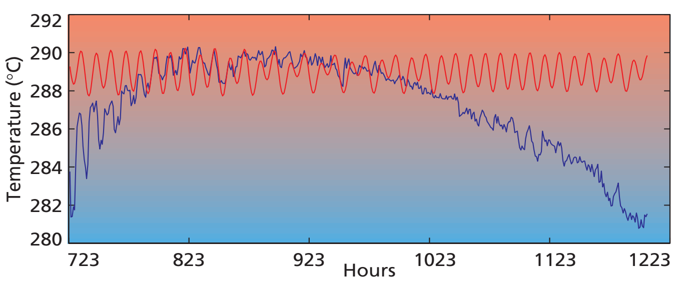
The Monolith and Table Vent sites are located along the Juan de Fuca Ridge some 200 miles off of the coast of Washington. Arrays of 18 thermocouples (C1 and C2) and arrays of 20 thermistors (S1, S2, and S4) were placed at the side of Monolith Vent and at the side and on top of Table Vent. (S2 is out of view near S1)

Juan de Fuca Ridge (approximately 200 miles off the coast of Washington) in 1994. We obtained continuous records of fluid temperatures over a 5.5 month interval at 19 to 21 discrete points in each of 4 locations.

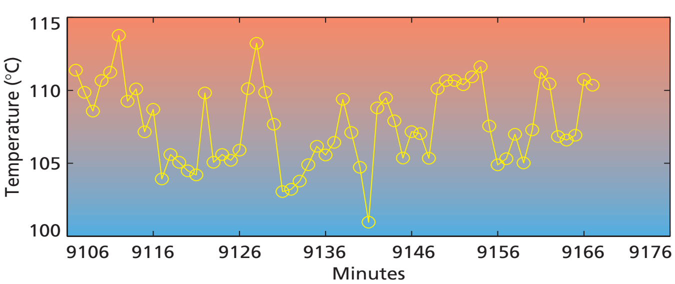
Temperatures measured at one site of focused, high-temperature flow documented the growth of a 304°C "beehive" chimney



Time-series records from the reference thermistors for the S1, S2, S4, and C1 and C2 arrays, after being filtered and resampled at once per hour, from 250 to 400 hours after emplacement. The tidal pressure (T) for the same time interval, which varies from -14.0 to 11.4 kiloPascals, is also shown. Note that maximum temperatures at S1ref and S2ref, which were located on top of Table Vent, correlate with maximum tidal pressure, while maximum temperatures at C1ref, C2ref, and S4ref correlate with minimum tidal pressure.



Temperature record from thermocouple B3 of array C1, after being filtered and resampled at once per hour, from 723 to 1,203 hours after emplacement of the array, and the tidal pressure (T), which varies from -12.7 to 12.4 kiloPascals, for the same time interval. The high temperatures recorded by the thermocouple are consistent with it having become embedded within the sulfide structure. The record shows variations in temperature, with maximum temperatures correlating with maximum tidal pressure.



Temperature record from thermocouple B3 of array C2, which was embedded in the outer portion of the beehive chimney wall, from 9,106 to 9,166 minutes after emplacement of the array. The fluctuations of temperature from 101° to 114°C probably result from variations in the amounts of advection of hydrothermal fluid outward across the chimney wall, and of seawater inward across the wall. These temperatures are favored by some hyperthermophilic (heat-loving) microorganisms.

(the term reflects the bulbous morphology of the 1- to 2-foot chimney top whose outer texture is reminiscent of a beehive). The data show the stability of the fluid temperature in the hottest portion of the chimney (304±2°C), expansion of this hot central area with time (from some 24 square centimeters to about 47 square centimeters), and the variability of temperature on time scales of minutes in outer portions of the chimney wall. Pore spaces within the outer chimney wall may provide favorable environments for hyperthermophilic (heat-loving) microorganisms.

Time-series temperature records from areas of diffuse flow at the Monolith and Table Vents indicate modulation of temperature by semi-diurnal tides, a phenomenon observed at a number of different active vent sites. At some of these sites temperature highs correlate with ocean tidal pressure maxima and minima, and temperature lows correlate with inflection points (where curvature of sine wave changes) in the tidal pressure signal. At other sites temperature maxima correlate with ocean tidal pressure minima. In our 5.5 month long instrument test, all temperature records are either in phase or about 180° out of phase with tidal pressure. Maximum temperatures at the base of Monolith Vent and at the side of Table Vent correlate with tidal pressure minima, and temperatures on top of Table Vent correlate with the tidal pressure maxima.

These observations are consistent with a model that indicates 1) *less* entrainment of cold seawater into structures at high tide and *more* entrainment of cold seawater into the structures at low tide, and 2) *more* updraft of cold bottom water along the sides of the hotter structures at high tide and *less* updraft of cold fluid along the sides of the structures at low tide. However, all but the observation of tidal variability of temperature within the vent structure could also be explained by tidally induced changes in horizontal bottom currents. Temperature data alone are not sufficient to distinguish between these mechanisms. Data on currents both above and within the boundary layers are also needed to determine whether the observed tidal variability is predominantly from changes in horizontal bottom currents or from variations in the extent of local seawater entrainment, fluid flow, and mixing within the vent systems. Seawater entrainment, fluid flow, and mixing can affect fluid chemistry and vent biota. The extent to which these processes are affecting the vent systems must be understood in order to accurately estimate fluxes of mass and heat through hydrothermal systems.

Scientists from four institutions (WHOI, University of Washington, University of Miami, and Cambridge University) plan to examine thermal and chemical variability in tidally perturbed seafloor hydrothermal systems with a variety of instruments as part of the observatory effort in 2000. The objective is to document the effects of tidal perturbations on fluid temperature, pressure, composition, and flow rate in areas of both high- and low-temperature flow. Observed tidal effects will provide information on how the system responds to identifiable perturbations, and they will allow development of models of subseafloor fluid flow and mixing patterns, and of the chemical, physical, and biological consequences of these patterns.

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

The department is active in the joint graduate program with MIT and includes a total of 23 graduate students who spend time at both MIT and WHOI. Our scientific staff, now numbering 34, is at an all-time high. We welcomed five new Assistant Scientists to the Physical Oceanography Department in 1998: Gidon Eschel focuses on climate dynamics and climate proxy reconstructions. David Fratantoni specializes in observations and numerical studies of general ocean circulation, and Joe Lacasce's research interests include two-dimensional turbulence. Cecilie Mauritzen studies general ocean circulation, including dense water formation. Vitali Sheremet investigates mesoscale eddies and rings as well as boundary currents and flow around corners and through gaps.

The department also includes 26 members of the technical staff and 25 laboratory assistants, and there are 10 administrative/staff assistant positions. Postdoctoral Investigators and Scholars and Visiting/Guest Investigators round out our complement.

During the past year, Phil Richardson stepped down as department chair to resume full-time research, and Terry Joyce began a four-year term as chair in July. Scientist Emeritus Nick Fofonoff was honored with the American Meteorological Society's Henry Stommel Research Award for his fundamental work on the general circulation and physical properties of the ocean and for development of observational techniques in physical oceanography. The Office of Naval Research (ONR) awarded a Secretary of the Navy/Chief of Naval Operations Oceanographic Research Chair to Bob Weller and named Steve Anderson an ONR/Institution Scholar.

—Terrence M. Joyce, Department Chair

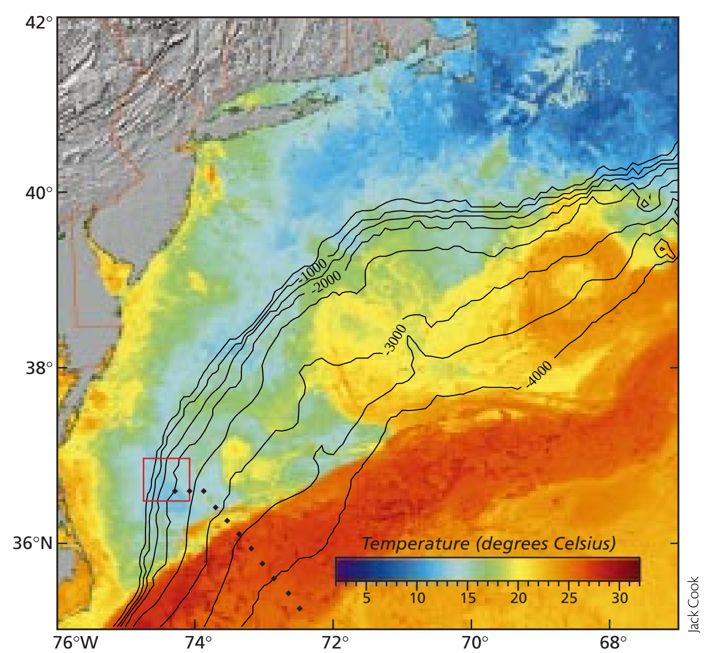
Topographic Roughness Begets Increased Oceanic Mixing

***Kurt Polzin**, Assistant Scientist*
***John M. Toole**, Senior Scientist*
***Raymond W. Schmitt**, Senior Scientist*

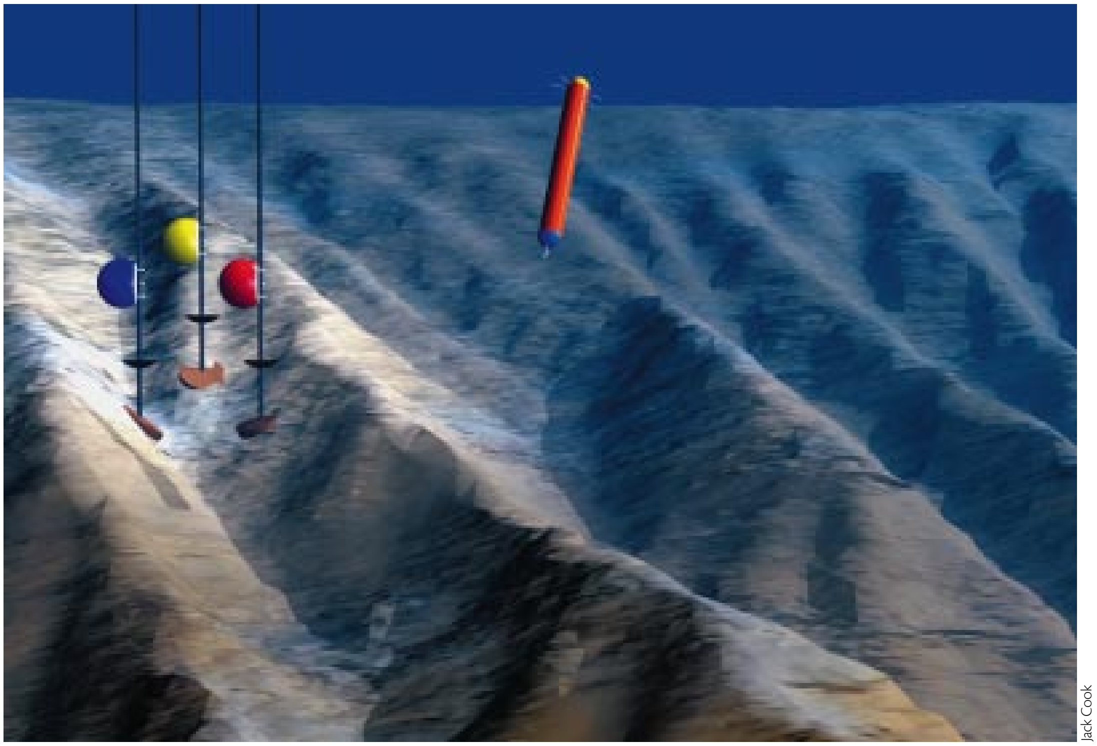
Winds and air-sea exchanges of heat and fresh water are ultimately responsible for basin-scale currents, or the general circulation of the oceans. In order to achieve a state where the energy of the ocean is not continuously increasing, some form of energy dissipation is required to balance the forcing. While this may seem obvious, little is known about how and where this dissipation occurs. In previous investigations we linked the decay of tidal energy to the generation and breaking of small-scale, deep-ocean internal waves generated by the tide flowing over rough bathymetric features. Such waves can also be generated by steady or slowly varying flows over topography. The breaking of subsurface waves generated by steady flows represents a possible damping mechanism to balance the wind's input of energy.

We strongly suspected such waves would be present on the continental slope just north of Cape Hatteras (map at right) as this region exhibits a combination of substantial flows and topographic roughness superimposed upon the slope. We conducted an Office of Naval Research supported field program in May 1998 with R/V *Oceanus* in order to quantify the internal wave field and turbulence associated with wave breaking. We used a combination of vertically profiling instruments including the freely falling High Resolution Profiler, which obtains samples of the ocean's temperature, salinity, and horizontal velocity field as well as associated dissipation rates of turbulent kinetic energy and temperature variance. We also deployed the newly developed Moored Profiler, which autonomously samples oceanic fine scale velocity, temperature, and salinity variability. Both instruments were designed and built at WHOI. Eric Kunze (University of Washington) deployed eXpendable Current Profilers (XCPs) and eXpendable CTDs (XCTDs) during the cruise. (CTD stands for conductivity, temperature, and depth measurements.) Lastly, we utilized a conventional, wire-lowered instrument package that included a CTD and a lowered acoustic Doppler current profiler.

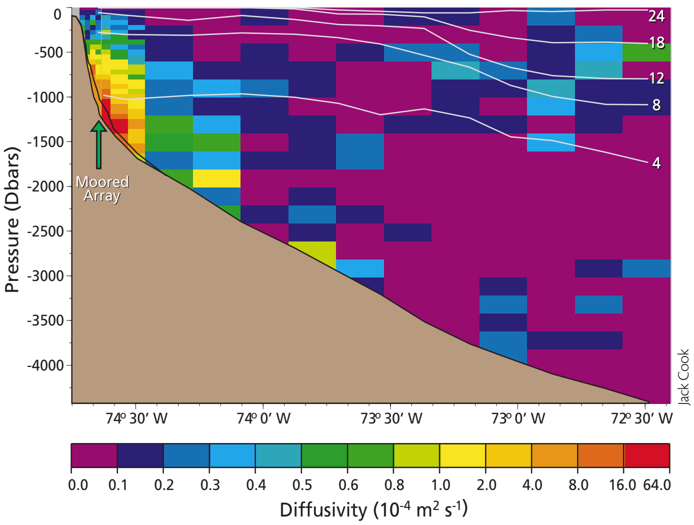
The experimental site is characterized by well-defined, small-horizontal-scale (2.5–3 kilometer horizontal wave length) ridges



Color map of sea surface temperature with bathymetry contours superimposed. Shades of orange and red indicate warm Gulf Stream waters. The authors' investigation focused within the small box at roughly 36°30'N, 74°30'W, just north of where the Gulf Stream separates from the continental slope. Black dots indicate High Resolution Profiler (HRP) stations occupied on the return to Woods Hole.



View of bathymetry at the work site looking at the continental slope from about 2,000 meters water depth. The shelf break at 100 meters water depth is represented by the horizon at the top of the figure. The continental slope is incised with ridges having horizontal wavelength of roughly 3 kilometers. The depth difference between the top of a ridge and an adjacent valley is 100-200 meters. The moored profiler array is shown as deployed and the free falling HRP is superimposed to the right of the moorings. The instruments are not drawn to scale.



