TABLE OF CONTENTS

Cover Photo: Research Associate Steve Manganini (dark shirt) and Turkish colleagues launch a sediment trap in the Black Sea. Photo by Bernward Hay.

Annual Report 1988:
Editor & Designer: Vicky Cullen
Macintosh Drawings: Jayne Doucette
Printer: Reynolds-DeWalt Printing, Inc.

John Steele stepped down as Director at the end of January 1989 to join the scientific staff as Senior Scientist based in the Marine Policy Center. His Comments reflect his nearly 12 years as Director of the Woods Hole Oceanographic Institution.

IN the eleven years since I became Director there have been major developments in ocean sciences, in the public attitudes to this science, and in our own view of the scientific process at the Institution. This is an appropriate time for me to review these changes.

We have acquired new ways of looking at the oceans. In 1978, the SEASAT satellite carried an altimeter to measure sea-surface elevation and thereby give global information on ocean currents. It operated for only three months but provided a completely new kind of data compared with traditional methods of lowering instruments from ships. Another satellite-borne instrument, the CZCS (Coastal Zone Color Scanner), was launched in 1978 and operated until 1987. It proved effective in measuring color in the open ocean and so provided data on basic productivity at global scales. The oceanographic community was unprepared technically and conceptually to assimilate these data, and much effort has been directed during this last decade to learning how to apply these results to ocean problems.

The data from satellites gives, quite literally, a superficial view of the ocean. This new perspective has to be combined with traditional methods. From space, the satellite images not only showed large scale features in the ocean but also revealed complex, smaller scale, and highly dynamic topography. We have had to invent new jargon – "rings," "squirts," "jets" –to describe what we can now observe. At the same time our abilities to work *within* the ocean have increased tremendously. Such technology as acoustic tomography, subsurface drifting floats, and long term moorings provide data on the deep interior of the sea without the restrictions of a ship's location. How do we combine these different methods and develop new ideas about ocean dynamics?

The global scale of the new data sets, and thus of the scientific questions, requires greater collaboration among scientists from diverse disciplines, separate institutes, and often from different countries. We are seeing the development of large programs with correspondingly complex systems of management, involving several agencies within the U.S. as well as international organizations and a proliferation of committees.

Even more significant are the much longer time scales. A remote sensing instrument can take 10 years or longer from initial design to launch. Establishment of a set of ground stations is often required, and, most difficult of all, the data receipt and transmission to the users must be integrated into an overall scientific plan which includes in situ systems and numerical modeling programs. This long term packaging is very different from the traditional approach of the individual investigator or the small group funded for one to three years to answer well specified questions. Such planning requires a change in style not merely in the funding agencies but also in the research organizations.

This is critical for WHOI where nearly all the research money has come to our scientists based on their strong record as individual researchers. Is such a change in style desirable or necessary for WHOI? Can we, within the Institution, influence the patterns of our activities? How should we respond to the outside forces?

There are two very different kinds of reasons for this long-term global approach – the scientific interest and the social concerns. Taking the latter first, there is the question of how climate may change as a result of the addition by man of carbon dioxide and other greenhouse gases. The predictions are based on the known physical and chemical processes in the atmosphere and on large numerical models which can forecast possible effects over the next 50 years or more. These forecasts have had a significant public impact. There are many uncertainties but the most critical involve the role of ocean processes. These models take the ocean dynamics as fixed – partly because of computing limitation but also because we do not have sufficient knowledge of how the ocean will respond to changes in atmospheric conditions. For this reason, we do not have predictions of changes in ice volume at high latitudes or in rainfall patterns, two factors that are possibly more significant for sea level and agriculture than global temperature change.

These are the extrinsic reasons for a large scale perspective of the oceans that will give us knowledge of how the ocean will respond to changes in atmospheric conditions. But to depict the *changes* which may occur, we require an improved understanding of the basic scientific processes. This needs a more analytic research approach and depends on the abilities of individual scientists to produce ideas, better theories, and new instrumentation. This has been our traditional approach at WHOI. The achievements of individuals have been our greatest strength. Given the size of this new endeavor, and the human and technical resources required, it is impossible for any single organization, or even any nation, to undertake the whole scope of this research. This is especially difficult given the lack of significant extra funding specifically for these projects and the uncertainty in year-to-year allocations. What, then should be the involvement of an institution such as WHOI in the long term process from preliminary concepts to completion?

It is relevant that nearly all those scientists who have devoted themselves to this lengthy process have been in "hard money" positions at universities, such as MIT or Harvard, or in national laboratories. Our scientists at WHOI have been involved in planning committees and, at later stages, in project management. Because of their scientific stature they are essential to the success of the implementation. To a large extent their lack of commitment in the early stages is a free choice based on their own scientific priorities. But to a significant degree this is imposed by the time scales, the style, and especially the criteria for survival in a "soft money" environment. As I have found, it is not possible to impose such commitment from above – nor is it appropriate to our requirements for the demonstration of individual excellence in research.

There is a more prosaic reason for the patterns we see both within and outside WHOI. It is now much more difficult to be assured of long term funding from the main federal agencies which support our work. In the last decade the average success rate for NSF grants has fallen from 70 percent to 30 percent. ONR support is much more erratic and unreliable now than a decade ago. Younger scientists are more aware of the issues of "security" in a personal rather than a military context. Thus, in selecting career prospects, many look at the potential for long term institutional support for themselves and their research as a factor in evaluating job options. So far this has not significantly affected our ability to attract and retain the best scientific and technical staff. We have shifted the emphasis of our private fund-raising to endowment for support of people through chairs and awards. These, combined with the education endowment and programmatic grants from private foundations, provide a quarter of the support for our scientific staff. But we will need to do much more in this development area if we are to make the Institutional commitment that appears necessary.

I have focused on the "global" programs because they exemplify two changes in our science – tremendous technical development and greatly increased public interest in the costs as well as the benefits of innovation. These same factors operate in other aspects of oceanography – the uses and misuses of the coastal ocean, the need for a better and more detailed knowledge of the environment for naval defense. The oceans are no longer viewed as a separate and mysterious part of the world but as an integral component of our environment along with the land and the air. Our research has always been driven by practical needs as well as by the inherent fascination of the oceans. The latter has predominated during the last decade mainly because of the recent philosophy for federal funding of science that has stressed the role of central government in support of basic research. This philosophy appears to be changing with a new emphasis on social concerns particularly as they affect the marine environment.

This pressure for applied oceanography in its broadest sense must be beneficial but it implies changes in the way we carry out our research. The combination of new technologies with a much longer time scale for planning could require – or impose – a different style of operation. We can recognize the impact these changes are already having on the Institution. There is a trend away from the mainly sea-going, observational work. This is seen clearly in the decreased number of Ph.D. theses from the Joint Program that involve collections of data at sea, with a corresponding increase in theoretical or modeling studies. Operations at sea have traditionally been a major factor in our preeminence. I am sure this must and will continue but probably in a different context. Many of the programs will be national or international in concept and planning. There is an increase in the number of longer term joint projects with other institutions. We are bidding successfully for the establishment of national or regional facilities at Woods Hole. Our staff are acting as coordinators on environmental issues such as red tides.

Internally, the growth of the Institution has required the development of formal management structures such as the system of scientific departments and the introduction of tenure. These structures must fit the continually evolving pattern of the science. Thus I am sure there will be – in fact, must be – further changes. We need a matrix of disciplinary and cross-disciplinary groupings to meet the scientific developments. A greater Institutional commitment to our scientists and to the technical staff seems essential if we are to compete successfully for the best oceanographers and bring in new areas of science and technology.

Yet the main thrust at the Institution – our style – remains the support and the reward of individual excellence in research on the fundamental processes in the ocean. The emphasis on developments in sea-going technology must continue to be a prime motivation and an essential part of our work. This style has been maintained through a variety of external changes in requirements for oceanography and changes in sources of funds over the last 50 years.

I believe that the freedom to follow new ideas, the sense of community, has developed along with the growth of the Institution. I am sure we shall continue to expand and enhance the vision of our science of the seas under new leadership. Above all, I hope that doing research will continue to be fun. Certainly, I have enjoyed my time as Director. I must thank all those who have worked with me to keep us preeminent. I look forward to the future at Woods Hole and to my own involvement.