A color map representing the magnitude of turbulent diffusion. These estimates are derived from measurements of centimeter-scale velocity fluctuation with special instrumentation on the HRP. The color scale is nonuniform. Purple indicates weak mixing characteristic of the mid-ocean thermocline and red/orange mixing about 100 times larger. The white traces are lines of constant potential temperature. Sloping isotherms give rise to the velocity jet associated with the Gulf Stream. The surface expression of the temperature field appears in the figure on page 21. The two black lines near the bottom and close to the moored array represent the bottom of the valley in which the moored array was placed and the tops of adjacent ridges.

oriented onshore-offshore and superimposed on the large-scale, planar continental slope (shown at left). Three moored profilers were deployed approximately 500 meters apart in about 1,150 meters of water on the continental slope just north of Cape Hatteras (36°34'N, 74°39'W). We synchronized the moored profilers and shipboard deployment of instruments to initiate all three types of vertical profiles every 1.5 hours during the month-long cruise. The High Resolution Profiler was used for repeat sampling at a grid of stations in water depths of 800 to 1,800 meters around the moored profiler array. In combination, these vertical profile data allow us to characterize the amplitude and direction of propagation of the small-scale internal wave field.

Preliminary analysis of the data reveals that turbulent mixing was greatly enhanced above the rough bathymetry on the continental slope. Vertical profiles of turbulent diffusivity indicate mixing enhancement at the bottom. At the moored array, the turbulent diffusivity in the bottom 200 meters is more than two orders of magnitude larger than that found in the upper 100 meters of the water column. Farther offshore, the turbulent diffusivity decreases. Within the Gulf Stream, vertical mixing is weak and independent of depth, despite the fact that the oceanic velocities within the Gulf Stream are typically much larger than on the continental slope. The key to mixing in this experiment, as with our previous investigations of tidal mixing, is the presence of rough bathymetry. Beneath the Gulf Stream, the ocean bottom is well sedimented and quite smooth.

Like many oceanographic instruments, the High Resolution Profiler is one-of-a-kind. Our cruise preparations were complicated by an explosion within its pressure case, apparently triggered by a faulty battery. After the battery blew up on April 23, it was not clear that the instrument could be repaired at all, let alone fixed in time to meet the May 10 cruise departure schedule. That the cruise took place as scheduled is due to the dedication and experience of many people in both our own and other WHOI departments. We are especially grateful to Ellyn Montgomery, who directed the repair efforts; Marshall Swartz, Steve Liberatore, Dick Koehler, and Al Fougere (Falmouth Scientific, Inc.), who provided significant engineering support and testing assistance; and Karlen Wannop, Jim Valdes's group, and Craig Taylor, who contributed assembly assistance and spare parts.

Crossing the Ridge: Rossby Wave Tunneling

***Joseph Pedlosky**, Senior Scientist*
***Michael Spall**, Associate Scientist*

The deep ocean is divided into smaller sub-basins by the dominating presence of mid-ocean ridges that very nearly span the abyssal ocean north to south. A continuing theoretical puzzle concerns communication between sub-basins. Observations of water mass properties indicate that there is overall steady circulation between the sub-basins through transform faults, narrow gaps that fracture the ridge into islandlike segments. There is another compelling question about whether the ridge system also allows the propagation from one basin to another of wavelike disturbances with large north-south scales, that is, waves whose size is much larger than the gaps they would have to squeeze through. Is there a mechanism that allows these disturbances, which may be generated by internal instability processes, to "tunnel" from one sub-basin to the next?

We are examining the basic theory of such tunneling possibilities by using mathematical models in idealized settings to study the propagation of large scale waves between sectors of a basin that is divided nearly in two by a barrier broken by only a few small gaps. The width of the gaps is much smaller than the north-sourth scale of the large scale waves impinging on the ridge, yet, remarkably, the theory suggests that under the right conditions most of the wave energy can squeeze through the gaps and reconstitute itself as a broad, large scale wave on the other side of the ridge.

The figure at left shows four snapshots of a rectangular basin in which localized forcing in the northeast segment of the basin excites a large scale Rossby wave. These waves spring from Earth's rotation, more exactly by the combination of the planet's rotation and its spherical shape. The westward propagating wave consists of a series of vortical motions whose scale is determined by the forcing frequency. When the frequency designated is one of the natural frequencies of that basin's oscillation, as it is in the figure, the response is both large and largely independent of the form of the forcing. Note that the wave, approaching the barrier, squeezes down in meridional size, extrudes itself through the two gaps, and emerges on the other side with, again, the meridional scale of the entire basin! For this mode, the ridge is essentially transparent to the wave, allowing its complete passage.

Modes of different frequencies, with different spatial forms, such as the one shown in the figure at right, are effectively limited to their original basins. For such modes the meridional barrier is opaque, and the wave motion is limited to its sub-basin of origin.

What explains one wave wriggling through the gaps and the other remaining trapped in its birth basin?

Our work shows that a fundamental theorem of fluid mechanics, called Kelvin's theorem, governs success or failure of wave passage.

In the present context, Kelvin's theorem tells us that the average velocity tangent to the barrier when measured clockwise *all around the islandlike ridge segment* must be zero. In the first figure**,** the wave's fluid motion is parallel to the ridge segment, at each instant, always in

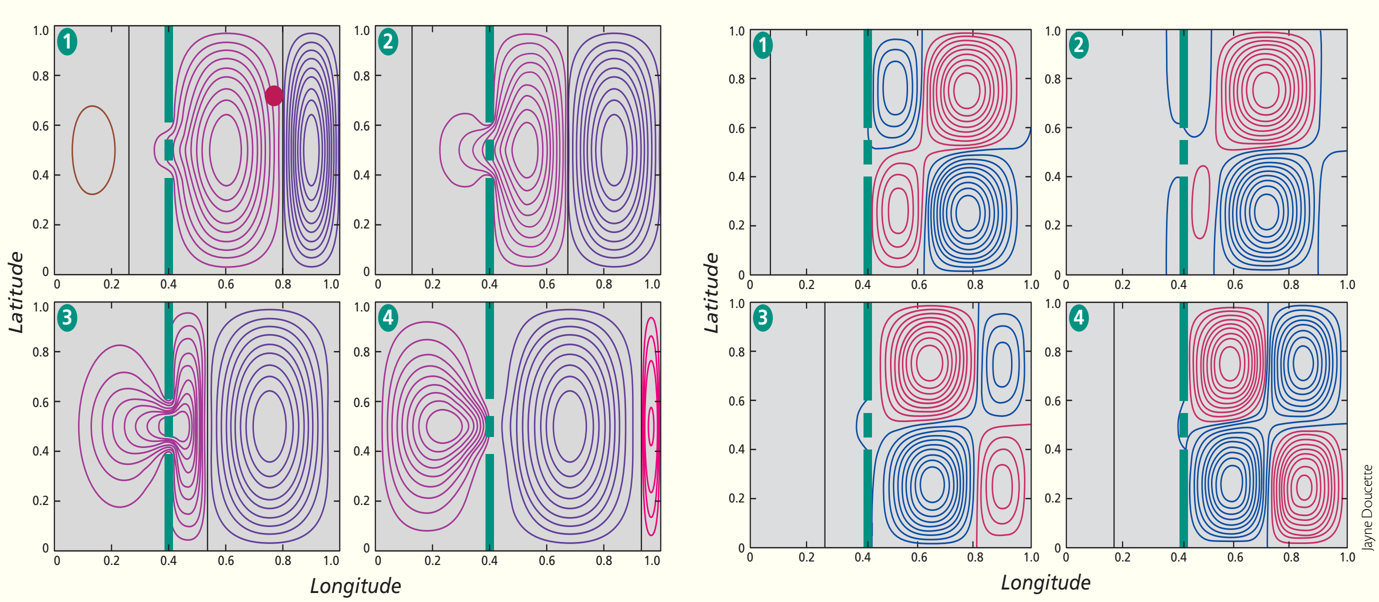


Figure at left: Four snapshots of an idealized ocean basin with a meridional barrier indicated by the cross hatches. There are two very small gaps in the middle of the barrier. A large scale Rossby wave impinges on the barrier and squeezes through the gaps. The origin of the wave is a localized source of energy (red dot) in the northeast segment of the basin, and the frequency of the wave forcing matches one of the natural modes of oscillation of the sub-basin. The snapshots clearly show the wave tunneling through the barrier. *Figure at right:* Similar to figure at left except that the frequency of the forcing causes a wave mode whose form consists of stacked, counter-rotating vortices so that the velocity averaged along the ridge on its eastern side is always zero. This wave's transmission is blocked.

one direction, either north or south. If the wave motion did not tunnel through, that is, were limited to only the basin of origin, Kelvin's theorem would be violated. Hence the wave must tunnel through. In doing so, southward motion on one side of the ridge is balanced by a similar southward motion on the other side of the ridge segment so that the average clockwise circulation around the segment is zero as the theorem demands. On the other hand, for the second figure wave the vortical motions are stacked in counter-rotating pairs so that the average tangential velocity along the eastern side of the ridge is already exactly zero. Kelvin's theorem is then satisfied without the wave tunneling through and, in fact, calculations of the forced motion, as shown, demonstrate that the wave is blocked.

We have done both analytical and numerical calculations of this phenomenon in idealized cases to verify these ideas. What remains is a greater challenge: With the collaboration of our colleagues, we hope to study the process in both the laboratory and the natural ocean to see whether this strange and dramatic tunneling phenomenon is robust enough to be a major factor in our understanding of ocean circulation.

Research Reveals Interdecadal N. Atlantic Atmosphere-Ocean Oscillation

Michael S. McCartney, Senior Scientist
Ruth Curry, Research Specialist

What is the ocean's role in Earth's climate system? When we, living in the atmosphere, perceive a shift in climate—most of the winters for a decade tending to be colder or wetter than those of the preceding decade, for example—are there concurrent changes in the oceanic component of the climate system? If so, are they merely a response to the changeable atmospheric climate, or do the oceanic changes feed back to alter the atmospheric climate?

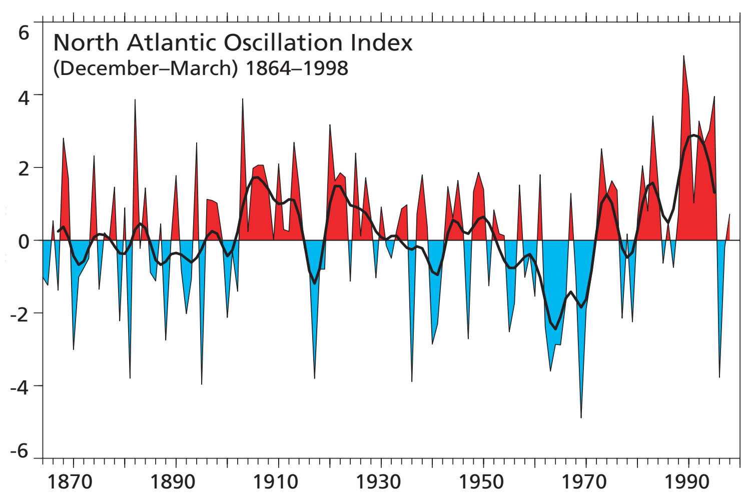
Some of our work focuses on defining the role of the North Atlantic Ocean in interannual/interdecadal fluctuations of climate. Atmospheric variability in the North Atlantic sector is dominated by the North Atlantic Oscillation (NAO): simultaneous strengthening or weakening of the Icelandic low pressure center and the Azores high pressure ridge along with lateral movements of their locations. The intensity of westerly winds reflects the pressure difference between these sites; thus NAO's principle signature is in the variable intensity of the westerlies and the latitude of their maximum winds.

Climatologists affirm that in Europe, Iceland, Greenland, and eastern North America fluctuations in climate—air temperature, humidity, rainfall, and storm frequencies and intensities—correlate with the NAO. But what of the North Atlantic Ocean beneath that NAO-fluctuating atmosphere?

The history of NAO fluctuations (see figure at right) reveals that the climate system in the North Atlantic has been running a 50-year experiment for us, with atmospheric forcing modulated interdecadally. The NAO index decreased from the 1950s through 1971, resulting in a 1960s record of weakened westerlies displaced southwards from their average location. Subsequently, the NAO index increased from 1972 through the mid-1990s, and the strengthened westerlies shifted northwards from their average location. What are the consequences of this fluctuation of atmospheric forcing of the ocean?

The most extensive oceanic sustained measurement archive available to us is sea surface temperature (SST). NAO-correlated air-sea heat exchange anomalies produce distinct patterns of SST anomalies—evidence that the upper ocean integrates the atmospheric forcing anomalies. In 1996 articles in the "Oceans and Climate" issue of *Oceanus* (Volume 39, Number 2), we discussed evidence that the observed winter SST anomalies are the surface expression of substantial upper ocean heat content anomalies. These reflect altered conditions along the pathway of upper ocean transformation of warm water to cold in the thermohaline overturning circulation of the North Atlantic (top figure opposite). We also showed that the altered products of this transformation could be detected returning southward through the subtropics beneath the thermocline.

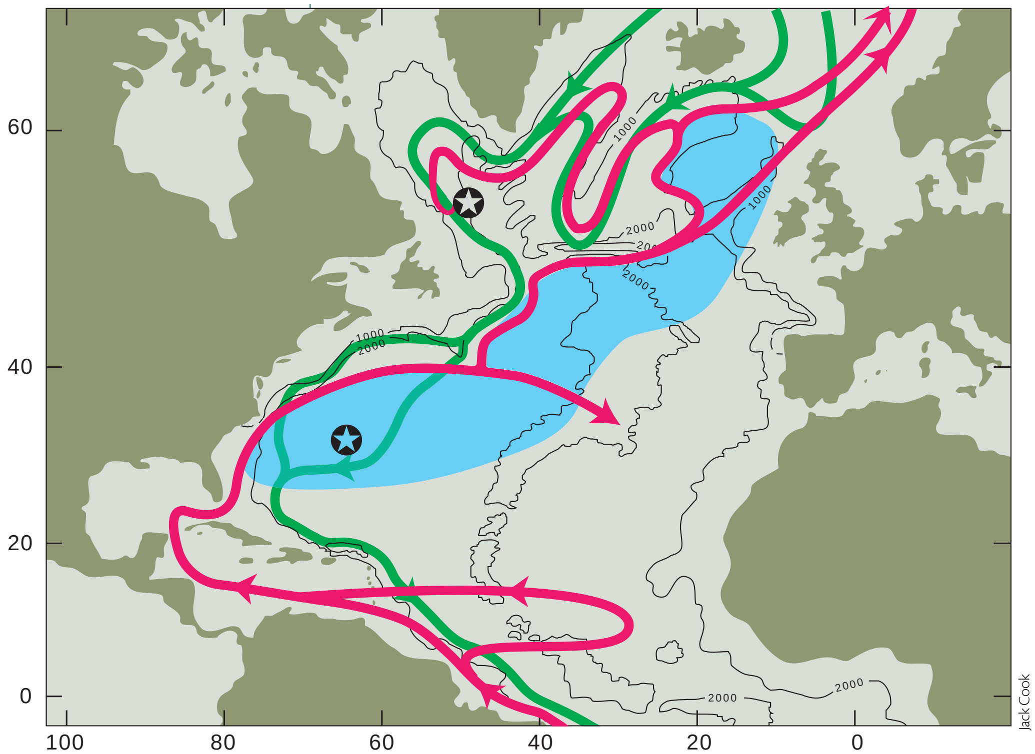
We now have another contribution to the growing evidence for this North Atlantic Atmosphere-Ocean Oscillation. We used two sustained measurement time series available in the subsurface North Atlantic, one near Bermuda and one in the central Labrador Sea (marked by stars on the map), to construct an ocean transport index analogous to the atmospheric NAO index. The two stations fall near the



A 134 year record of the North Atlantic Oscillation (NAO) index using sustained sea level pressure measurements in Iceland and Portugal, constructed by Jim Hurrell of the National Center for Atmospheric Research. The index uses average sea level pressure for the cold season months (December to March) in Iceland, reflecting the strength of the Icelandic low pressure center, and in Portugal reflecting the strength of the subtropical "Azores" high pressure ridge. When the sea level pressure difference is large, "high NAO" conditions prevail (positive index), with westerly winds stronger than average, and centered on the 45°N to 60°N belt. When the difference is small, "low NAO" conditions prevail (negative index), with westerly winds weaker than average, and distinctly shifted southwards of the average latitude.

centers of subtropical and subpolar circulation gyres, and the difference of pressure between these two locations is a measure of the flow along the thermohaline transformation pathway, much as the atmospheric NAO index reflects the intensity of the westerly winds.

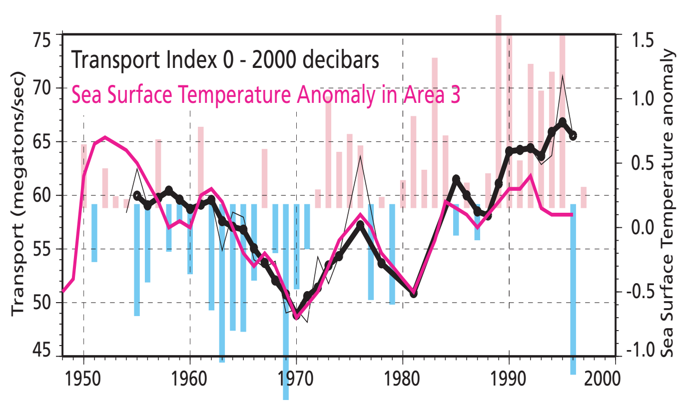
Comparison of the ocean transport index with the NAO index (figure below right) shows that in the last half of this century the thermohaline transformation pathway has responded, sluggishly, to the NAO correlated changes in buoyancy- and wind-forcing. Weakening of ocean transport to a minimum in 1971 occurred during the period of declining NAO index. This was followed by strengthening transport to a maximum in 1995 during the period of rising NAO index. We have included in the figure the time history of SST along the transformation pathway south of Nova Scotia. It demonstrates that the oceanic transport index and SST vary together: that the weaker phase of pathway transport involved colder waters while the stronger phase of pathway transport involved warmer waters. This indicates that the interdecadal North Atlantic Atmosphere-Ocean Oscillation of the past half century has involved fluctuation in heat transport along the transformation pathway, and ultimately of oceanic heat released to the overlying atmosphere.



The primary pathways involved in the North Atlantic warm-to-cold water transformation. The basin scale gyre recirculations of the tropical, subtropical, and subpolar circulations are suppressed here to emphasize the warm water transformation pipeline of the upper ocean (red pathways) and the compensating cold return flows at depth (green pathways). The blue area indicates the belt where winter sea surface temperature anomalies slowly propagate from the western subtropical gyre into the eastern subpolar gyre with a typical transit time of a decade. These winter sea surface temperature signals are upper ocean heat content anomalies that reflect fluctuations of the balance between the large annual heating of the atmosphere by the release of heat from the ocean in that belt, and the supply of that heat to and through the belt by the flow of water along the red pathway. The two stars indicate the two sustained measurement time series, near Bermuda and in the central Labrador Sea, used to construct the index of the oceanic flow along the belt.

The most important, and most controversial, physical process question raised by these observations is whether or not the fluctuations of oceanic heat content and transport at mid latitudes feed back to force changes in the atmosphere. If so, the seeds for future climate prediction may lie with the slow and majestic fluctuation of the ocean. Indeed, those seeds may already be germinating, for as this report goes to press we have received word that three independent numerical models of the atmosphere have simulated the observed time history of the NAO since 1950 by applying as a boundary condition the observed SST history. With a global observing system to monitor upper ocean heat content and circulation, and a physically sound ocean circulation model to forecast the evolution of the ocean and its coupling to the atmosphere, climate forecasting will follow.

We continue to address this crucial climate issue. This research is sponsored by grants from the National Science Foundation and the National Oceanic and Atmospheric Administration along with an award from the Andrew W. Mellon Foundation Endowed Fund for Innovative Research.



The blue and red bars show the annual values of the cold season NAO index. The black curve is the estimated transport of water along the conveyor belt pathway connecting the western subtropical gyre to the eastern subpolar gyre, the pathway delivering warm subtropical waters to higher latitudes. It indicates an interdecadal fluctuation of about 30 percent of the mean flow rate. The red curve represents the history of sea surface temperature anomalies in the blue belt of the accompanying map at a location southeast of Newfoundland. The red and black curves link the weak transport phase with cooler temperatures, and the stronger transport phase with higher temperatures.

Marine Policy Center

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

Many MPC research projects reflect the increasing demand for approaches to environmental policy that are compatible with the goals of economic efficiency and growth. Examples include MPC studies on the economics of ecosystem disruptions, pollution remediation, and environmental regulation. Economic analysis figures prominently as well in MPC's major new research concentration in offshore aquaculture development.

Recent MPC studies have focused on the economic consequences of harmful algal blooms and hypoxia, or abnormally oxygen-poor conditions. An hypoxic "dead zone" in the northern Gulf of Mexico has grown dramatically since it was first mapped in 1985, and the increase is generally believed to be associated with high levels of nutrient inputs via the Mississippi and Atchafalaya Rivers. In 1998, MPC Director Andrew Solow led the economic component of a White House-commissioned study to evaluate the ecological and economic consequences of hypoxia, including impacts on Gulf of Mexico fisheries and the regional and national economy. The study, whose results are due to be released by the White House in the near future, represents a first step toward developing appropriate mitigation policies for the region in light of hypoxia's economic consequences and the costs of alternative mitigation strategies.

Over the past several decades, harmful algal blooms (HABs) have involved an increasing number of species and have occurred in a growing number of locations in US coastal waters and around the world. Despite continuing debate as to the association between such trends and increased nutrient and pollutant loadings, there is little question that HABs can result in a range of adverse public health and environmental effects, with significant economic impacts. In 1998, MPC researchers, in collaboration with the WHOI Biology Department and the Massachusetts Maritime Academy, completed the first comprehensive economic impact assessment of all economically measurable HAB events in US waters between 1987 and 1992. The study yielded conservative estimates totaling $50 million in annual direct economic impacts across four major areas: public health, commercial fisheries, recreation and tourism, and public outlays for monitoring and management.


Hauke Kite-Powell

Fish ponds on the island of Pemba, Zanzibar. MPC is participating in research to improve the yield and the ecological sustainability of aquaculture in East Africa.

MPC plans to refine these findings in future studies to estimate both direct and indirect impacts at the regional level, using economic "multipliers" that can capture the effects of local and regional market structure and interactions. The first of such studies will focus on New England and will benefit from ongoing MPC projects to develop economic input-output models of the New England coastal economy. The input-output approach estimates the value of goods and services produced in different economic sectors that are linked to a marine sector, such as commercial fishing.

In one such project launched in 1998, MPC researchers are collaborating with researchers from NOAA's Northeast Fisheries Science Center to assess the socioeconomic impact of alternative approaches to New England fisheries regulation. Recent legislation requires that regional Fishery Management Plans, whose main purpose has been to achieve sustainable optimal yield, now consider the likely effects of conservation and management measures on fishery participants and fishing communities. Most impact assessments of fisheries management options capture only the direct impact on landings and fishing effort. The input-output model will permit estimation of the full effects of alternative strategies on the regional economy, with an emphasis on local jobs and income.

Another MPC project is aimed at identifying the most cost-effective options for cleaning up PCB contamination in the lower Hudson River. MPC researchers will integrate an existing physical model of the region's multiple PCB sources, flows, and rates of bioaccumulation in commercially and recreationally important fish, such as striped bass, with an economic model for estimating the cost-effectiveness of various combinations of treatment or mitigation technologies. In addition to advancing the development of least-cost management strategies for PCB reduction, the project will demonstrate more generally how scientific and engineering information, incorporated into an economic optimization framework, can provide a valuable decision tool for environmental management.

In the area of aquaculture development, MPC's growing expertise includes federal policy analysis and access system design; modeling of offshore project economics and risk; and practical experience at experimental facilities in New England and East African waters.

In the United States, ocean mariculture is increasingly discussed as a supplement or alternative to traditional offshore fishing, but there is no coherent US policy concerning access to federal waters for aquaculture operations. Legislation that would provide such a policy is under development, and MPC is contributing to this effort with research to develop a framework for analyzing access system design, characterize an economically optimal access system, and recommend appropriate laws and regulations. Key areas of inquiry include the legal rights necessary to provide security of tenure and attract investment, and the economically optimal way for the public to garner a return on the use of its scarce resources.

MPC is also developing a generic model of the economics of an offshore aquaculture operation and will apply it to planned or hypothetical offshore ventures in New England. The model is designed to estimate the economic feasibility of an individual operation at a particular location and to determine the minimum efficient scale of operation. The latest information about construction requirements and biological growth processes will be incorporated in the model, as well as the effects of engineering and biological uncertainties, the costs of regulatory compliance, and variability of supply and demand in the relevant product markets

Two potentially important sources of information are MPC's joint experimental ventures in Rhode Island Sound and on the East African island of Zanzibar, Tanzania. The Rhode Island Sound project, a collaboration with WHOI biologists and engineers and a local commercial harvester and processor, is testing the engineering feasibility, biological productivity, and survivability of longline technology for ocean culture of the blue mussel (*Mytilus edulis*). On Zanzibar, MPC is collaborating with the Institute for Marine Science at the University of Dar es Salaam and the National Center for Mariculture in Israel. In 1998 the team opened a facility consisting of integrated ponds fed by tidal flow, where they have begun to grow rabbitfish (*Siganus sp.*, a locally popular commercial species), shellfish (*Anadasa sp.* and *Cardium sp.*), and seaweed (*Euchema spinosum*, *Euchema cottonii*, and *Ulva sp.*). The facility is producing useful information about growth rates, pond construction, and water supply. An experimental hatchery will be added next, followed by more growout facilities.

Rinehart Coastal Research Center

The Rinehart Coastal Research Center (RCRC) is a "center without walls" that cuts across department boundaries to support and facilitate coastal research activities within the WHOI community. Coastal research has been growing in importance over the last decade, due to the broad recognition of the many threats to the health and sustainability of coastal environmental resources. RCRC encourages the involvement of WHOI scientists in coastal research through direct funding of research, advanced laboratory facilities, seagoing instrumentation, a fleet of small boats, support for education, and communication of research results to the scientific community and the public.

1998 marked the first year that proposals were funded principally from the generous endowment established by Gratia Rinehart Montgomery. Three of these awards exemplify the broad range of research supported by the center and the balance between issues of grave societal concern and fundamental scientific inquiry into coastal processes.

Senior Scientist Hal Caswell (Biology Department) received a grant to develop demographic models for the North Atlantic Right Whale. Using a large database from the New England aquarium dating back to 1980, Caswell and colleagues quantified key variables about this small population that migrates into Cape Cod Bay every spring. Their results were dramatic. They documented a hitherto unexpected decline in annual survival probability, from about 0.99 (that is about a one percent chance of death each year) in 1980 to about 0.95 in 1995. The trend is highly significant. They incorporated these results into a population growth model, and found that by the late 1990s, conditions for the right whale had deteriorated to the point that the population is unable to persist. Given current conditions, extinction is likely to occur within the next 100 to 400 years. These results, while discouraging, are not hopeless. Conditions in the early 1980s appear to have supported positive population growth; thus, mortality need be reduced only to levels appropriate to 20 years ago to regain the species' viability.

The rapidly eroding cliffs in Truro, Cape Cod, provide a dynamic field site for the investigation of shoreline erosion and its linkage to oceanographic processes. Neal Driscoll and Mark Kurz were supported by the Rinehart Coastal Research Center to develop new methods to determine the timing of major erosional events.

Assistant Scientist Neal Driscoll (Geology & Geophysics Department) and Senior Scientist Mark Kurz (Marine Chemistry & Geochemistry Department—MCG) were funded to develop a new technique for dating erosional surfaces on sea cliffs, focusing on the rapidly retreating cliffs of outer Cape Cod. Their research is providing a better understanding of the linkage between erosion pro-

Jon Woodruff

Coastal oceanography is receiving considerable attention in urban centers, due to the confluence of fresh water, salt water, sediment, contaminants, and money. Woods Hole researchers Craig Marquette, Peter Traykovski, Rocky Geyer, and Jay Sisson recover moorings set in the Hudson River to measure currents and sediment transport. The measurements revealed a complex interplay of tides and river flow in controlling the fate of the sediments.

cesses on land and oceanographic processes in the nearshore zone. The patterns of cliff erosion appear to be associated with variations in beach width that, in turn, are related to hydrodynamic processes within the surf zone. The shoreline is also becoming increasingly prominent in other WHOI research activities with the addition of two surf zone dynamics specialists, Steven Elgar and Britt Raubinheimer, to the scientific staff arriving in 1999, and the development of a WHOI nearshore observatory off the south coast of Martha's Vineyard.

Another coastal research area rapidly gaining prominence at WHOI is the study of groundwater inputs to the coastal zone. One of the 1998 RCRC awards went to Associate Scientist Ken Buesseler and Postdoctoral Scholar Matt Charette (MC&G) to initiate a study of groundwater infiltration into the coastal zone. The research was motivated by the potential importance of groundwater as a source of fresh water (and land-derived contaminants) to the coastal zone. Buesseler and Charette are developing methods for using radium isotopes to study the rates of groundwater inflow into harbors and bays. These methods may provide a much more precise means of quantifying the inputs of fresh water as well as providing estimates of the flushing of small water bodies. Their work could have important consequences for the monitoring and management of coastal water bodies subject to contaminant and excessive nutrient inputs. This research is part of a trend toward unifying the investigation of oceanographic and terrestrial processes in the nearshore zone.

These RCRC-funded studies represent only a small fraction of the coastal research activities pursued by WHOI scientists. Nevertheless, RCRC support for the initiation of research allows our scientists to maintain their leadership in coastal science and engineering. The research funding, as well as instrument and facilities support, and communication of research results through the semi-annual *RCRC Newsletter* and special seminars help maintain the vibrant pulse of coastal research at WHOI.