John H. Steele

Amy Rader

John Steele

Ellyn Montgomery

Ed Denton, left, and Alden Cook attach a direction-finding antenna to the mast of R/V *Oceanus*.

Craig E. Dorman became the sixth Director on 1 February 1989. His Comments look to the future of the Woods Hole Oceanographic Insitution.

RETURNING to Woods Hole from the Navy nearly two decades after entering the Joint Program, I am impressed by the continuity of WHOI's traditional seagoing scientific excellence and strong sense of community in the face of funding variations, the development of two campuses, and vast increases in the sophistication of oceanographic issues and techniques. Cynthia and I are excited to be back, and we welcome the challenges of the next decade.

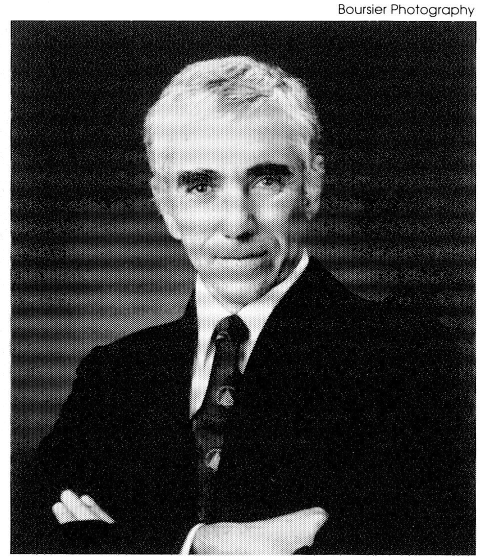
I spent most of my first weeks walking through our facilities and talking with WHOI people. The common threads I perceive are a delight in the Institution, a pride in and sense of responsibility for maintaining our role as a world leader in ocean sciences, and a commitment to be even better. While it is much too early in my tenure to speak of change – and any course of action for the Oceanographic must be thoroughly discussed and evaluated by both staff and Corporation – certain aspects of our future are clear:

- Our strength will continue to lie in the excellence of our people and in their ability to extract information from the sea and use it to understand process and change.
- New technologies will enable our scientists to ask better questions, and the need to comprehend dynamics and interactions throughout the oceans will likewise drive technological advance. Theory, experimentation and observation, analysis, prediction, and instrument development must be tightly coupled; each is today sufficiently sophisticated that collaboration among specialists in the various disciplines is essential to progress.
- Our funding as well as our excellence derives from the ingenuity and drive of our individual scientists. The entrepreneurial freedom to pursue the most meaningful questions is at the heart of our structure and must be enhanced through mutual support as well as Institutional support.
- As a research institution we must help our scientists maintain both their competitive edge and their long range vision. Without Institutional support, these may conflict. Costs and opportunities must be carefully balanced and resource allocations directed to enhancing the total climate for science – addressing simultaneously the immediacy of individual contracts and grants, the direction of ocean science research and education, and WHOI as a whole.
- We must maintain the excellence of those who enable science, our technical, administrative, facilities, support, and managerial staffs. We are blessed with high quality, low bureaucracy and people who care about each other. We must continuously foster equity, supportive relationships, and the sense of community that historically has been synonymous with WHOI.
- Education has become an indemnible thread in the WHOI fabric. It is a critical component of our research process and of individual as well as Institutional growth. For the good of the nation, the community, and ourselves, our outreach, involvement, and our teaching and mentoring skills must expand.
- Our strengths complement those of our neighbors and partners. We share research and community interests and needs with our local colleagues at the Marine Biological Laboratory, the U.S. Geological Survey, and the National Marine Fisheries Service. The desire to increase our mutually beneficial interactions and our contributions to our community is shared by us all. Likewise we share with our Joint Program partner, the Massachusetts Institute of Technology, a growing quest for individual and institutional coordination in science and technology as well as education.
- As a world leader in oceanography, our role and interactions transcend state and national boundaries. Our ties with colleagues and institutional partners across the country and around the world will strengthen as we grow. The national and international contributions of our individual scientists – as educators, spokespersons, editors, coordinators, and panel members as well as collaborators – can be abetted by Institutional support.
- The Federal Government is increasingly unable to support the totality of our requirements, let alone our desires. As a private institution, we have a growing need to develop greater independence in order to preserve the intellectual freedom to ask and answer the right questions with the best set of tools. Science – especially our brand of seagoing science – is expensive. But it is also crucial to the competitive posture of our nation, and to the health of the world. There is a strong case, as well as a critical need, for expanded Institutional development and interaction with industry.

Our five previous directors have helped our scientists build the world's best place for ocean science. In particular, my immediate predecessor, John Steele, has helped ensure that the quality of our scientific, technical, and support staff is unparalleled. He has managed our resources prudently and well. Cynthia and I appreciate the beauty and strength of that heritage and will do all we can to make the Woods Hole Oceanographic Institution an even better community.

Craig E. Dorman

Boursier Photography



Craig Dorman

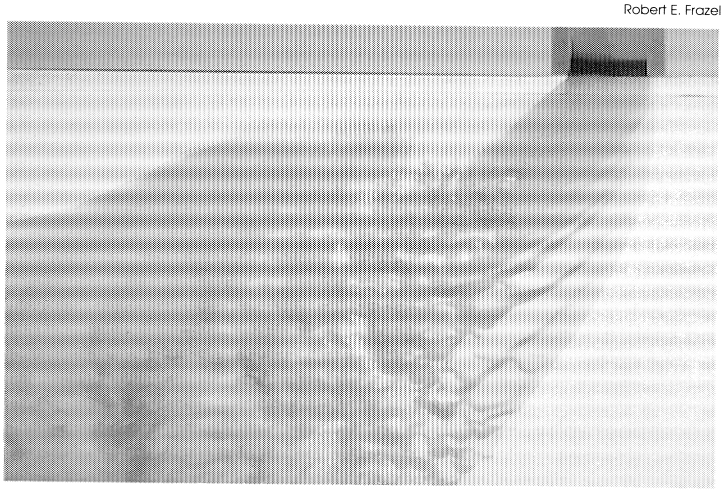
Biology

The broad aim of biological oceanographers is to study the temporal and spatial distributions of populations of marine organisms and their interactions with each other and their environment. The work is predominantly ecological in its attempts to provide the basic information required to understand how the ocean works biologically. Among the specific research interests of Institution biologists are microbiology, biochemistry, molecular biology, planktonology, ichthyology, benthic biology, physiology, biogeochemistry, bioacoustics, mathematical ecology, and animal behavior. Work on marine pollution includes research on the effects of hydrocarbons and the biochemical and molecular responses of animals to these and other pollutants. The "patchy" distribution of many marine animals is under investigation through field and mathematical modeling studies as are the physiological adaptions of deep sea organisms to sparseness of food, low temperatures, high pressures, and deep sea hydrothermal vents. Answers to questions about the food supply in the oceans are sought in studies of particles falling from the surface waters through the water column to the bottom of the sea, in studies of upwelling areas, through investigations of sulfur oxidizing organisms in the deep sea and shallow coastal ponds, and in laboratory experiments that complement field investigations. The uses of sound by marine mammals, the behavior of large marine animals (tracked by miniature acoustic telemetry tags), the spatial and temporal variations in abundance and size distribution of zooplankton (determined using high frequency sound), and the frequency and intensity of spawning by coral reef fishes (monitored by passive underwater listening devices) are being studied. Other work concentrates on salt marsh ecology and conservation and on nutrient cycling in coastal waters. The symbiotic relationships between marine microbes and other organisms (including woodborers) and between algal components and their microzooplankton hosts are a recent focus. Gelatinous organisms of the plankton (salps, ctenophores, and jellyfish) are being studied with new techniques that finally allow us to begin to properly evaluate the roles of these organisms in the oceans. The introduction of molecular biological tools and techniques into the mainstream of biological oceanography is permitting many of the above longstanding but current problems to be addressed in entirely new ways. Recent effort using these techniques includes studies of jellyfish bioluminescence, cancer in flatfish in Boston Harbor, and toxic dinoflagellate blooms ("red and brown tides") in coastal waters.