The newsletter has become a showcase for coastal research at WHOI, with full-color layout and effective partnering of scientific contributors and editors. The newsletter highlights the results of RCRC-funded studies, but it also provides a forum for the communication of the results of major and minor coastal research programs by WHOI scientists to a broader audience. This inclusive approach to the newsletter embodies the spirit of RCRC as a "center without walls," which seeks to expand the scope and impact of coastal research at WHOI through communication of results among scientists and the broader community.

Sea Grant Program

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

During 1998 the WHOI Sea Grant Program supported 18 concurrent research projects and 14 new initiative awards. The 1998–2000 research projects are included in three theme areas: Estuarine and Coastal Processes, Fisheries and Aquaculture, and Environmental Technologies. Many of the projects address local and regional needs; some have national or even global implications. Investigators from

Jeffrey Donnelly, BrownUniversity

With WHOI Sea Grant support, Brown University graduate students and their advisor are conducting field studies, including Vibracore operations in New England salt marshes, to learn more about the impacts of sea level rise on coastal wetlands.

the Woods Hole scientific community, universities throughout Massachusetts, and scientists from industry and other states all participate in WHOI Sea Grant's competitive funding process. Examples of currently funded projects include studies of:

- source populations and downstream impacts of the toxic dinoflagellate *Alexandrium* in the Gulf of Maine;
- impacts of accelerated sea level rise in storm-induced sedimentation on southern New England coastal wetlands;
- the stability of the Ria Formosa, a multiple tidal inlet system in Portugal;
- the importance of salinity in nitrogen flux from estuarine sediments;
- laboratory-based transmission of the QPX parasite in cultured hard clams and tracking the progression of the disease;
- the bioeconomic feasibility of potential offshore mariculture operations;
- the commercially important squid, *Loligo pealei*, including reproductive strategies and their contribution to genetic diversity as well as life cycle flexibility;
- the predatory impact of lobate ctenophores on commercially important fishes and their prey;
- the behavioral and hydrodynamic components of postlarval bivalve transport within coastal embayments;
- molecular biomarkers of chemical sensitivity; and
- the biochemical toxicology of cetaceans exposed to pollutants.

In 1998 WHOI Sea Grant provided 32 months of support for graduate students through research awards. WHOI Sea Grant also sponsors qualified graduate students from throughout the Commonwealth in the Dean John A. Knauss Marine Policy Fellowship Program and other national fellowship programs sponsored by the National Sea Grant College Program.

In terms of informal education, WHOI Sea Grant maintains close working relationships with the Massachusetts Marine Educators, the National Marine Educators Association, and the Woods Hole Science and Technology Education Partnership. At the local level, Sea Grant is an active participant in science fairs, with staff serving as project advisors and judges. Each year, top science fair winners are guest speakers at the opening night of the "Oceans Alive" lecture series. For the seventh consecutive year, WHOI Sea Grant sponsored "Sea Urchins," a summer program for children ages five to seven. Perhaps Sea Grant's most important contribution to education in our region is the provision of educational materials to numerous programs, including Children's School of Science, Cape Cod Children's Museum, Cape Cod Museum of Natural History, Association for the Preservation of Cape Cod, Cape Cod National Seashore, Wellfleet Audubon Sanctuary, New England Aquarium, Thornton W. Burgess Society, and school districts throughout Southeastern Massachusetts and the world. Sea Grant is also represented on the advisory board for the joint venture of Turnstone Publishing Group, Inc. and WHOI to develop books on ocean topics for students in grades K–12.

Transferring the results of research and providing general marine-related information are important components of the WHOI Sea Grant Marine Extension and Communications Programs. Both facilitate communication among users and managers of marine resources, including members of the fishing community, aquaculturists, local officials, environmental regulatory agency managers, educators, and the general public. Two areas of particular interest in the marine extension program are coastal processes and fisheries and aquaculture. Both topics have been the focus of numerous workshops and outreach efforts with an emphasis on better management of resources at the local and regional levels.


Dave Gray

In April, WHOI Sea Grant organized an open house, titled "Marine Science and Technology in Woods Hole," for state and local officials and community leaders. Massachusetts senator Therese Murray discusses a poster with Sea Grant coastal processes specialist Graham Giese.

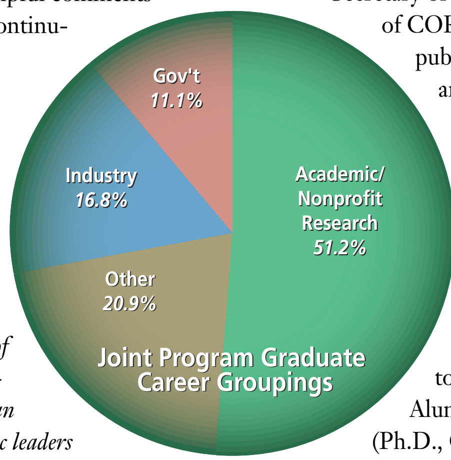
In 1998 WHOI Sea Grant completed a five-year strategic plan entitled *Making the Most of Sea Grant's Investment in Massachusetts*. This plan outlines WHOI Sea Grant's vision for integrating research and outreach activities for the twenty-first century and represents the collective concerns of the Massachusetts marine community at all levels. It is intended to highlight important marine issues and research needs, suggest investigative approaches to resolving these issues, and, perhaps most importantly, to serve as a catalyst for creative thinking. The implementation process is designed to be sufficiently flexible to adjust to changing opportunities and to respond to imaginative ideas. Selection of the research and outreach themes reflects information needs for the Massachusetts economy and developing industries.

WHOI Sea Grant provides information to a broad audience through a variety of means, including a Web site (http://www.whoi.edu/seagrant) that offers access to information on current research and outreach projects and funding opportunities. Other communication vehicles include the *Directory of Cape and Islands Coastal Outreach Organizations; Marine Science Careers: A Sea Grant Guide to Ocean Opportunities*; *Two If By Sea*, our joint newsletter published with MIT Sea Grant; and *Nor'easter* magazine, a publication of the six northeast Sea Grant programs. Two new projects launched in 1998 were Sound Waves, a low-power radio project targeted at auto passengers traveling from Woods Hole to Martha's Vineyard by ferry, and "Focal Points," a series of informational bulletins on current topics in research and outreach geared for legislators, policy-makers, and the general public.

Dean's Report

The MIT/WHOI Joint Program celebrated its thirtieth anniversary in 1998. One of the year's significant activities was an external review of the Joint Program commissioned by WHOI Director Robert Gagosian and MIT Provost Joel Moses. The committee, chaired by Sean Solomon, Director of the Carnegie Institution Department of Terrestrial Magnetism, met with faculty, staff, and students of the Joint Program at both MIT and WHOI during August 17 to 19. Their report provides helpful comments and advice that will guide the Joint Program to continuing excellence. We are particularly proud of their overall assessment:

The Joint Program is the top graduate program—or arguably one of the two top programs—in marine science in the world. It consistently draws the most outstanding applicants from both the U.S. and abroad, and the program has managed to recruit a consistently high fraction of those admitted. The students encountered by the Review Committee were articulate and highly motivated. The variety of areas of research and training that they represented was laudatory, as was the quality of their research. The more than 500 alumni and alumnae include many of the scientific leaders of oceanography.



Fall 1998 Joint Program enrollment totaled 134. During 1998, 35 degrees (23 Ph.D. and D.Sc. degrees and 12 master's degrees) were awarded. These new graduates joined a distinguished group of MIT/WHOI Joint Program alumni and alumnae pursuing several different kinds of productive and satisfying careers in the United States and worldwide. A general grouping of careers is provided in the accompanying pie chart.

Many alumni and alumnae joined present students, faculty, and staff for a September celebration of the thirtieth anniversary with events both in Woods Hole and at MIT. We began with a Friday evening clambake/barbecue shared with those attending the annual WHOI Associates' Day of Science. A highlight of the event was Bob Gagosian's announcement of a generous gift from the Stanley W. Watson Foundation to support graduate fellowships for the Joint Program.

On Saturday morning, Jamie Austin (Ph.D. Geology and Geophysics, 1979), President of the MIT/WHOI Joint Program Alumni/ae Association, presided over an Association business meeting. Then graduates, faculty, and students took the familiar commute north for lunch at the MIT faculty club. Admiral James D. Watkins USN (Retired), President of the Consortium for Ocean Research and Education (CORE), was the luncheon speaker. He drew on the experience of a distinguished career, including an appointment as Chief of Naval Operations and service as Secretary of Energy prior to his appointment as the President of CORE, to discuss the importance of educating the public, and especially young people, about the oceans and about science and technology.

Jamie Austin chaired an afternoon symposium, "Ocean Science and Engineering Education—Meeting the Challenge," which consisted of brief presentations by alumni/ae followed by a lively discussion. Saturday's events concluded with a reception and dinner at the New England Aquarium where Jamie Austin and Joint Program Alumni/ae Association Executive Director Jake Peirson presented the first Joint Program Alumni/ae Service Award to Christopher Tapscott (Ph.D., Geology and Geophysics, 1979) and Susan Tapscott (O.E., Ocean Engineering, 1975).

The anniversary celebration ended Sunday morning with a careers discussion brunch involving current Joint Program students and alumni/alumnae and launch of the new MIT/WHOI Joint Program Alumni/ae Association Web page.

As part of the year's regular Education Office activities, ten Postdoctoral Scholars were appointed in 1998 from an applicant pool of 134. The Postdoctoral Scholar program continues to be an important tool for recruitment of outstanding scientists and engineers to WHOI from around the world.

Twenty-five Summer Student Fellows were chosen from an applicant group of 250, and three Minority Traineeships were awarded from an applicant group of 35. The main focus of these education programs is involvement of students in summer research projects under the supervision of WHOI scientific and senior technical staff. In addition, a summer lecture series consisting of 26 seminar presentations by WHOI Scientific and

External Review Committee for the MIT/WHOI Joint Program in Oceanography and Applied Ocean Science and Engineering

August 17–19, 1998

- **Chair: Sean C. Solomon**, Director of the Department of Terrestrial Magnetism of the Carnegie Institution, Washington, DC
- **Eric J. Barron**, Director of the Earth System Science Center and Associate Professor of Geosciences, Pennsylvania State University
- **Robert A. Duce**, Professor, Chemical Oceanography, Department of Oceanography, Texas A & M University
- **Robert A. Frosch**, Senior Fellow, Center for Science and International Affairs, Kennedy School of Government, Harvard University
- **Christopher J.R. Garrett**, Professor, Lansdowne Professor of Ocean Physics, University of Victoria, British Columbia, Canada
- **Louis J. Lanzerotti**, Distinguished Member of Technical Staff, Bell Laboratories, Lucent Technologies
- **James J. Morgan**, Marvin L. Greenberg Professor of Environmental Engineering Science, California Institute of Technology
- **S. George Philander**, Professor and Chair, Department of Geosciences, Princeton University
- **Mary Silver**, Professor of Ocean Sciences, University of California, Santa Cruz
- **Keith S. Thomson**, University Distinguished Scientist in Residence, New School for Social Research, New York
- **Karen L. Von Damm**, Professor, Geochemistry, Department of Earth Sciences, University of New Hampshire (Alumna of the MIT/WHOI Joint Program)

Symposium on Ocean Science and Engineering Education: Meeting the Challenge

Chair: James A. Austin, Senior Research Scientist, Institute for Geophysics, University of Texas at Austin

Public Education: K–12
William S. Spitzer, Director of Education, New England Aquarium

Undergraduate Education
Margaret L. Delaney, Professor, Institute of Marine Sciences, University of California, Santa Cruz

Graduate Education
Robert S. Detrick, Senior Scientist, Woods Hole Oceanographic Institution

Business and Industry
Peter J. Stein, President, Scientific Solutions, Inc.

Technical Staff provides an introduction to a broad range of ocean sciences, ocean engineering, and marine policy topics. A new feature pioneered this year by Ed Sholkovitz, Faculty Coordinator for Summer Undergraduate Programs, was an introductory, get-acquainted dinner with a science talk by Dick Norris of the Geology and Geophysics Department.

"Astrophysical and Geophysical Flows as Dynamical Systems" was the topic for the Geophysical Fluid Dynamics Summer Study Program's ten fellows (graduate students and postdoctoral fellows) who interacted with about 98 staff and visitors in lectures, seminars, and productive informal gatherings on the porch and lawn of Walsh Cottage. The printed volume of lectures and papers were joined this year by publication of the volume on a Web site.

The High School Teacher Summer Fellowship Program brought four Massachusetts high school science and math teachers to WHOI to participate in the first part of a two-summer research experience. In other K-12 activities, WHOI launched a formal partnership with Turnstone Publishing Group, Inc. to produce books, teacher guides, and a Web site for grade four through eight curriculum supplements.

The Institution also cosponsored, with New England Aquarium, the "Blue Lobster Bowl," Massachusetts competition in the first National Ocean Science Bowl, a nationwide CORE activity. The Massachusetts winner, Lexington High School, also won the national competition! This entitled the team to participate in a Naval oceanographic cruise in the Mediterranean, including a port stop at the Lisbon World's Fair with its focus on the oceans. The team also received R/V *Atlantis* jackets from WHOI with their names embroidered on them. These K-12 activities add to the long-standing and highly successful community efforts of WHOI employees to support science and math learning in local schools through science fairs and through the Woods Hole Science and Technology and Education Partnership, which celebrates its tenth anniversary in 1999.

I note with sadness the death this year of Kenneth O. Emery but remember with pleasure his many contributions to the Joint Program. A renowned marine geologist, K.O. Emery served as the first Dean during the early months of WHOI's formal graduate education program. On the occasion of the Joint Program's thirtieth anniversary, we are grateful for the guidance and leadership of K.O. and succeeding deans along with many others at both MIT and WHOI who helped set and maintain a course for success.

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

Among those enjoying the thirtieth anniversary celebration dinner at the New England Aquarium were Joint Program graduate Bruce Brownawell (1986), left, and his student advisor, Dean John Farrington.

Current Joint Program students, from left, Bridget Berquist, Mike Braun, Liz Kujawinski, and Tom Marchitto were captured at the New England Aquarium dinner.

WHOI Education Office Photos

Others students celebrating the anniversary included Alex Techet, left, and Kelsey Jordahl, right. 1997 graduate Craig Lewis is second from right next to Alex's guest Elliot Aten.


Ckristopher Knight

R/V *Atlantis* & DSV *Alvin*

Total Nautical Miles in 1998—19,976
Total Days at Sea—234
Total Number of Alvin *Dives—134*

In its first full year of operation, *Atlantis* took part in a range of expeditions in the Pacific to explore deep-sea biology and hydrothermal vent systems. The ship first visited the San Diego Trench for studies of the impact of predatory species in a deep-sea ecosystem, then came mapping of vent structures in the Guayamas Basin of the Sea of Cortez using ROV *Jason*. Three cruises to the East Pacific Rise (EPR) followed, all involving *Alvin* dives: the first to seek new hydrothermophilic species at hydrothermal vents, the second to investigate succession and predation in vent ecosystems, and the third to photograph and collect samples of whale carcasses on the seafloor.