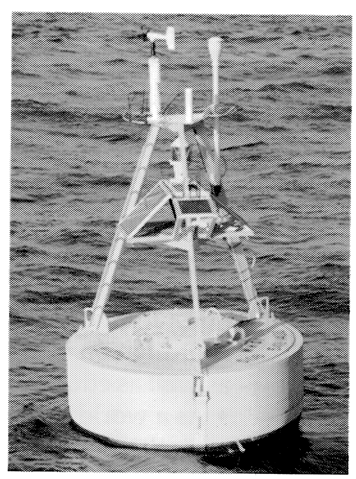
Chemistry

The main goal of chemical oceanographers is to understand the distribution and transport of chemicals within the oceanic environment and to assess the physical and biological factors that directly affect them. They also use chemical and isotopic distributions in the water column (i.e., tritium, helium-3, freons, strontium-90, and radiocarbon) as ways for determining ocean circulation itself. It is important to know how fast the ocean mixes in order to estimate the absorption of anthropogenic pollutants into the ocean. More and more, chemical oceanographers tailor experiments to account for the ocean's temporal variability. Climate, for instance, is increasingly recognized as a major factor controlling the distribution of chemicals in the ocean. Records of chemicals in sediments, shells, and corals serve as

Robert E. Frazel

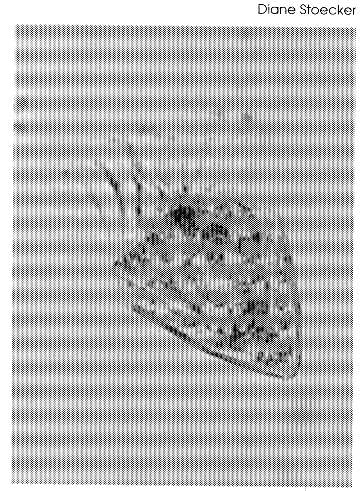


This model cataract was created in Jack Whitehead's laboratory by introducing a stream of salt water into a rotating tank of fresh water. The objective is to study the role played by giant undersea cataracts in determining deep ocean temperature and salinity.



This hardy, weather-resistant, economical surface mooring is being developed by Henri Berteux and Alex Bocconcelli.

Diane Stoecker



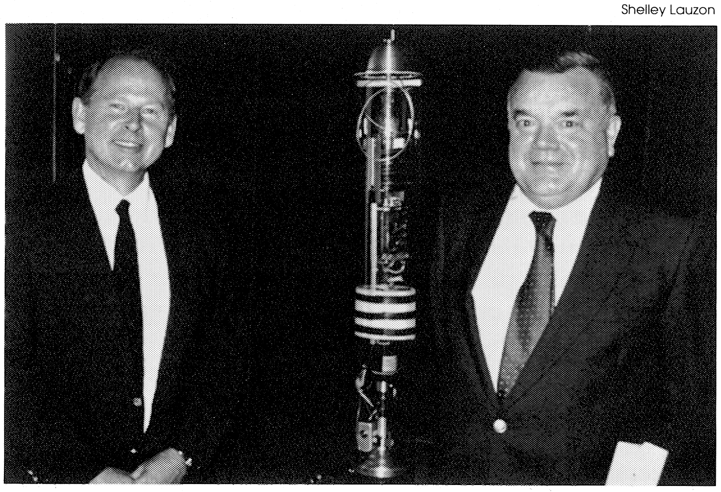
The biology of planktonic ciliates, including this *Strombidium* species, is being studied in the laboratory of Diane Stoecker.

integrators of past climatic occurences on such diverse time scales as El Niño/Southern Oscillation (a few years) and glacial/interglacial cycles (100,000 years). Some of the questions under investigation revolve around the vertical transport and transformations in particles as they fall from the surface to the bottom of the water column, as well as the processes responsible for formation and changes in organic matter in sediments. The photochemistry of the surface ocean and the marine atmosphere is critical to our understanding of the global sources and sinks for many gases, as well as alterations in the organic matter in the surface water. A recent revolution in the field of organic geochemistry involves the quantification, source identification (whether marine- or terrestrially-derived), and the molecular characterization of dissolved organic matter in seawater. The genesis and compositon of the ocean crust and its interaction with seawater is important to a general understanding of the oceanic system. Such questions as how long do hydrothermal events last and how important are certain types of vent systems in establishing the chemical composition of seawater are being addressed. Mantle processes are being pursued using stable isotopic studies in rocks. Work on the interstitial water chemistry of deep sea sediments improves our understanding of the diffusive flux of ions (natural or anthropogenic) between sediments and the oceans.

Geology and Geophysics

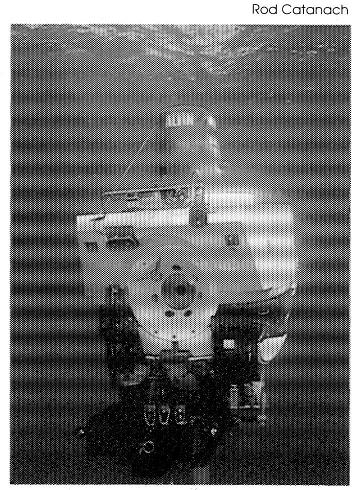
The primary research objective of the scientists in the Geology and Geophysics Department is the understanding of the genesis of present-day ocean basins and continental margins. Their interests include rifting processes associated with the opening of ocean basins, magmatic processes and hydrothermal circulation at mid-ocean ridges, structure and composition of the crust forming the foundation of ocean basins, and how the crust varies in space and time. Paleogeography, paleoclimatology of ocean basins as documented in fossils, and the chemistry, lithology, and seismic stratigraphy of the sediments are also studied. The morphology of the seafloor and how it relates to plate tectonics, the nature of the processes that control or have controlled the deposition and erosion of sediments, and the dynamical framework of geology's most fragile boundary, the shoreline, are also under investigation. As history is concerned with forces that have influenced the development of social structure, so earth scientists are concerned with processes that have produced our present global environments. The establishment of plate tectonics as the primary kinetic process creating and shaping ocean basins focused attention at the boundaries where plates interact. At divergent plate boundaries, or mid-ocean ridges, this includes processes that bring up hot materials to create ocean crust and lithosphere. Investigations of rifted continental margins are important to our understanding of how continental plates initially break apart. Finally, subduction of oceanic lithosphere beneath continental or other oceanic lithosphere is a process ultimately associated with the creation of deep-sea trenches and back-arc basins, and accompanied by the important geological phenomena of earthquake belts and volcanic island arcs. Other research concerns processes of particulate flux in the ocean ("marine snow"), carbonate and silicate dissolution, and other phenomena relevant to the transport of biogenic

Shelley Lauzon



Tom Rossby, left, of the University of Rhode Island, and Doug Webb, of Webb Research Corporation, received the 1988 Bigelow Medal for their contributions to ocean technology, including development of the SOFAR (sound fixing and ranging) float.

Rod Catanach



DSV *Alvin* made 200 dives in 1988, including Dive # 2000, working in the Pacific from the Washington coast to Mexico.

By December of 1988, the steel framework for an addition to the Clark Laboratory was in place.

material to the seafloor. The results are essential to a better understanding of the fossil record, which, in combination with studies of its oxygen isotopic variation, reveals changes in climate and ocean environment over periods of thousands to millions of years. The study of the dynamics of sediment distribution on the ocean floor is important to deciphering the fossil record and interpreting seafloor morphology. Marine geologists also study near-shore and shallower regions such as continental shelves and coasts where earth, ocean, and atmosphere dynamically interact.

Ocean Engineering

The field of ocean engineering encompasses a wide range of scientific and technical areas of research and development. The department maintains its leading position worldwide in sensor development and technical support. Within the past several years, the department has grown into a major center for research in a wide spectrum of scientific areas. The areas of research include fluid mechanics, physical oceanography, acoustics, microwave scattering, remote sensing of the ocean, remote sensing of animals in the ocean and in the air, robotics, biological processes, image processing, signal processing and estimation, and the dynamics of ocean cables. Active fluid mechanics and physical oceanography programs include sediment transport in the deep sea, on the continental shelf, in estuaries, and in the shoaling and surf zones; the dynamics of internal waves; the dynamics of boundary layers at the bottom and the surface; the study of large-scale fluctuations of temperature and currents; and the biological processes which influence benthic transport. The acoustic efforts include ocean acoustic tomography at the mesoscale and the basin-scale, sound propagation in the Arctic, scattering from in-situ particles, remote sensing of the roughness of the bottom from scattering data, and the study of the acoustic properties of the first few hundred meters of the sea bottom. Microwave backscattering from the air/sea interface provides information on gravity-capillary wave spectral densities, near-surface air flow, short wave modulations, surface currents, and satellite imaging techniques. Satellite data are processed to study the wave spectrum and wind speed at the surface. The unmanned submersibles program is active in the robotics area. Biologists study the importance of applied fluid stresses in the life cycles of benthic fauna. A vigorous engineering support effort covers areas as diverse as the deep manned submersible *Alvin*, fast vertical profiling vehicles, free-drifting satellite data telemetry platforms, acoustic telemetry systems, acoustic sensors, low power underwater computer systems, mooring dynamics, pressure housing, and underwater imaging.

Physical Oceanography

Physical oceanography is the study of the physics of the ocean. Its central goal is to describe and explain oceanic motions occurring over a wide range of scales, from millimeters to megameters, and seconds to centuries. On a large scale, the sun heats equatorial waters and the ocean transports this heat toward the poles, thus smoothing out the earth's climate and making large parts of it habitable. Variations of temperature and salinity, the driving effects of winds, the rotation of the earth, and the pull of the sun and the moon all contribute to these motions. There are grand persistent currents like the Gulf Stream, and there are transient waves and turbulent eddies of almost all sizes and speeds, from high frequency acoustic and surface gravity waves to slower internal gravity waves beneath the sea surface. Large regions of the oceans are dominated by intermediate scale, eddying, vortical patterns of flow, embedded within the large scale oceanic gyres, that display visual and dynamic similarity to atmospheric weather patterns. As in the atmosphere, relatively intense frontal systems exist. Important mixing and stirring of the ocean is accomplished by a variety of physical processes, some of great subtlety, like the phenomenon of "salt fingers" on the centimeter scale and "subduction" on the large scale. Important scientific questions also arise in considering the interaction of the ocean and the atmosphere, which drive each other in an as yet poorly understood way. Exchanges of energy between the air and sea are important in determining the climate of both the atmosphere and the oceans. Physical processes in coastal regions are strongly affected by atmospheric forcing and bottom topography, and the current and wave systems in this complicated region are of vast importance to local climate and ecology. Physical oceanographers are involved in experimental, theoretical, laboratory, and numerical investigations. Small programs involving a few researchers as well as large international projects are underway, and multidisciplinary efforts are increasing. Our ultimate goal is to understand the structure and movement of the world's oceans, the interaction of the sea with its boundaries, and the physical role of the ocean in the global thermodynamic engine we call Earth.

Coastal Research Center

The Coastal Research Center (CRC) was founded in 1979 to broaden our base of knowledge and improve our understanding of the coastal ocean in order to provide a basis for wise management of coastal resources. Interaction of multi-disciplinary groups of scientists is encouraged, and the Center also supports multi-organizational and multinational efforts.

The CRC provides facilities support for various coastal research activities. This includes laboratory and office space and two research flumes in the Coastal Research Laboratory (CRL) building. A small boat fleet, ranging in length from 14 to 50 feet, is maintained for nearshore research.

Currently, four principal project areas are emphasized. One concerns the coastal impacts of global climate change. Man's addition of radiatively-active trace gases to the atmosphere has raised the specter of significant changes in global climate, which could alter temperature, precipitation patterns, and water and sediment budgets, among other environmental parameters. These global changes will impact the coastal zone at the local and regional scale in such forms as sea-level rise, storm climate changes, salinity intrusion into aquifers, and disequilibrium of river deltas. The CRC program is directed towards predicting and assessing the potential coastal impacts of climate change, and, in addition, Marine Policy Center and CRC scientists are evaluating the potential costs and responses to such impacts.

A second CRC project area is assimilative capacity of coastal oceans. This multidisciplinary effort is funded through Institution Sea Grant funds as well as private foundation funds. The initial CRC assimilative capacity effort focused on contaminants in Buzzards Bay and their transport through that coastal system. Recently, this effort has expanded to other coastal waters (including Massachusetts and Cape Cod Bays), emphasizing a cross-disciplinary approach to these problems. Increased focus has also been placed on toxic dinoflagellate blooms, which are responsible for the "red tide" and related fisheries mortalities.

The other major CRC emphases are on instrumentation and rapid response. The instrumentation effort provides seed funding for the development of new instrumentation for multidisciplinary coastal research programs. Two large seawater flumes completed under the instrumentation program are used for experiments on turbulence, sediment resuspension and transport, and interactions with marine biota. The rapid response program provides funds for quick response to marine "events." Because conventional funding channels normally require long lead times, opportunities to acquire baseline data immediately after an "event" are often lost. Rapid response projects funded recently include Black Sea mixing using radionuclides from the Chernobyl disaster and the cause of a major whale mortality off the Massachusetts coast. In both cases it was imperative that initial data be collected immediately if the event were to be understood.

The Coastal Research Center focuses on basic scientific questions in the coastal environment, but the heavy demand on coastal resources often requires that these basic science investigations be quickly translated into policy and management actions. The work of CRC investigators therefore serves as an important bridge between scientific research and the application of research results to societal problems.

Center for Marine Exploration

The Center for Marine Exploration (CME) was established in late 1986 to foster new technologies, including unmanned systems, for the deep ocean and to provide a focal point for marine scientists and others exploring the deep sea. CME has four primary goals:

- to provide scientists with advanced engineering and cost-effective techniques for deep ocean exploration and experiments,
- to provide marine archaeologists and other social scientists opportunities to utilize this technology for cultural and historic puposes,
- to increase public awareness of the marine environment, and
- to stimulate career interest in engineering and the natural sciences.

The capabilities and promise of unmanned robotic submersibles gained international attention with the discovery of R.M.S. *Titanic* in 1985. The *Argo* and *Jason Jr.* prototype vehicles, developed in the Institution's Deep Submergence Laboratory, were deployed and tested for the first time in the search for *Titanic* in 1985 (*Argo*) and the detailed exploration of the wreck and its interior in 1986 (*Jason Jr.*). These systems will allow many more scientists and the public to participate in marine exploration, to see and experience the challenges, excitement – and setbacks – of scientific discovery.

In the spring of 1989, for instance, 250,000 students in the U.S. and Canada will participate in a voyage of discovery to the deep waters of the Mediterranean Sea. Using advanced "telepresent" technology and live satellite transmissions, The *Jason* Project will explore active underwater volcanoes and the remains of ships lost beneath the ancient trade routes of the Mediterranean. Through a unique collaborative effort involving private industry, scientific research facilities, museums, and educational organizations, color television images will be transmitted live for the first time to a network of museums for viewing by students and the general public. A two-way audio link will allow viewers to address questions to Expedition Leader Dr. Robert Ballard aboard ship. The Jason Project features advanced technologies in robotics, fiber optics, television production, computer science, mechanical and electrical engineering, and satellite communications. It marks the completion of the *Argo/Jason* unmanned imaging system and the beginning of a new era in ocean exploration.

A major scientific focus of the Center is the continued exploration of the 46,000-mile Mid-Ocean Ridge, the largest geological feature on the earth. Research on this vast underwater mountain range has led to the accepted theory of plate tectonics and seafloor spreading, but the ridge system remains largely unexplored and little understood. The Institution's's *Argo* system can image in just one week an area of ridge terrain equal to all that previously viewed from manned submersibles.

CME provides a meeting ground where skilled technicians and experts in such areas as materials science, electronics engineering, image processing, acoustics, optics, mechanical engineering, computer sciences, robotics, and telecommunications come together with marine scientists to develop the technology for unmanned exploration of the deep ocean. The objective is to provide a scientific and cultural window to the deep ocean toward furthering basic knowledge and man's ability to use the marine environment wisely.