Then *Atlantis* headed north along the coast to the Juan de Fuca Ridge for experiments in a borehole drilled into the seafloor, collection of optical data on "vent glow" using the new ALISS (Ambient Light Imaging & Spectral System), testing of a theory that a substantial microbial biosphere exists within the ocean crust, and further ecological studies of hydrothermal vent communities. Following a return trip to the San Diego Trench, work aboard *Atlantis* included recovering instruments for the Ridge Inter-Disciplinary Global Experiments (RIDGE) Flux Project and investigating chemical processes at hydrothermal vents, both at 18°S on the EPR. The year concluded with a study for the Larvae At Ridge Vents (LARVE) Project, exploring how larvae of vent species migrate and colonize new sites, and with a full-scale investigation of the ecology, biology, and geology of hydrothermal vents, involving some two dozen *Alvin* dives at vent sites from 13° to 26°S on the EPR.

Chief scientists for 1998 were: B. Walden (Voyage 3, Legs XIIIA and XIIIB, 3 dives); C. Hollister (3-XIV); J. Eckman, Office of Naval Research (3-XV, 6 dives, 3-XXVI, 7 dives); D. Yoerger (3-XVI and 3-XVII, *Jason*); H. Jannasch (3-XVIII, 8 dives); L. Mullineaux (3-XIX, 14 dives); C. Smith, Univ. of Hawaii (3-XX, 6 dives); B. Carson., Lehigh Univ. (3-XXI, 3 dives); A. Chave (3-XXII, 6 dives); J. Cowen, Univ. of Hawaii (3-XXIII, 15 dives); C. Fisher, Pennsylvania State. Univ. (3-XXIV, 10 dives); T. Urabe, Geological Survey of Japan (3-XXVII, 10 dives); M. Lilley, Univ. of Washington (3-XXVIII, 25 dives); D. Manahan, Univ. of Southern Calif. (3-XXIX, 12 dives); and R. Vrijenhoek, Rutgers Univ. (3-XXX, 9 dives).*

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

R/V *Knorr*

Total Nautical Miles in 1998—37,422
Total Days at Sea—247

Knorr started its year in harsh, icy conditions in the Labrador Sea, deploying the Autonomous Ocean Sampling Network system, a tool to study physical oceanography. Following maintenance in the early spring, *Knorr* was involved in two Navy programs, first to conduct bottom and water column surveys of the USN Atlantic Undersea Test and Evaluation Center (AUTEC) at sites in the Tongue of the Ocean and the Barry Islands, and second to provide support for autonomous underwater and remotely operated vehicles for the Navy's Joint Advanced Concept Technologies Demonstration off the coast of Newfoundland. Then *Knorr* scientists took sediment cores for paleoclimate studies in the Grand Banks and Norwegian Sea areas and participated in a study of the North Atlantic Current extension and water mass formation south of Greenland. In August, *Knorr* scientists took giant piston cores to study seabed slope processes in the Gulf of Mexico, then the ship returned to the Atlantic for further use of the giant piston corer to recover high-resolution paleoceanographic samples from the Brazil Margin. *Knorr* ended the year in balmy waters of the eastern equatorial Atlantic for a study of chemical processes in the water column and on the seafloor.

Chief scientists for 1998 were: J. Bellingham, MIT (Voyage 156); T. Szlyk, Naval Underwater Weapons Center, P. Lemmond (Voyage 157, Leg II); B. Almquist, Office of Naval Research (158-I, IIA, III); G. Bond, Lamont-Doherty Earth Observatory (158-IV); T. Rossby, Univ. of Rhode Island (158-V); A. Silva, Univ. of Rhode Island (159-II, III); D. Oppo (159-V); R. Jahnke, Skidaway Institute of Oceanography (159-VII).*


Shelley Lauzon

Jayne Doucette

R/V *Oceanus*

Total Nautical Miles in 1998—22,667
Total Days at Sea—231

Oceanus spent most of the year in the Gulf of Maine or on Georges Bank, involved primarily in three major projects: the US Global Ocean Ecosystems Dynamics (GLOBEC) Program, the Convex Experiment, and the Ecology and Oceanography of Harmful Algal Blooms-Gulf of Maine (ECOHAB-GOM) Project. *Oceanus* took part in ten GLOBEC cruises. GLOBEC seeks to comprehend the interrelated biological, chemical, and physical processes in a complex ecosystem that hosts the historically abundant Georges Bank fishery, and to provide insights on declining fish stocks. Three ECOHAB-GOM cruises investigated the ecology and oceanography of toxic *Alexandrium* blooms in the Gulf of Maine in an effort to understand their cause and to find remedies. Three Convex Experiment cruises, two at the start of the year and one in May, explored convection and water mass formation in the Gulf of Maine's Wilkinson Basin. Other *Oceanus* voyages included two that measured speciation and metal concentrations in the Sargasso Sea; a cruise for the Littoral Internal Wave Initiative (LIWI) studying turbulence above irregular, sloping bathymetry of the continental shelf off Cape Hatteras; a Sargasso Sea cruise to collect cores for a study of climate variability in the Holocene Era; a seismic study of the New Jersey shelf; two cruises to study plankton and circulation in Cape Cod Bay in anticipation of the 1999 Coastal Ocean Predictive Skill Experiment (COPSE); and a four-day cruise to provide seagoing oceanographic science experience for New England teachers.

Christopher Griner

Chief scientists for 1998 were: F. Bub, Univ. of New Hampshire (315, 316 & 323); D. Mountain, NOAA/NMFS (317); J. Moffett (318 & 325); P. Wiebe (319); N. Pettigrew, Univ. of Maine (320); J. Irish (321, 331-A & B); C. Miller, Oregon State Univ. (322); K. Polzin (324); L. Keigwin (326); E. Barron, Penn. State Univ. (327); R. Signell, USGS (328-I); D. Townsend, Univ. of Maine (328-IIA); J. Collins (329); J. Bellingham, MIT (330-A & B); C. Greene, Cornell (332A & B, 334); and R. Limeburner (333).*

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Tom Kleindinst

Three WHOI Chairmen of the Board attended the annual meetings in May 1998. Shown here with Director Bob Gagosian, left, they are Jim Moltz, right, who was elected at that meeting to succeed Frank Snyder, second from left, who accepted the gavel from Guy Nichols in 1995.

Tom Kleindinst

Associate Scientist Peter Kelemen discusses his work following lunch with his Corporation partner, Dick Mintz.

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A main lab full of foul weather work suits attests to the state of the weather during *Oceanus* Voyage 333 in November 1998 for the Global Ocean Ecosystems Dynamics Georges Bank program.

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Jeff Lord, Charlie Flagg (Brookhaven National Laboratory), and Will Ostrom, launch an acoustic Doppler current meter during Georges Bank Global Ocean Ecosystems Dynamics work.

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James R. Valdes
Senior Engineer

Bruce A. Warren
Senior Scientist

Robert A. Weller
Senior Scientist

John A. Whitehead
Senior Scientist and Paul M. Fye Chair

Geoffrey G. Whitney, Jr.
Research Associate II

Jonathan Wylie
Postdoctoral Scholar

Christine M. Wooding
Research Associate II

Jiayan Yang
Associate Scientist

Shuliang Zhang
Postdoctoral Investigator

Marine Policy Center

Andrew R. Solow
Director and Associate Scientist

Jesse H. Ausubel
Adjunct Scientist

Grete Hovelsrud-Broda
Research Fellow

Daniel A. Curran
Senior Research Fellow

Scott Farrow
Senior Research Fellow

Arthur G. Gaines, Jr.
Research Specialist

Hillel Gordin
Senior Research Fellow

Porter Hoagland III
Research Associate

Denise M. Jarvinen
Assistant Scientist

Di Jin
Associate Scientist

Hauke L. Kite-Powell
Research Specialist

Robert Repetto
Senior Research Fellow

Leah Smith
Senior Research Fellow

Woollcott Smith
Senior Research Fellow

John H. Steele
Scientist Emeritus

Rinehart Coastal Research Center

Bruce Tripp
Research Associate

Computer and Information Services

Julie M. Allen
Information Systems Specialist

Eric F. Cunningham
Information Systems Associate II

Roger A. Goldsmith
Information Systems Specialist

Hartley Hoskins
Research Associate

Robert W. Katcher
Information Systems Associate II

David J.E. Kershaw
Information Systems Associate II

John Krauspe
Information Systems Associate III

William S. Little
Information Systems Specialist

Andrew R. Maffei
Information Systems Specialist

Scott A. McIntyre
Information Systems Associate III

Elizabeth B. Owens
Information Systems Associate II

Warren J. Sass
Information Systems Specialist

Patricia B. Savage
Information Systems Associate II

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Margot Brown Garritt
Information Systems Associate II

Colleen D. Hurter
Information Systems Associate III

Melissa Lamont
Information Systems Associate II

Margaret A. Rioux
Information Systems Associate III

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Applied Ocean Physics and Engineering Department

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Philip J. Bernard
Anthony Berry
Andrew S. Billings
Paul R. Bouchard
Dolores H. Chausse
James M. Cooper
Charles E. Corwin
Thomas Crook
Steven M. Cross
Edward A. Denton
Betsey G. Doherty
Terence G. Donoghue
James M. Dunn
Joshua N. Eck
Kenneth D. Fairhurst
Kenneth S. Feldman
Allan G. Gordon
Matthew R. Gould
Beven V. Grant
Carlton W. Grant
Susan M. Grieve
Paula M. Harmon
Sheila K. Hurst
Thomas P. Hurst
John N. Kemp
Jeffrey B. Lord
Christopher Lumping
Marguerite K. McElroy


Tom Kleindinst

Monthly early morning coffees for employees were initiated in the fall of 1998 by the WHOI Women's Committee and organized by committee member Terry McKee of the Physical Oceanography Department.

Neil M. McPhee
George A. Meier
Stephen D. Murphy
Anita D. Norton
Stanley G. Rosenblad
David S. Schroeder
John J. Schwind, Jr.
William J. Sellers
John D. Sisson
Gary N. Stanbrough
Nancy W. Stedman
Samuel W. Tolkoff
Nancy Y. Trowbridge
Karlen A. Wannop
Jonathan D. Ware
Judith A. White

Biology Department

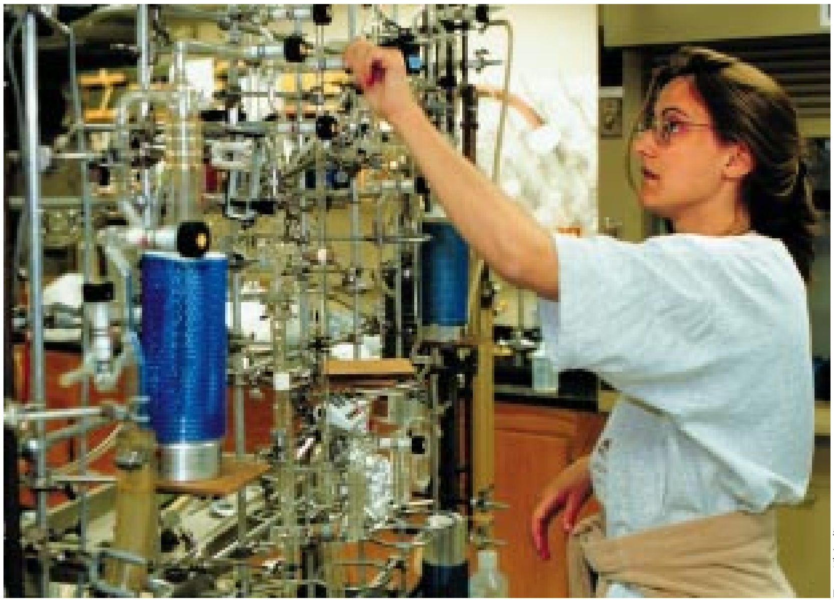
Mari Butler
Anne C. Canaday
Marjorie K. Clancy
Nancy J. Copley
Scott R. Cramer
Mary Ann Daher
Matthew R. Dennett
Sheri D. DeRosa
Nancy A. DiMarzio
Diana G. Franks
Andrew P. Girard
Linda G. Hare
Kristin E. Gribble
David M. Kulis
Bruce A. Lancaster
Ethel F. LeFave
Jane E. Marsh
Susan W. Mills
Stephen J. Molyneaux
Dawn M. Moran
Kristina M. Mullin
Samuel H. Patterson III
Daniel W. Smith
Lisa G. Taylor
Mary Jane Tucci
Rebecca C. Vieira
Margaret M. Walden

Geology & Geophysics Department

Linda Angeloni
John W. Bailey
Anthony H. Berry
S. Thompson Bolmer
Katherine W. Brown
Emily Burns
Karen L. Coluzzi
Lori A. Dolby
David L. DuBois
Pamela V. Foster
C. Eben Franks
Charlene Gibson
Parker Hackett
C. Frances Halbrooks
Robert E. Handy
Seth H. Hitchings
Nathan Hobart
Marleen H. Jeglinski
Janet M. Johnson
Huichan Lin
Karen Littlefield
Patricia Long
Shannon McDaniel
Tracey Morin
Teresa A. Norris
Carrie Odegaard
Stephen P. O'Malley
Anita M. Palm
Julianne Palmieri
Kira Pratt
Susan Prew
Rachel Richards
William V. Robertson
Ellen R. Roosen
Erik Ross
Dana R. Stuart
Sean Sylva
Elaine A. Tulka
Rochelle Ugstad
LuPing Zou

Marine Chemistry & Geochemistry Department

Rebecca A. Belastock
Scot P. Birdwhistell
L. Susan Brown-Leger
Sheila A. Clifford
Nicole Colasacco
Glenn Crossin


Tom Kleindinst

Karen Coluzzi extracts carbon dioxide from seawater for carbon isotope studies.