Marine Policy Center

The Marine Policy Center is the multidisciplinary social science and policy research unit of the Woods Hole Oceanographic Institution. Since its establishment in 1971, the Center has been a principal source of independent, authoritative assessment of national and international marine policy issues. A resident staff and Research Fellows conduct objective social science research on issues of importance to public policy. Emphasis is placed on the economics of ocean space

Terri Tallman

Jim Broadus, right, Marine Policy Center Director, and Art Gaines discuss a coastal resources management project.

and on the role of science in governmental and industrial decision making.

The Marine Policy Center's threefold functions are:

• *Research* through the efforts of an experienced professional staff and Research Fellows;

• *Education* through the Fellowship program, Institution seminars, and interaction with students;

• *Information exchange* through the sponsorship of workshops and conferences.

Individually and as small teams, the Marine Policy Center staff engages in both specialized disciplinary and broader interdisciplinary research projects in four thematic areas: 1) marine science and public policy, 2) development and management of ocean resources, 3) ocean jurisdictions, law of the sea, and international relations, 4) areawide planning and management.

Recent research at the Center has addressed such diverse topics as benefits to marine recreational fishing from estuarine quality improvement, establishment of new marine reserves, the economic and legal status of historic shipwrecks, Soviet maritime Arctic policy, comparative U.S.-Soviet marine protection, the economics of marine pollution, the economics of the ocean sector, and exploration cycles for marine minerals.

Current study areas include the dynamics and structure of the international marine electronics industry, global warming and sea level rise, the significance of the oceans to global biodiversity, and areawide planning and management.

Our Marine Policy and Ocean Management Fellowship Program offers Research Fellowships to professionals from the social sciences, humanities, law, or natural sciences to apply their training to problems that involve the use of the oceans. In addition to their research efforts, Fellows are encouraged to participate in Woods Hole seminars and study groups and to develop collaborative research with members of the scientific and technical staffs at the Institution. Program applicants must have completed a doctoral level degree or possess equivalent professional qualifications through career experience. Opportunities also exist for senior scholars on sabbatical leave to participate in the Center's activities.

Terri Tallman

Bob Ballard, Director of the Center for Marine Exploration, describes plans for The Jason Project in the Mediterranean Sea.

Sea Grant Program

The WHOI Sea Grant Program supports research, education, and advisory projects to promote wise use and understanding of ocean and coastal resources. Since 1973, WHOI Sea Grant has channelled the expertise of Institution scientists toward meeting the research and information needs of users of the marine environment, especially in Massachusetts.

The WHOI Sea Grant Program is part of the National Sea Grant College Program of the National Oceanic and Atmospheric Administration (NOAA). Sea Grant is a network of 30 individual programs located in each of the coastal and Great Lakes states. It fosters cooperation among government, academia, and industry; one-third of total Sea Grant project support is provided as matching funds from nonfederal sources.

WHOI Sea Grant supports 12 to 15 research projects and a number of smaller "New Initiative" efforts aimed at taking the first steps into promising new areas, sometimes involving sponsorship of workshops and conferences. Program thrusts generally address local and regional needs. Emphases include fisheries degradation, water quality, coastal processes and erosion, and marine resources development. Sea Grant projects include:

• the physiology and ecology of toxic red and brown tides,

• growth and reproduction dynamics of Iceland scallops off Massachusetts,

• water quality studies of coastal ponds in Falmouth using local volunteers,

• effects of climate change on extreme sea levels along the U.S. coast,

• effects of suspended sediments on coastal currents,

• cyclical behavior in marine minerals research and development, and

• international marine science cooperation.

WHOI Sea Grant's major product is publications – in its 16-year history, the program has supported nearly 600 scientific publications, including journal articles, theses, and books.

THE importance of the coastal zone to our economy, environment, health, and national defense becomes increasingly more apparent as this decade progresses. As landfills become full, as human activities increase along our shores, and as pressures mount from an ever growing population, coupled with aging sewage treatment plants and lack of sewage treatment, the importance of understanding the processes controlling the coastal environment increases dramatically.

The coastal zone is affected in a number of important ways by man's impact on the overall global climate system. Included in this are coastal flooding due to acceleration in sea-level rise potential, changes in storm paths and precipitation patterns caused by changing stability of the atmosphere, and changes in estuarine circulation and evolution. It is most important for the health of the coastal zone to identify the likely impacts for different climate change scenarios so that we can respond with rational, well-considered management plans once a scientific consensus is suffciently well established. Recognizing the need to address these problems, the Institution created the Coastal Research Center in 1979 to bring into focus this area of research. This Center promotes improved communication and more formal interdisciplinary interactions to study specific coastal research problems more effectively. The Institution's Sea Grant Program has also been very valuable in this endeavor.

The need to better understand the physical, biological, geological, and chemical processes associated with the coastal zone has also been addressed by the National Science Foundation, the Office of Naval Research, the National Oceanic and Atmospheric Administration, the Environmental Protection Agency, and the Department of Energy. They have supported a number of major interdisciplinary programs in which the Institution's scientists have participated. Over the last decade, the results from the Coastal Ocean Dynamics Experiment (CODE), the Organization of Persistent Upwelling Structures (OPUS), the Coastal Transition Zone (CTZ), the Sediment Transport Study on the Shelf (STRESS), the Shelf Edge Exchange Processes (SEEP), and the Shelf MIxed Layer Experiment (SMILE) programs have had a major impact on our understanding of the basic fluid, sedimentary, and biological processes of the coastal ocean. Plans are currently underway by a group of coastal physical oceanographers to develop a program (CoPO) to address the understanding of the processes dominant in the transfer of matter, momentum, and energy across the continental margin.

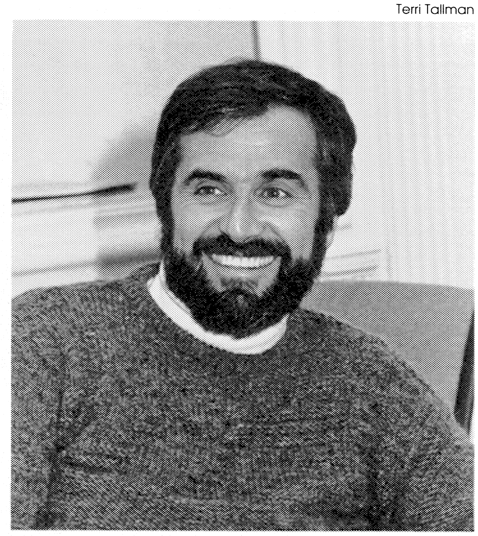
In order to more fully understand the driving forces that control our coastal environment, several of the research questions being addressed by Institution scientists are included in the articles to be found in this year's annual report. These include the origin, exchange, and transport of shelf water for prediction of sea surface oscillations in harbors in order to minimize the damage to harbor facilities and ships, how waves and currents combine to generate the stress and other conditions that erode and transport sediment, and the role of estuarine and coastal processes in regulating the biogeochemical cycles in the marine environment. Our understanding of circulation and mixing is still very limited, due in large part to the overwhelming complexity of the response of coastal waters to numerous forcing variables such as tides, winds, run-off, and atmospheric heat exchange. However, new types of atmospheric and oceanic instruments, such as current and wave measuring devices and buoys with meteorological sensors, have been developed. To further investigate the dynamics and the detailed nature of the flow field, numerical models of tidal flow have been developed using supercomputers.

Satellite oceanography, in conjunction with seagoing studies, is playing a major role in furthering our understanding of the physical dynamics of the coastal ocean. New structures called "filaments" have been discovered by remote sensing oceanography. These filaments concentrate the cold, upwelled water near the coast into a thin jet which can extend hundreds of kilometers offshore.