Joshua M. Curtice
Linda Davis
Marcia W. Davis
Martha A. Delaney
Justin DuMouchelle
Joanne E. Goudreau
Joanna F. Ireland
Lisa Max
Virginia McKinnon Howe
Jillian Norton
Anastasia Prapas
Nathan Ralph
Margaret M. Sulanowska
Carly H. Tarr
N. Joye Wirsen
Mary Zawoysky

Physical Oceanography Department

Kenton M. Bradshaw
Nancy J. Brink
Margaret F. Cook
Lawrence P. Costello
Jane A. Dunworth-Baker
David Fisichella
Penny C. Foster
Rosanna R. Fucile
Barbara Gaffron
Veta M. Green
Brian J. Guest
William H. Horn
Heather D. Hunt
George P. Knapp III
Barbara P. LaCasce
Ellen Levy
Mary Ann Lucas
Theresa K. McKee
Gail McPhee
Anne-Marie Michael
William M. Ostrom
Maren Tracy Plueddemann
John B. Reese
John F. Salzig
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Susan A. Tarbell
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Bryan S. Way
W. David Wellwood
Scott E. Worrilow

Jeanne A. Young
Marguerite E. Zemanovic

Marine Policy Center

Andrew Beet
Gretchen McManamin
Mary E. Schumacher

Rinehart Coastal Research Center

Olimpia I. McCall

Computer and Information Services

Michael Bishop
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Nancy Stafford
Francis H. Taylor

Administrative Staff

Rachel Barnard
Institution Meetings and Office Systems Coordinator
Nancy E. Barry
Assistant Human Resources Manager
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Procurement Representative II
Peggy A. Billings
Communications and Development Administrator
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Department Administrator, Physical Oceanography
Jane R. Bradford
Director of Planned Giving
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Education Planning and Finance Administrator
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Linda L. Church
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Sea Grant Communicator
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Manager of Information, Publications, and Graphic Services
Cheryl C. Daniels
Accountant
Kyle Eberle
Project Manager/Database Manager
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Development Officer
Judith Fenwick
Department Administrator, Biology
Susan Ferreira
Grants Administrator II
Karen E. Flaherty
Business Systems Representative
Larry D. Flick
Center Administrator, Deep Submergence Laboratory, and Security Officer
Annda W. Flynn
Center Administrator, Computer and Information Services
Dennis J. Fox
Procurement Manager
David G. Gallo
Director of Special Projects
Justine Gardner-Smith
News Officer
Ellen Gately
Center Administrator, Marine Policy Center
Janice Gildawie
Management Information Services Manager
Monika Grinnell
Senior Grants Administrator
Susan K. Handwork
Center Administrator, National Ocean Sciences Accelerator Mass Spectrometry Facility
Frederic R. Heide
Assistant Manager of Graphic Services
Ann C. Henry
Department Administrator, Applied Ocean Physics & Engineering
Kathleen Hudock
Administrator for Office of Finance and Administration
Kevin F. Hudock
Benefits Administrator
Michael Hurst
Senior Accountant II
Barbara J. Inzina
Director of Computer and Information Services
Richard B. Kendall
Procurement Representative II
Judith L. Kleindinst
Center Administrator, Biology
Kathleen P. LaBernz
Human Resources Manager
Michael P. Lagrassa
Assistant Procurement Manager

Shelley Lauzon

Bob Tavares sets up a PALACE float. (PALACE stands for Profiling Autonomous LAgrangian Circulation Explorer.)

Dennis Lander
Network Group Leader
Shelley M. Lauzon
Senior News Officer
Laurence S. Lippsett
Science Editor
Katherine A. Madin
Curriculum Coordinator
Stacey L. Medeiros
Manager of Budgets and Financial Analysis
Laura A. Murphy
Payroll Manager
Steven M. Murphy
Grants Administrator II
Thomas G. Nemmers
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Director of Principal Gifts
Catherine N. Norton
Director, MBL/WHOI Library
Maureen F. Nunez
Controller
Maryanne F. Pearcey
Department Administrator, Geology and Geophysics
James Rakowski
Director of Major Gifts
Claire L. Reid
Executive Assistant to the Director of Research
Leslie M. Reilly
Development Officer
Patricia E. Remick
Administrator for Office Programs
R. David Rudden, Jr.
Assistant Controller
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Senior Procurement Representative
Marcella R. Simon
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Maurice J. Tavares
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Donna Weatherston
Manager of Government Regulations
Julia G. Westwater
Assistant Registrar
Patrick Wheeler
Desktop Systems Analyst
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Retirement Benefits Administrator
John A. Wood, Jr.
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Manager of Treasury Operations

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Fay L. McIntyre
Patricia A. McKeag
Donna Mortimer
Oliver J. Muldoon
Sandra E. Murphy
E. Paul Oberlander

Tom Kleindinst

Oceanus is loaded for a June 1998 cruise.

Sharon J. Omar
Kathleen Patterson
Wendy Patterson
Isabel M. Penman
Jeanne A. Peterson
Jeannine M. Pires
John Porteous
Lisa M. Raymond
May A. Reed
Tariesa Reine
Dena Richard
Brenda Rocklage
Peggy A. Rose
Emily H. Schorer
Sandra L. Sherlock
Nancy Stafford
Michele Stokes-Mattera
June E. Taft
Mildred Teal
Judith A. Thrasher
Alison Tilghman
Susan F. Tomeo
Joanne Tromp
Dacia Tucholke
Susan E. Vaughan
Carlos Velez III
Shirley Waskilewicz
Robert J. Wilson

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Jonathan Alberts
Marine Operations Coordinator
Lawrence T. Bearse
Master, R/V Oceanus
Richard S. Chandler
Submersible Operations Coordinator
Ernest G. Charette
Assistant Facilities Manager
Gary B. Chiljean
Master, R/V Atlantis
Arthur D. Colburn III
Master, R/V Knorr
Joseph L. Coburn, Jr.
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William A. Eident
Chief Engineer, R/V Oceanus
Stephen M. Faluotico
Deep Submergence Vehicle Pilot
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Chief Engineer, R/V Atlantis
Richard E. Galat
Facilities Engineer
Matthew C. Heintz
Deep Submergence Vehicle Pilot
J. Patrick Hickey
Deep Submergence Vehicle Pilot
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Safety Officer
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William E. McKeon
Facilities Manager
Donald A. Moller
Marine Operations Coordinator
Theophilus Moniz III
Marine Engineer
Richard F. Morris
Chief Engineer, R/V Oceanus
David I. Olmsted
Boat Operator
Terrence M. Rioux
Diving Safety Officer
Manuel A. Subda
Marine Personnel Coordinator
Barrie B. Walden
Manager, Operational Science Services
Steven A. Walsh
Chief Engineer, R/V Knorr
Ernest C. Wegman
Port Engineer
Robert L. Williams
Deep Submergence Vehicle Pilot

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

Michael T. Aiguier
Esmail Ali
Douglas H. Andrews III
Kenneth Antis
Wayne A. Bailey
Courtenay Barber III
Linda J. Bartholomee
Harold A. Bean
Richard C. Bean
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Andrew Carter
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John A. Cawley
Richard Chase
John P. Clement
Charles Clemishaw
Jeffrey D. Clemishaw
Alberto Collasius, Jr.
Torii M. Corbett
Gregory Cotter
John A. Crobar
Donald A. Croft
William B. Cruwys
Rowland Cummings
Judith O. Cushman
Sallye A. Davis
Elizabeth Delaney
Mark DeRoche
Craig D. Dickson
John Donovan
Francis J. Doohan
Gardiner S. Doughty
James H. Dufur, Jr.
William J. Dunn, Jr.
Daniel B. Dwyer
Geoffrey K. Ekblaw
Deidra L. Emrich
Anthony Ferreira
John Fetterman
Michael J. Field
Robert Flynn
Joseph Giacobbe
Edward S. Good
David Graham
Edward F. Graham, Jr.
Jerry M. Graham
Robert J. Greene
Derek Greenwood
Billy Guest
Cecile Hall
K.I. Faith Hampshire
Carol Harrington
Patrick J. Harrington
Craig Henderson
Robert W. Hendricks
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Penelope Hilliard
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Sharon L. Hunt
Phillip M. Hurlbutt
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Paul A. Kay
Fred W. Keller
Andrew King
Sara J. Kustan
Marc Leandro
Donald C. LeBlanc
Paul E. LeBlanc
Charles Lewis
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Tim Logan
Glen R. Loomis
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Brett Maloney
Piotr Marczak
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Paul Martin
Eduigez L. Martinez
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Joseph Mayes
Robert A. McCabe
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Robert H. McMurray
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Jaimie Morlett
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Jose E. Mota
David Motto
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John R. Murphy, Jr.
Bruce Mushet
Tim Nagle
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Charles A. Olson
Brian M. O'Nuallain
Michael O'Toole
Sheila T. Payne
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Patrick M. Pike
Vasco Pires
Douglas R. Quintiliani
Dennis Reardon
John P. Romiza
Matthew Rooney

Steven Rossetti
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Michael J. Sawyer
Emily Sheasley
Kent D. Sheasley
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Timothy M. Silva
Daniel Slevin
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Andrew E. Solkolowski
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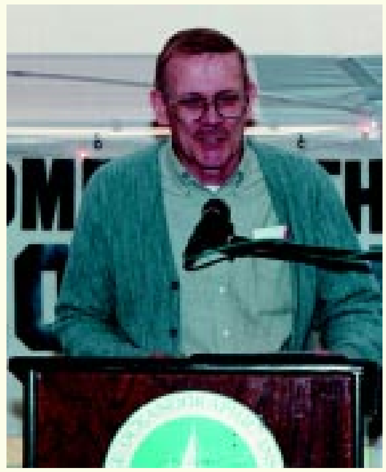
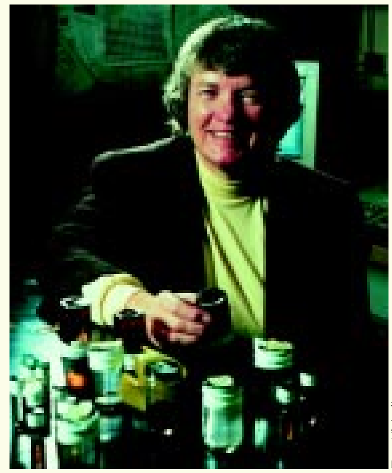
Mark L. St. Pierre
Jeffrey M. Stolp
Wayne A. Sylvia
William R. Tavares, Jr.
Anne M. Taylor
Kevin D. Thompson
Maeve Thurston
Anne Toal
Phil M. Treadwell
Marcel Vieira
Herman Wagner
Colin Walcott
Robert Wichterman
Eileen R. Wicklund
Lance Wills
Kathleen D. Wilson
Carl O. Wood
Bonnie L. Woodward

1998 Retirees

Pamela R. Barrows
Martin Bartlett
Richard J. Carter
James E. Coddington
Robert Hessler
Janet M. Johnson
Adrianus J. Kalmijn
William R. McBride
Zofia J. Mlodzinska
Patrick O'Malley
Robert W. Schreiter
Brian W. Schroeder
David L. Shores
John K. Sweet, Jr.
Robert J. Thayer
William A. White
Elaine M. Wilcox

Employee Recognition 1998


Tom Kleindinst


Tom Kleindinst


Jayne Doucette


Tom Kleindinst

Hartley Hoskins, top left, received the 1998 Vetlesen Award for exceptional contributions to the WHOI community over a long period of time. Jean Whelan, top right, received the Linda Morse-Porteous Award for leadership, mentoring, dedication to work, and involvement in the WHOI community. The Penzance Award, for a group characterized by overall exceptional performance, WHOI spirit, and contributions to the personal and professional lives of Institution staff, went to the Telecommunications Group; in the middle photo, from left, Isabel Penman, Dennis Ladino, Linda Benway celebrate their award. In the bottom photo, Director Bob Gagosian addresses the large crowed gathered for the recognition ceremony.

Degree Recipients

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

Doctor of Philosophy

Jess F. Adkins
BS, Haverford College
Special Field: *Chemical Oceanography*
Dissertation: *Deep-Sea Corals: A New Oceanic Archive*

Katherine A. Barbeau
BS, Long Island University
Special Field: *Chemical Oceanography*
Dissertation: *Influence of Protozoan Grazing on the Marine Geochemistry of Particle Reactive Trace Metals*

Ewann A. Berntson
BS, University of Washington
Special Field: *Biological Oceanography*
Dissertation: *Evolutionary Patterns within the Anthozoa* (Phylum Cnidaria) *Reflected in Ribosomal Gene Sequences*

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

Derek A. Fong
MS, Stanford University
BS, Stanford University
Special Field: *Physical Oceanography*
Dissertation: *Dynamics of Freshwater Plumes: Observations and Numerical Modeling of the Wind-forced Response and Alongshore Freshwater Transport*

Daniel R. Goldner
BA, Harvard University
Special Field: *Physical Oceanography*
Dissertation: *Steady Models of Arctic Shelf-Basin Exchange*

Robert J. Greaves
BA, Boston University
MS, Stanford University
Special Field: *Marine Geology &Geophysics*
Dissertation: *Seismic Scattering of Low-Grazing-Angle Acoustic Waves Incident on the Seafloor*

Constance Ann Hart
BA, College of St. Catherine
Special Field: *Biological Oceanography*
Dissertation: *Feminization in Common Terns* (Sterna hirundo)*: Relationship to Persistent Organic Contaminants*

E. Maria Hood
BS, Texas A&M University
Special Field: *Chemical Oceanography*
Dissertation: *Characterization of Air-Sea Gas Exchange Processes and Dissolved Gas/Ice Interactions Using Noble Gases*

Youngsook Huh
MS, Korea University, Korea
BS, Korea University, Korea
Special Field: *Chemical Oceanography*
Dissertation: *The Fluvial Geochemistry of the Rivers of Eastern Siberia and Implications for the Effect of Climate on Weathering*

Stefan A. Hussenoeder
BS, St. Louis University
Special Field: *Marine Geology &Geophysics*
Dissertation: *Seismic and Magnetic Constraints on the Structure of Upper Oceanic Crust at Fast and Slow Spreading Ridges*

Rafael Katzman
MS, Tel-Aviv University, Israel
BS, Tel-Aviv University, Israel
Special Field: *Marine Geology & Geophysics*
Dissertation: *Structure And Dynamics of the Pacific Upper Mantle*

Linda V. Martin Traykovski
BASc, University of Waterloo, Canada
Special Field: *Biological Oceanography*
Dissertation: *Acoustic Classification of Zooplankton*

Elizabeth C. Minor
BS, College of William & Mary
Special Field: *Chemical Oceanography*
Dissertation: *Compositional Heterogeneity Within Oceanic POM; A Study Using Flow Cytometry And Mass Spectrometry*

Marjorie F. Oleksiak
BS, Massachusetts Institute of Technology
Special Field: *Biological Oceanography*
Dissertation: *Diversity and Characterization of Novel Cytochrome P450 2 Genes in the Marine Teleost* Fundulus heteroclitus

Francois W. Primeau
MSc, University of Alberta, Canada
Bmath, University of Waterloo, Canada
Special Field: *Physical Oceanography*
Dissertation: *Multiple Equilibria and Low-Frequency Variability of Wind-Driven Ocean Models*

James M. Pringle
BA, Dartmouth College
Special Field: *Physical Oceanography*
Dissertation: *Cooling and Internal Waves on the Continental Shelf*

Bonnie J. Ripley
BA, Occidental College
Special Field: *Biological Oceanography*
Dissertation: *Life History Traits and Population Processes in Marine Bivalve Molluscs*

Gorka A. Sancho
Licenciado, Universidad Autonoma Madrid, Spain
Special Field: *Biological Oceanography*
Dissertation: *Behavioral Ecology of Coral Reef Fishes at Spawning Aggregation Sites*

Jennifer J. Schlezinger
BS, Boston College
Special Field: *Biological Oceanography*
Dissertation: *Involvement of Cytochrome P450 1A in the Toxicity of Aryl Hydrocarbon Receptor Agonists*

Miles A. Sundermeyer
BA, University of California, Santa Cruz
Special Field: *Physical Oceanography*
Dissertation: *Studies of Lateral Dispersion in the Ocean*

Gaspar Taroncher Oldenburg
License, Universidad Autonoma Madrid, Spain
Special Field: *Biological Oceanography*
Dissertation: *Cell Cycle Dynamics and the Physiology of Saxitoxin Biosynthesis in* Alexandrium fundyense *(Dinophyceae)*

Peter A. Traykovski
BS, Duke University
Special Field: *Oceanographic Engineering*
Dissertation: *Observations and Modeling of Sand transport in a Wave Dominated Environment*

Jubao Zhang
MS, Institute of Atmosphere and Physics, Chinese Academy of Science
BS, University of Science and Technology of China
Special Field: *Pysical Oceanography*
Dissertation: *Impacts of Double-diffusive Processes on the Thermohaline Circulation*

Master of Science

Jeffrey N. Berry
BS, Pacific Lutheran University
Special Field: *Chemical Oceanography*
Dissertation: *Sulfate in Foraminiferal Calcium Carbonate: Investigating a Potential Proxy For Sea Water Carbonate Ion Concentration*

Vikas Bhushan
BS, University of Toronto, Canada
MS, University of British Columbia, Canada
Special Field: *Physical Oceanography*
Dissertation: *Modeling Convection in the Greenland Sea*

Carrie T. Friedman
BA, University of California, Berkeley
Special Field: *Marine Geology &Geophysics*
Dissertation: *Analysis of Stable Sulfur Isotpes and Trace Cobalt on Sulfides From the TAG Hydrothermal Mound*

Michiko Martin
BS, US Naval Academy
MSEd, Troy State University
Special Field: *Ocean Engineering*
Dissertation: *An Investigation of Momentum Exchange Parameterizations and Atmospheric Forcing for the Coastal Mixing and Optics Program*

Mary Ann Schlegel
BA, University of Vermont
MA, University of Vermont, Burlington
Special Field: *Marine Geology & Geophysics*
Dissertation: *Paleoceanographic Variability on a Millenial Scale: A High Resolution Record of the Latest Deglaciation From the Blake Outer Ridge, Western North Atlantic*

Alexandra H. Techet
BSE, Princeton University
Special Field: *Oceanographic Engineering*
Dissertation: *Vortical Patterns Behind Tapered Cylinders*

Wen Xu
BS, University of Science and Technology, China
MS, Institute of Acoustics, China
Special Field: *Oceanographic Engineering*
Dissertation: *Signal Amplitude and DOA Estimation for a Multiple-row Bathymetric Sidescan Sonar*

Xiayoun Zang
BS, Nanjing Institute of Meteorology, PRC
MS, Institute of Atmospheric Physics, PRC
Special Field: *Physical Oceanography*
Dissertation: *Space and Time Scales of Low Frequency Variability in the Ocean*

Yanwu Zhang
BS, Northwestern Polytechnic University
MS, Northwestern Polytechnic University
Special Field: *Ocean Engineering*
Dissertation: *Current Velocity Profiling from an Autonomous Underwater Vehicle with the Application of Kalman Filtering*

Master of Engineering in Ocean Engineering

Elizabeth J. Bruce
BS, University of Washington
Special Field: *Ocean Engineering*
Dissertation: *The Characterization of Particle Clouds Using Optical Imaging Techniques*

Kurtis W. Crake
MS, Virginia Tech
BS, University of Michigan
Special Field: *Ocean Engineering*
Dissertation: *Probabilistic Assessment of Ship Damage in Collisions*

Charles E. Rawson
BS, US Coast Guard Academy
Special Field: *Ocean Engineering*
Dissertation: *A Probabilistic Method for Predicting Damage and Oil Outflow from Grounded Tankships*

MIT/WHOI Joint Program
1998-1999 Fall Term

AmyMarie Accardi
Rensselaer Polytechnic Institute

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

Lihini I. Aluwihare
Mt. Holyoke College

Erik J. Anderson
Gordon College

Brian K. Arbic
University of Michigan

Juli K. Atherton
McGill University

Michael S. Atkins
University of California, Santa Cruz

Jay A. Austin
California Polytechnic Institute, San Luis Obispo

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Stanford University
Université de Nantes

Kyle M. Becker
Boston University
Pennsylvania State University, MS

Mark D. Behn
Bates College

Natalia Y. Beliakova
Moscow State University, Russia

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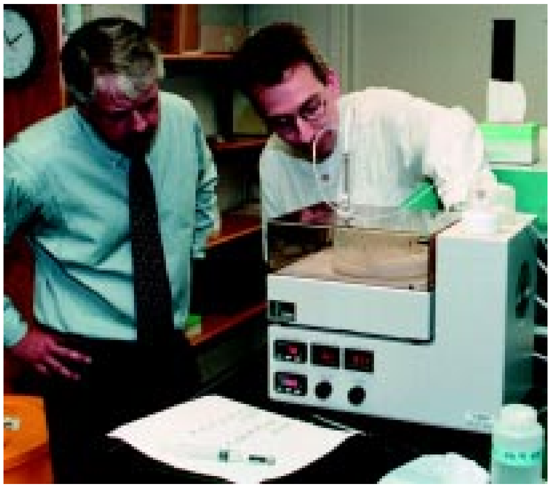

Tom Kleindinst

Bernard Peucker-Ehrenbrink discusses mass spectrometer sample preparation with Corporation Member and Joint Program Alunmi/ae Association President Jamie Austin.

Shelley Lauzon

The deck of R/V *Oceanus* is crammed with gear for a November GLOBEC cruise.


Christopher Knight

The *Alvin* group works into the night preparing the sub for the next day's work during a March 1998 cruise.

Financial Statements

The 1998 audited financial statements reflect another strong year for the Woods Hole Oceanographic Institution. Although government sponsored research declined in 1998 from 1997 levels, the Institution fully recovered its overhead expenses and achieved an operating surplus.

The financial markets remained strong during 1998 and WHOI's endowment showed an 8 percent return, increasing in market value to $231.6 million compared to $215.5 million at the end of 1997. During 1997 and 1998, the Investment Committee changed its asset allocation targets to more closely mirror those of the most successful university endowment funds. The disappointing performance in 1998 can be attributed to the transition of assets toward private equity investments, which have not yet begun to experience returns, and to the performance of WHOI's investments in emerging markets and value funds, both of which are expected to recover in 1999. It is anticipated that endowment performance in future periods will improve as a result of the asset allocation changes that have been made.

A financial milestone for 1998 was the approval of a modest increase in distributions from the endowment to support current operations. This increase, which provides a total of $1.5 million in additional resources for science, education, and unrestricted accounts, was made possible by the performance of the endowment over the last few years. In another milestone, the Board of Trustees, for the first time, approved the issuance of debt to fund capital projects. Although the projects could have been funded internally, the use of debt has a substantial financial benefit to WHOI based on the application of government regulations and the low cost of borrowing.

Total sponsored research revenue was $73.3 million in 1998 compared with $76.4 million in 1997, while government sponsored research, excluding ship and submersible operations, was $49.1 million in 1998 compared to $53.6 million in 1997. Although these results represented declines of 4 percent and 8 percent, respectively, the Institution's labor bases, against which fringe benefits and overhead are recovered, finished the year ahead of budget, resulting in a modest overrecovery of overhead expenses. Overrecoveries are like "money in the bank" and help to reduce future overhead rates, contributing to WHOI's continued competitiveness. The Institution is in full compliance with all federal regulations, and in 1998, for the fourth consecutive year, all government audits are current.

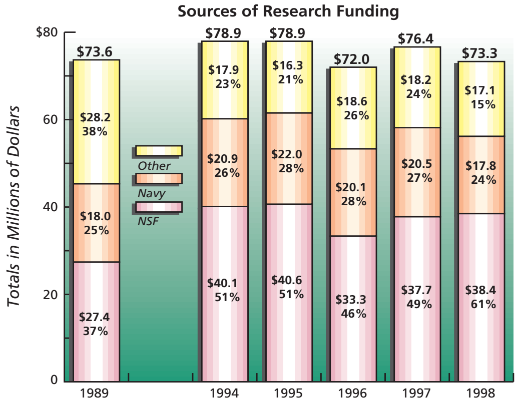


Table 1
Sources of Research Funding

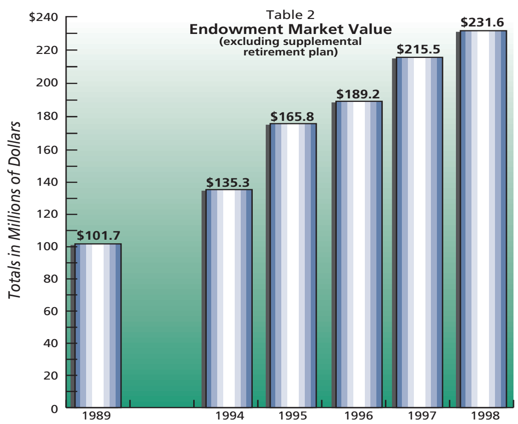


Table 2
Endowment Market Value
(excluding supplemental retirement plan)

Unrestricted income from gifts and pledges was in line with budget while "bridge support" for scientists between funding again came in under budget, contributing to the operating surplus. This surplus allowed WHOI to set aside reserves for a major cost sharing commitment for advanced ocean instrumentation. In 1995 and 1996, reserves were established in anticipation of a planned 1998 regulatory change that eliminated including graduate student tuition as part of overhead. In 1998, as expected, these reserves were substantially drawn down, and it is anticipated that the drawdown will continue in 1999. Clearly, funding of the education program represents a major challenge for the near future.

Gifts, grants, and pledges from private sources totaled $8.5 million in 1998, making it the best non-capital-campaign year ever. Outstanding pledges at the end of 1998 were $4.8 million, as compared to $3.8 million in 1997 and $6.4 million in 1996.

During 1998, WHOI personnel implemented mission critical Year 2000 human resource and payroll systems and in 1999 are concentrating efforts toward Y2K testing of these and other administrative systems. WHOI is confident of its ability to meet Y2K compliance issues.

Progress continues on the projects initiated and supported by the ad hoc Trustee Committee on Business Development such as the licenses to Turnstone Publications, Inc. and BBH, Inc. (see Director's report). In addition, plans are being developed to establish a for-profit entity that will produce REMUS (Remote Environmental Measuring UnitS) vehicles. Presently the proposed entity has contracts completed or in process for approximately $5 million including a project for the City of New York to survey the condition of 45 miles of water pipe.

To remain competitive in both the conduct of research and the recruitment of the best scientists, research facilities must be replaced and modernized. Future plant needs are under review and a campus plan and financing strategy are being developed. The planning process is made more complex by the disappointing trends in government research support and, accordingly, WHOI must continue to build endowment, seek other sources of funding, aggressively pursue nongovernment projects, and generate unrestricted revenues from business development and other activities.

Management is continuing to follow a strategy of improving service to science while reducing administrative costs. An "Internet strategy" has been developed that seeks to provide information, transactions, and services over the Intranet and Internet. The results have been very satisfactory to date.

In summary, WHOI continues to meet its financial goals and remains financially strong. In the future, cost sharing, the need for major new and renovated facilities, maintaining a state-of-the-art technology infrastructure, and funding the education program will be the biggest challenges.

—Paul Clemente, Associate Director for Finance & Administration

Statements of Financial Position

as of December 31, 1998 (with comparative totals for 1997)

Assets	1998	1997
Cash and cash equivalents:		
Operating	$ 22,320,253	$ 20,957,954
Sponsored research prepayment pool	1,694,628	1,511,124
Endowment	5,999,926	12,751,386
	30,014,807	35,220,464
Supplemental retirement	6,892,383	6,197,096
Accrued interest and dividends	1,136,902	996,267
Receivable for investments sold	1,279,721	874,541
Reimbursable costs and fees:		
Billed	1,146,056	2,282,264
Unbilled	2,074,051	2,123,117
Other receivables	432,092	408,129
Pledges receivable	4,814,062	3,810,977
Inventory	692,957	640,617
Deferred charges and prepaid expenses	323,319	172,688
Investments	230,551,497	207,593,039
Other current assets	4,387,928	4,359,882
Total current assets	283,745,775	264,679,081
Property, plant and equipment:		
Land, buildings and improvements	47,069,200	45,138,925
Vessels and dock facilities	2,754,406	2,860,533
Laboratory and other equipment	8,355,383	7,511,279
Work in process	421,575	59,868
	58,600,564	55,570,605
Accumulated depreciation	(32,163,272)	(29,555,091)
Net property, plant and equipment	26,437,292	26,015,514
Remainder trusts	1,216,667	1,175,091
Total assets	$ 311,399,734	$ 291,869,686
Liabilities		
Accounts payable and other liabilities	8,903,204	10,255,750
Accrued payroll and related liabilities	4,824,765	4,898,325
Payable for investments purchased	2,845,856	1,023,779
Accrued supplemental retirement benefits	6,892,383	6,197,096
Deferred revenue and refundable advances (research)	7,333,703	7,668,959
Deferred fixed rate variance	3,568,392	1,756,612
Total liabilities	34,368,303	31,800,521
Commitments and contingencies		

Net Assets

	Unrestricted	Temporarily Restricted	Permanently Restricted		
Undesignated	$ 2,258,508	$ 6,246,356		8,504,864	7,502,962
Designated	3,036,743			3,036,743	3,056,544
Plant and facilities	30,700,582	358,242		31,058,824	30,803,188
Education	-	2,859,995		2,859,995	3,176,835
Endowment and similar funds	59,981,708	138,410,098	$ 33,179,199	231,571,005	215,529,636
Total net assets	$95,977,541	$ 147,874,691	$ 33,179,199	277,031,431	260,069,165
Total liabilities and net assets				$ 311,399,734	$ 291,869,686

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

Statements of Cash Flows

for the year ended December 31, 1998 (with comparative totals for 1997)

	1998	1997
Cash flows from operating activities:		
Total change in net assets	$ 16,962,266	$ 26,164,128
Adjustments to reconcile increase in net assets to net cash provided by operating activities:		
Depreciation	2,935,236	3,623,430
Donated vessel	-	(337,505)
Net realized and unrealized (gain) loss on investments	(14,241,327)	(25,933,512)
(Increase) decrease in:		
Supplemental retirement	(695,287)	(6,197,096)
Accrued interest and dividends	(140,635)	394,110
Reimbursable costs and fees:		
Billed	1,136,208	264,561
Unbilled	49,066	100,305
Other receivables	(23,963)	245,156
Pledges receivable	(1,003,085)	2,560,374
Inventories	(52,340)	(33,084)
Deferred charges and prepaid expenses	(150,631)	573,267
Other current assets	(28,046)	(2,709,010)
Remainder trusts	(41,576)	18,629
Increase (decrease) in:		
Accounts payable and other liabilities	(1,352,546)	1,298,103
Accrued payroll and related liabilities	(73,560)	309,209
Net payable for investments purchased	1,416,897	(253,432)
Deferred revenue	(335,256)	(2,820,456)
Accrued supplemental retirement benefits	695,287	137,096
Deferred fixed rate variances	1,811,780	38,791
Net cash provided (used) by operating activities	6,868,488	(2,556,936)
Cash flows from investing activities:		
Capital expenditures:		
Additions to property and equipment	(3,356,684)	(2,601,154)
Endowment:		
Proceeds from the sale of investments	464,439,261	174,721,760
Purchase of investments	(473,156,722)	(172,667,604)
Net cash provided by (used) by investing activities	(12,074,145)	(546,998)
Net increase (decrease) in cash and cash equivalents	(5,205,657)	(3,103,934)
Cash and cash equivalents, beginning of year	35,220,464	38,324,398
Cash and cash equivalents, end of year	$ 30,014,807	$ 35,220,464