Biological implications of our changing coastal environment are also of serious concern. Red tide and now brown tide events have proliferated to a worrisome degree during the last several years. The toxins from the dense accumulations of single celled marine plants in red tides have been responsible for a series of outbreaks which have seriously affected the health of man and marine mammals alike. Study of the organisms responsible for these devastating outbreaks involves a variety of investigations ranging from field programs to determine the physical and biological mechanisms underlying development and transport of coastal blooms to laboratory studies at the cellular and molecular level.

As well as coastal concerns, this year's annual report presents research on one of the most famous inland bodies of water, the Black Sea. During 1988, WHOI launched a major interdisciplinary, interinstitutional expedition into this area. Significant advances in theory and technology now allow many questions raised on earlier expeditions in 1968 and 1975 to be addressed. Some of the major objectives of this expedition were to recon-

Terri Tallman



Bob Gagosian, Associate Director for Research, introduces the research reports.

struct the environmental evolution of the Black Sea and surrounding land masses and to explore the relationship between the chemistry of the oxic/anoxic interface with the biology of the microorganisms living in this region of the water column. The expedition was very successful in increasing sediment and water column chemistry and biology sample data bases available to the international research communities interested in the Black Sea. Because some of the results from this unique environment are very exciting, we have included reports on some of this preliminary geological and biological data.

Robert B. Gagosian
Associate Director for Research

The Origin of Shelf Water in the Middle Atlantic Bight

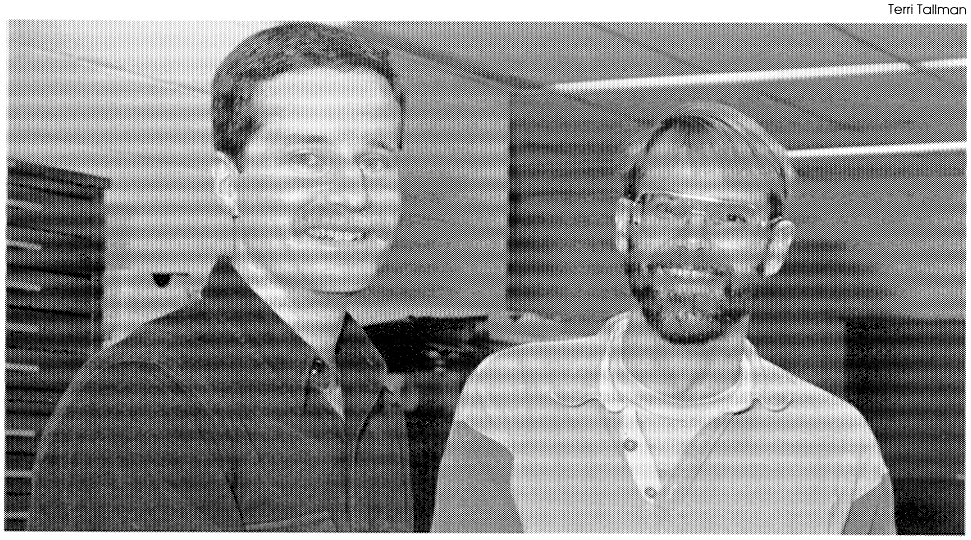
David C. Chapman and Robert C. Beardsley

THE observed mean flow of water over the continental shelf in the Middle Atlantic Bight (MAB) is alongshore to the southwest with a transport of about 400,000 cubic meters per second. The origin of the shelf water, which tends to be colder and fresher than the water found offshore over the continental slope, as well as the forces which drive it have been the subject of study and some controversy for nearly three decades. One possibility is that the shelf water in the MAB is simply a mixture of local freshwater runoff, which enters through the major MAB estuaries, and the more saline offshore slope water, but the annual supply of freshwater is inadequate. Another possibility is that the MAB shelf water originates somewhere to the north, for example from the St. Lawrence River, and is the downstream extension of a density-driven coastal current. However, the prevailing idea in the 1970s and early 1980s was that the MAB shelf water is primarily offshore water forced onto the shelf by the effects of the nearby Gulf Stream and its associated recirculation.

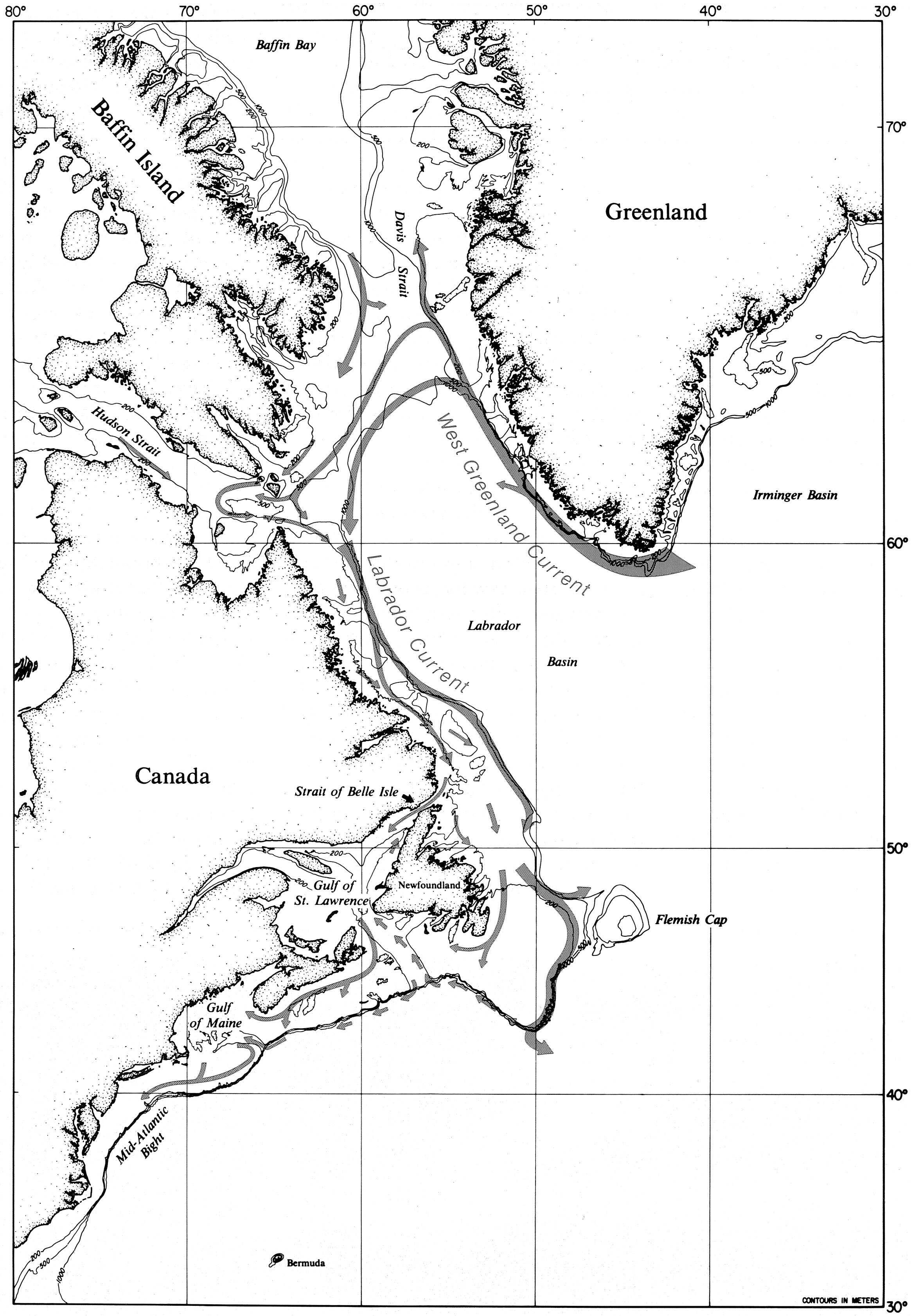
When analysis of the stable oxygen isotope ^{18}O became relatively routine in the early 1980s, it provided the means for distinguishing among the possibilities. Each freshwater source along the east coast of North America has a unique ^{18}O signal that is different from the nearly uniform ^{18}O signal in the deep offshore water. The shelf water in the MAB, then, can be traced to its freshwater point of origin. The first detailed use of ^{18}O for this purpose showed clearly that the shelf water in the MAB is a downstream continuation of the mean alongshore flow over the continental shelf off Nova Scotia. This eliminated the hypothesis that the deep-ocean circulation offshore of the MAB was forcing the mean flow. However, the research did not identify the ultimate origin or driving mechanism for the mean flow, because the same questions can be asked about the mean flow over the Scotian Shelf. Where does it originate and what forces it?

Somewhat surprisingly, the ^{18}O analysis in the MAB suggested that the ultimate origin of the MAB shelf water might, in fact, be well to the north, even north of the Gulf of St. Lawrence. Indeed, a recent careful examination of the limited available ^{18}O measurements from the Labrador Sea and Baffin Bay, along with available hydrographic data, has led to the rather remarkable conclusion that the MAB shelf water is actually the downstream continuation of an extraordinarily long (5,000 kilometer) density-driven coastal current which originates along the southern coast of Greenland – by far the longest coastal current known! We hypothesize that the driving mechanism is the buoyancy effect produced by glacial meltwater and river runoff entering the shelf along the coasts of Greenland and Labrador. This has important dynamical implications, although we do not yet understand how the current can remain on the shelf over such a long distance without mixing more extensively with the deep-ocean water. The exchange across the shelf is apparently much weaker than has previously been assumed. We hope to answer these and other questions in the future as observational and modeling efforts are directed toward the study of this fascinating coastal current.

Terri Tallman



Authors Dave Chapman and Bob Beardsley discuss current views on the origin of shelf water, the subject of both study and controversy for nearly three decades.



A proposed circulation pattern shows the possible pathways for coastal water from the West Greenland Current to the Middle Atlantic Bight. Broader arrows denote regions of higher current concentration, and broken arrows correspond to deeper flows.

Red Tides and Toxic Algal Blooms

Donald M. Anderson

THE last several years may be remembered as the time that man's impact on the global environment caught the public eye in a powerful and ominous fashion. For some, the signs of our environmental neglect came with forecasts of global warming trends and sea level rise, while others experienced the more immediate and personal impact of raw sewage and medical wastes being washed up on beaches. In my laboratory, these times were marked by the need to respond to a worrisome increase in "red tide" events. This term is most often used to describe the dense accumulation (bloom) of tiny, single celled marine plants (phytoplankton) that discolor coastal waters, but it also refers to events where the toxin produced by certain algae accumulates in shellfish or kills fish and other marine life, often at cell concentrations that do not discolor the water.

Researchers working on red tide problems typically focus on regional events that do not occur every year but that that are somewhat predictable because of their long histories. One example is the bloom phenomenon that causes Paralytic Shellfish Poisoning (PSP), a common event in New England that also occurs in many other coastal areas of the US and the world. Another is the Florida red tide, which is caused by a different phytoplankton species. Its main impact is the mortality of fish that wash up on beaches and cause major losses for the tourist industry.

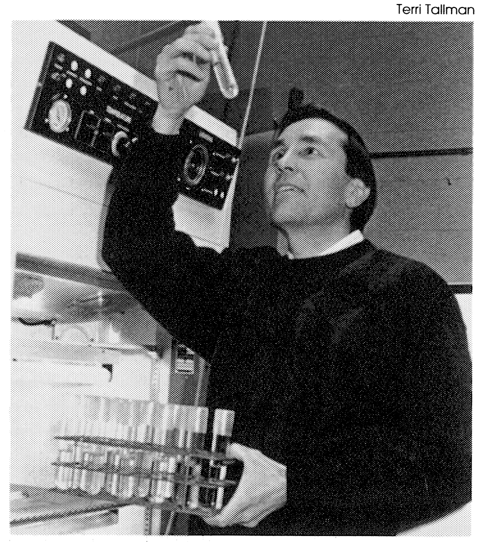
On many occasions in recent years, we have had to put aside our ongoing research in order to deal with unexpected outbreaks – those caused by new species of algae or that involve a new toxin, a new location, or even the mortality of a previously unaffected animal. For example, several Canadians died and hundreds were hospitalized in late 1987 after eating mussels containing a new toxin of algal origin called domoic acid. Although, the initial outbreak was isolated near Prince Edward Island, the toxin was subsequently found in other Canadian shellfish as well as in Maine scallops. We are now developing the analytical capability needed to define the geographic range of this toxin in the rich shellfish growing regions of New England not yet tested.

Concurrent with the Canadian episode, 14 humpback whales washed ashore in Cape Cod Bay, an unprecedented mass mortality which we eventually linked to the PSP toxin, not in shellfish, but, suprisingly, in the livers of mackerel eaten by the whales. The mackerel presumably obtained this toxin from zooplankton and other small animals that graze on the toxic algae, but 1987 was a year with virtually no PSP in New England shellfish. The origin of the toxin, the manner in which this important commercial fish accumulated it without dying, and the impact on other segments of the food chain are all topics of further investigation.

These are just two examples of events that reinforced our growing suspicion that something is changing in coastal waters – that phytoplankton are responding to a fundamental change in their environment and that bloom-forming, noxious species are more often dominant. Red tides are not new – they certainly predate man historically. What is new is the manner in which the number, magnitude, geographic extent, and species complexity of such events have all expanded in recent years. The examples above may be natural phenomena that cannot be

Greg Early, New England Aquarium

Humpback whales like this one washed ashore from Cape Cod Bay were victims of a "red tide" toxin that was found concentrated in the livers of the mackerel they ate.



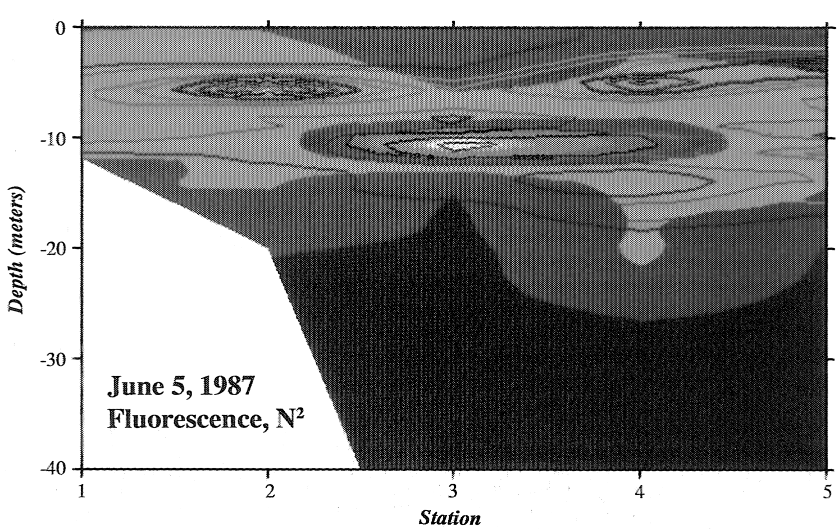
Terri Tallman

Don Anderson checks "red tide" samples in his laboratory.

blamed on man in any way. Others, however, are not so easily dismissed. The obvious question is whether the general expansion of the red tide phenomenon is the result of natural fluctuations in the environment or is instead an indication of human influences on a global scale. A related question is whether man's influence occurs directly through pollution, dredging, and other modifications to the coastal zone or indirectly through atmospheric phenomena such as acid rain or the "greenhouse effect."