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

Statements of Activities

for the year ended December 31, 1998 (with comparative totals for 1997)

	Unrestricted					
	Operating	Sponsored Research	Temporarily Restricted	Permanently Restricted	1998	1997
Operating:						
Revenues:						
Fees	$ 373,399				$ 373,399	$ 540,998
Sponsored research:						
Government		$ 62,809,830			62,809,830	64,794,094
Nongovernment		10,463,521			10,463,521	11,641,133
Sponsored research assets released to operations	73,273,351	(73,273,351)			-	-
Education:						
Tuition	2,652,371				2,652,371	2,688,826
Endowment income	3,231,553		$ 444,967		3,676,520	3,482,927
Sponsored research	11,284				11,284	175,466
Gifts and transfers			867,189		867,189	180,208
Education funds released from restriction	1,628,996		(1,628,996)		-	-
Investment return designated for current operations	2,541,019				2,541,019	2,263,024
Contributions and gifts	2,622,178			$ 3,941,755	6,563,933	4,262,739
Contributions and gifts released from restriction	(1,094,047)		1,094,047		-	-
Rental income	774,880				774,880	718,875
Communication and publications	318,615				318,615	180,299
Other	565,387				565,387	76,258
Total revenues	86,898,986		777,207	3,941,755	91,617,948	91,004,847
Expenses:						
Sponsored research:						
National Science Foundation	38,488,430				38,488,430	37,710,475
United States Navy	17,840,136				17,840,136	20,461,324
Subcontracts	5,835,413				5,835,413	6,050,770
Advanced Research Projects Agency	189,894				189,894	485,487
National Oceanic & Atmospheric Administration	3,277,420				3,277,420	2,585,965
Department of Energy	778,412				778,412	1,205,005
United States Geological Survey	546,070				546,070	536,324
National Aeronautics & Space Administration	992,714				992,714	1,310,075
Other	5,324,862				5,324,862	6,089,802
Education:						
Faculty expense	2,238,580				2,238,580	2,182,244
Student expense	2,953,751				2,953,751	1,748,679
Postdoctoral programs	510,402				510,402	384,319
Other	495,287				495,287	596,387
Business development	527,467				527,467	205,635
Rental expenses	418,649				418,649	431,851
Communication publications and development	2,592,063				2,592,063	2,927,893
Unsponsored programs	2,178,658				2,178,658	1,398,379
Other expenses	1,670,942				1,670,942	2,633,221
Total expenses	86,859,150				86,859,150	88,943,835
Change in net assets from operating activities	39,836		777,207	3,941,755	4,758,798	2,061,012
Nonoperating income:						
Investment return in excess of amounts designated for sponsored research, education and current operations	3,412,713		8,566,212		11,978,925	23,857,473
Other nonoperating revenue			899,808		899,808	337,505
Nonoperating expenses:						
Other nonoperating expenses	100,776		574,489		675,265	91,862
Change in net assets from nonoperating activities	3,311,937		8,891,531		12,203,468	24,103,116
Total change in net assets	3,351,773		9,668,738	3,941,755	16,962,266	26,164,128
Net assets at beginning of year	92,625,768		138,205,953	29,237,444	260,069,165	233,905,037
Net assets at end of year	$ 95,977,541	-	$ 147,874,691	$ 33,179,199	$ 277,031,431	$ 260,069,165

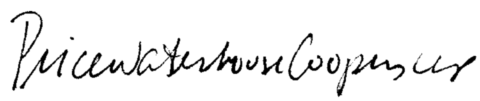
The accompanying notes are an integral part of the financial statements.

Report of Independent Accountants

To the Board of Trustees of Woods Hole Oceanographic Institution:

In our opinion, the accompanying statement of financial position and the related statements of activities and of cash flows present fairly, in all material respects, the financial position of Woods Hole Oceanographic Institution (the "Institution") at December 31, 1998 and the changes in its net assets and its cash flows for the year then ended, in conformity with generally accepted accounting principles. We previously audited and reported upon the financial statements of the Institution for the year ended December 31, 1997; totals for the year are shown for comparative purposes only. These financial statements are the responsibility of the Institution's management; our responsibility is to express an opinion on these financial statements based on our audit. We conducted our audit of these statements in accordance with generally accepted auditing standards which require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements, assessing the accounting principles used and significant estimates made by management, and evaluating the overall financial statement presentation. We believe that our audit provides a reasonable basis for the opinion expressed above.

March 12, 1999



A. Background:

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

The Institution is exempt from federal income tax as an organization described in Section 501(c)(3) of the Internal Revenue Code of 1954 as it is organized and operated exclusively for education and scientific purposes.

B. Summary of Significant Accounting Policies:

Basis of Presentation

The accompanying financial statements are presented on the accrual basis of accounting and have been prepared to focus on the Institution as a whole and to present balances and transactions according to the existence or absence of donor-imposed restrictions. The presentation follows the provisions of Statement of Financial Accounting Standards ("SFAS") No. 116, *Accounting for Contributions Received and Contributions Made*, and No. 117, *Financial Statements of Not-for-Profit Organizations.* SFAS No. 116 generally requires that contributions received, including unconditional promises to give, be recognized as increases in net assets in the period received at their fair values. SFAS No. 117 requires that the Institution display its activities and net assets in three classes as follows: unrestricted, temporarily restricted, and permanently restricted. Additionally, it requires the presentation of a statement of cash flows.

The financial statements include certain prior-year summarized comparative information in total, but not by net asset class. The prior-year information presented does not include sufficient detail to constitute a presentation in conformity with generally accepted accounting principles. Accordingly, such information should be read in conjunction with the organization's financial statements for the year ended December 31, 1997, from which the summarized information was derived.

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

Permanently Restricted Net Assets

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

Temporarily Restricted Net Assets

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

Unrestricted Net Assets

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

Contributions

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

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

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

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

Operations

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

Cash and Cash Equivalents

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

Included in cash at December 31, 1998 and 1997 is $1,694,628 and $1,512,294, respectively, representing advances received from the United States Navy and other U.S. Government and state agencies (the sponsored research prepayment pool). Such amounts are restricted as to use for research programs. Interest earned on unspent funds is remitted to the federal government. Cash and cash equivalents also include uninvested amounts from each classification of net assets (e.g., endowment).

Investments

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

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

Options and Futures

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

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

Investment Income Utilization

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

The Board of Trustees has appropriated all of the income and a specified percentage of the net appreciation (depreciation) to operations as prudent considering the Institution's long and short-term needs, present and anticipated financial requirements, expected total return on its investments, price level trends, and general economic conditions. Under the Institution's current endowment spending policy, which is within the guidelines specified under state law, between 4 percent and 5.5 percent of the average of the market value of qualifying endowment investments at September 30 of each of the previous three years is appropriated. This amounted to $7,588,902 and $6,945,710 for the years ending December 31, 1998 and 1997, respectively, and is classified in operating revenues (research, education, and operations). The Institution has interpreted relevant state law as generally permitting the spending of gains on endowment funds over a stipulated period of time.

Inventories

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

Contracts and Grants

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

Property, Plant and Equipment

Property, plant and equipment are stated at cost. Depreciation is provided on a straight-line basis at annual rates of 2% to 12 1/2% on buildings and improvements, 3 1/2% on vessels and dock facilities, and 20% to 33 1/3% on laboratory and other equipment. Depreciation expense on property, plant, and equipment purchased by the Institution in the amounts of $2,834,460 and $3,531,568 in 1998 and 1997, respectively, has been charged to operating activities.

Depreciation on certain government-funded facilities (the Laboratory for Marine Science and the dock facility) amounting to $100,776 and $91,862 in 1998 and 1997, respectively, has been charged to nonoperating expenses as these assets are owned by the Government. There were no gains on the disposal of property, plant and equipment in 1998 and 1997.

Use of Estimates

The preparation of the financial statements in conformity with generally accepted accounting principles requires management to make estimates and assumptions that affect the reported amounts of assets and liabilities and the disclosure of contingent assets and liabilities as of December 31, 1998 and 1997, as well as the reported amounts of revenues and expenses during the years then ended. Actual results could differ from the estimates included in the financial statements.

Reclassification of Amounts

Certain prior year amounts have been reclassified to conform to the December 31, 1998 presentation.

C. Investments:

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

	1998		1997	
	Cost/(Premium Received)	Market	Cost/(Premium Received)	Market
U.S. Government				
and government agencies	$ 9,455,685	$ 9,569,265	$ 13,173,280	$ 13,610,082
Corporate bonds	15,655,157	16,014,417	13,124,913	13,556,058
Other bonds	5,374,862	5,093,275	3,053,621	3,086,994
Equity securities				
and mutual funds	100,109,271	123,803,114	104,656,472	144,559,252
International mutual funds	56,647,950	50,363,401	9,420,852	9,549,820
Venture Capital and				
Investment Partnerships	19,103,213	25,219,328	17,843,263	21,800,471
Other	1,121,854	1,284,992	1,338,363	1,430,362
Subtotal investments	207,467,992	231,347,792	162,610,764	207,593,039
Purchased call options	57,203	23,311	-	-
Written call options	(25,625)	(783,701)	-	-
Written put options	(21,000)	(35,905)	-	-
Total investments	$207,478,570	$230,551,497	$162,610,764	$207,593,039

Amounts held in Venture Capital and Investment Partnerships and other investments are invested in securities or other assets for which there is not necessarily a publicly-traded market value or which are restricted as to disposition. The return on such investments was $2,241,146 and $841,848 for the years ended December 31, 1998 and 1997, respectively, including dividends, distributions and changes in the estimated value of such investments.

At December 31, 1998, open future contracts sold short were as follows:

Futures	Expiration Date	Aggregate Face Value	Market Value
10 Year U.S. Treasury Note	3/22/99	$834,461	$834,093
30 Year U.S. Treasury Bond	3/22/99	$260,621	$255,563

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

	Unrestricted	Temporarily Restricted	1998 Total	1997 Total
Dividend & interest income	$ 6,270,710	$ 444,967	$ 6,715,677	$ 6,137,111
Investment management costs	(692,340)		(692,340)	(663,787)
Net realized gains	10,121,557	26,033,722	36,155,279	27,876,237
Change in unrealized				
appreciation	(4,446,442)	(17,467,510)	(21,913,952)	(1,942,725)
Total return on investments	11,253,485	9,011,179	20,264,664	31,406,836
Investment return designated for:				
Sponsored research	(2,068,200)		(2,068,200)	(1,803,412)
Education	(3,231,553)	(444,967)	(3,676,520)	(3,482,927)
Current operations	(2,541,019)		(2,541,019)	(2,263,024)
	(7,840,772)	(444,967)	(8,285,739)	(7,549,363)
Investment return in excess of amounts designated for sponsored research, education and current operations	$ 3,412,713	$ 8,566,212	$11,978,925	$23,857,473

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

	1998	1997
Unit value, beginning of year	$3.6785	$3.3191
Unit value, end of year	3.9089	3.6785
Net change for the year	.2304	.3594
Investment income per unit for the year	.0868	.0918
Total return per unit	$ .3172	$ .4512

D. Pledges Receivable:

Pledges receivable consist of the following at December 31:

	1998	1997
Unconditional promises expected to be collected in:		
Less than one year	$2,615,729	$1,577,977
One year to five years	2,198,333	2,233,000
	$4,814,062	$3,810,977

E. Deferred Fixed Rate Variance:

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

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

Deferred Fixed Rate Variance (liability), December 31, 1996	$ (1,717,821)
1997 indirect costs	31,584,174
1997 adjustment	67,108
Amounts recovered	(31,690,073)
1997 (over)/under recovery	(38,791)
Deferred Fixed Rate Variance (liability), December 31, 1997	(1,756,612)
1998 indirect costs	30,307,084
1998 adjustments	11,669
Amounts recovered	(32,130,533)
1998 (over)/under recovery	(1,811,780)
Deferred Fixed Rate Variance (liability), December 31, 1998	$ (3,568,392)

As of December 31, 1998, the Institution has recovered a cumulative amount in excess of expended amounts of $3,568,392 which will be reflected as a reduction of future year recoveries. This amount has been reported as a liability of the Institution.

F. Retirement Plans:

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

The aggregate benefit obligation, fair value of assets and funded status of the plans at December 31 were as follows:

	1998	1997
Fair value of plan assets	$ 158,790,517	$ 149,537,244
Benefit obligation	(120,973,195)	(110,576,618)
Funded status	$ 37,817,322	$ 38,960,626
Prepaid pension cost	$ 1,422,497	$ 1,086,742
Accrued benefit liability	$ (3,553,592)	$ (3,570,725)

At December 31, 1998, the defined benefit plan assets listed above are held in the Woods Hole Oceanographic Retirement Trust. The Institution has accrued a liability sufficient to fund future supplemental plan benefits at December 31, 1998 and 1997. During 1997, the Institution transferred $6,060,000 related to the Supplemental Benefit Plan to a segregated account available to fund Supplemental Plan benefits. The assets of the Retirement Trust are comprised primarily of common stock and fixed income securities, while the Supplemental Plan assets are invested primarily in common stock.

The supplemental benefit plan had projected benefit obligations of $3,685,379 and $3,576,307 and accumulated benefit obligations of $2,929,876 and $2,728,074 at December 31, 1998 and 1997, respectively. Income related to the plans amounted to $141,392 in 1998 and $462,891 in 1997. For the year ended December 31, 1998 and 1997, there were no employer contributions to the plans and the benefits paid in 1998 and 1997 were $4,847,597 and $4,489,540, respectively. For both December 31, 1998 and 1997, the funded status was determined using a discount rate of 6.75%, a rate of increase in future compensation of 4.5%, and an expected return on plan assets of 9%.

G. Other Post Retirement Benefits:

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

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

The plan's benefit obligation, fair value of assets and funded status at December 31 were as follows:

	1998	1997
Benefit obligation	$(21,998,913)	$(18,675,643)
Fair value of plan assets	13,731,020	11,621,126
Funded status	$ (8,267,893)	$ (7,054,517)
Prepaid postretirement cost	$ 788,826	$ 846,474

Expenses related to the plan amounted to $1,011,648 in 1998 and $1,211,597 in 1997. For the year ended December 31, 1998 and 1997, employer contributions to the plan were $954,000 and $1,366,620 and the benefits paid in 1998 and 1997 were $753,358 and $640,533, respectively.

For December 31, 1998 and 1997, the funded status was determined using a discount rate of 6.75% for both years. The expected long-term rate of return on plan assets used in determining the net periodic postretirement benefits cost was 9.00% in 1998. The rate of increase in the per capita costs of covered health care benefits is assumed to be 5.0% in 1998 and in future years.

H. Commitments and Contingencies:

The Defense Contract Audit Agency (DCAA) is responsible for auditing both direct and indirect charges to grants and contracts on behalf of the ONR. The Institution and the ONR had settled the years through 1997. The current indirect costs recovery rates, which are fixed, include the impact of prior year settlements. While the 1998 direct and indirect costs are subject to audit, the Institution does not believe settlement of this year will have a material impact on its results of operations (change in net assets) or its financial position.

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