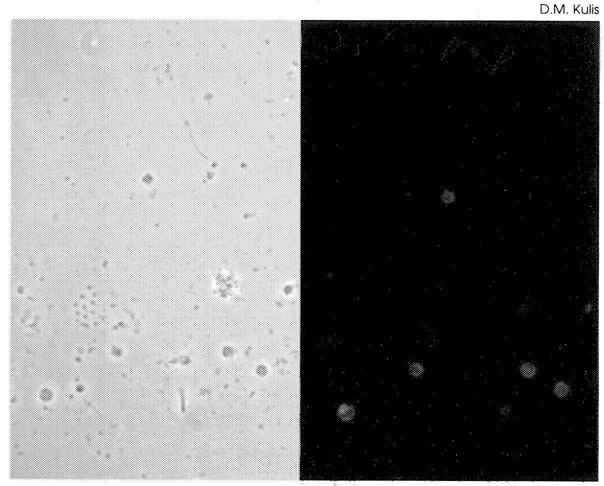
Given the many different phenomena that fall under the "red tide" umbrella, our core research program necessarily involves a wide variety of phytoplankton species and lines of investigation, ranging from field programs to determine distributions of the causative organisms in the marine environment to laboratory studies at the cellular and molecular level. An example of the former is a program funded by Sea Grant and the Office of Naval Research examining phytoplankton blooms in the southern Gulf of Maine. Our objective has been to determine the physical and biological mechanisms underlying the development and transport of certain coastal blooms. A key to this program has been the simultaneous aquisition of biological and physical data using a pump-CTD-transmissometer system that gives us vertical profiles of chlorophyll, light transmittance, depth, temperature, and salinity, in addition to samples for nutrients and cell counts of the phytoplankton species of interest. The need for such detailed vertical profiles is related to the tendency of many phytoplankton blooms to be localized phenomena, often occurring in thin "lenses" well below the water surface as a result of organism behavior such as vertical migration, and physical forcing such as density discontinuities or upwelling. The figure at left below shows an example of one of these subsurface blooms situated 15 to 20 kilometers from Portsmouth, NH, at 10 meters. Other cruises showed that this cell distribution was not just an isolated event but was instead indicative of a widespread coastal feature in that region. In effect, the cells bloom in a continuous, subsurface "ribbon" extending several hundred kilometers alongshore. As we work toward understanding the mechanisms underlying this bloom localization, we will collect additional field data in years with different wind and rainfall patterns and develop mathematical models to help identify the most important physical and biological processes.

A totally different type of project was initiated in response to the sudden appearance of the "brown tide," a new and serious threat to shellfish and submerged aquatic vegetation resources in the northeastern US. The first outbreaks occurred in 1985, but the problem has recurred in each subsequent year. The tiny alga responsible for the brown tide is a previously undescribed chrysophyte given the name *Aureococcus anophagefferens*, which loosely translates to "small golden sphere that causes the lack of feeding." The name derives from the mortality of shellfish which starve to death despite the presence of tremendous concentrations of *A. anophagefferens* cells. This very small nondescript organism is easily confused with other species under the microscope, so it is exceedingly difficult to monitor natural waters for brown tide cells except when they are in bloom concentrations. The Schumann Foundation supported a rapid response to this new problem with initial funds for development of an immunofluorescent "tag" for *A. anophagefferens*. The objective was to use immunological methods from the medical sciences to produce antibodies that would "recognize" only *A. anophagefferens*, allowing that species to be discriminated from others using fluorescence microscopy. Protocols were developed to preserve intact brown tide cells for concentration and injection into rabbits, thus exposing the rabbit's immune system to the outer cell wall



Plot shows a subsurface dinoflagellate bloom off Portsmouth, NH. Colored regions depict cell abundance, and contour lines show areas of low turbulence.

D.M. Kulis



Left: Natural phytoplankton sample viewed with standard light microscope. Right: Same sample after treatment with brown tide antibody. Cells with green "halo" are *A. anophagefferens*.

proteins of *A. anophagefferens*. The last figure shows how the blood serum subsequently obtained from the rabbits can be used in what is known as an indirect immunofluorescent protocol to identify *A. anophagefferens* cells in natural water samples. The distinct green "halo" in the figure shows that the antibodies are binding specifically to the cell wall. At dilutions that yielded excellent labelling of the brown tide cells, the antiserum did not cross-react with any of the 48 cultures of co-occurring or morphologically similar phyoplankton species that we tested; it therefore appears that we have developed a species-specific "tag." A blood sample from one rabbit provides sufficient serum for the enumeration of more than 50,000 separate samples. We are currently working with the Suffolk County Department of Health Services and others on Long Island to train personnel and distribute the antiserum to active research programs. Interestingly, when we surveyed waters outside the regions where the brown tide is a recognized problem, we discovered low concentrations of cells in Massachusetts, Rhode Island, and Connecticut. Further field work is now needed to follow these small populations to determine what conditions might trigger their growth into the tremendous blooms that characterize the brown tide elsewhere.

As a growing world coastal population demands more and more marine food resources, this type of research has increasing practical implications. If we are correct in our interpretation that events over the past years are indicators of a global expansion of red tides and toxic episodes, some of our research effort must necessarily shift to investigations of the causes for such a major change in ecosystem dynamics. The expanding biological response we are now witnessing may reflect the cumulative effect of decades of human abuse of coastal waters. Given the lag times inherent in such complex biogeochemical systems, the fascinating problems and challenges of this field are likely to continue for many years.

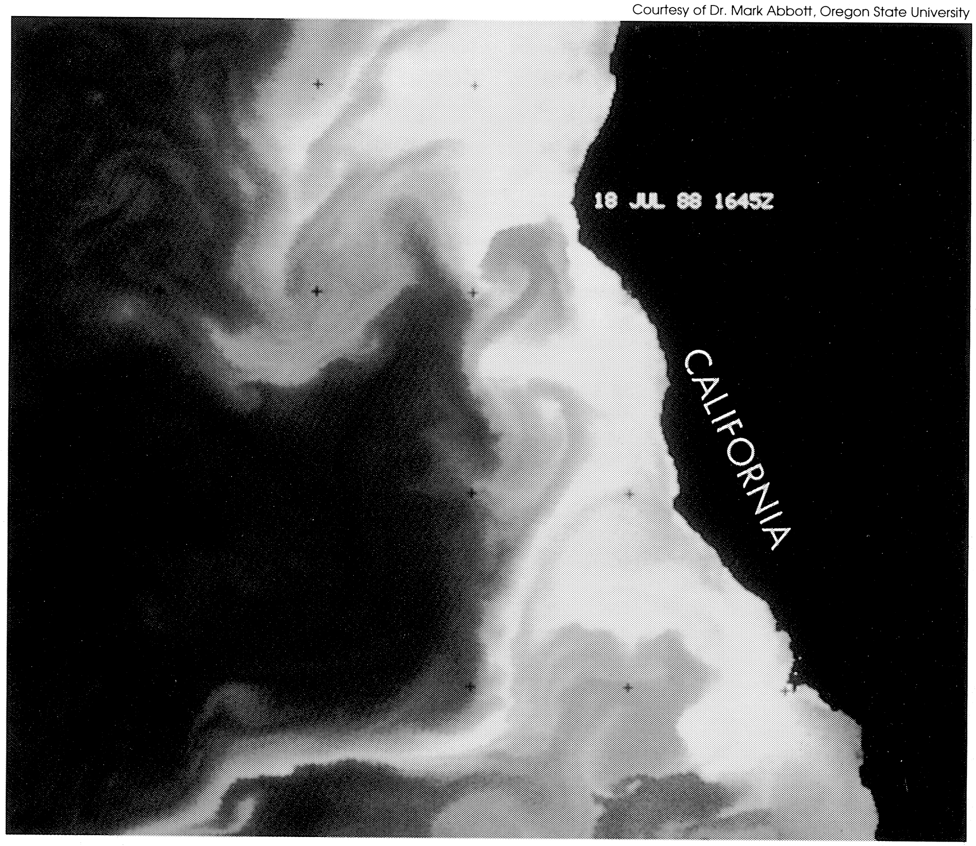
Cold Current Off California

Kenneth H. Brink

ONE of the early accomplishments of satellite oceanography was the revelation that the ocean has a much richer physical structure than anyone ever expected. Originally, in the early 1970s, there was a good deal of skepticism about the meaning of satellite images of sea surface temperature. After all, the sensor only detected the temperature in a thin (less than a centimeter) layer at the very surface of the ocean. What reason was there to believe that the complicated structures revealed by the sensors really represen-ted anything more than anomalous conditions at the very surface? Put another way, did the surface temperature images really tell us anything about what takes place in the bulk of the water column?

An example of how satellite results really changed our vision of the ocean was in the California Current system, off the west coast of the United States. Traditionally, the system had been viewed as simply a very broad (hundreds of kilometers), slow moving drift towards the south. This illusion was dispelled in 1977 by Bernstein, Breaker, and Whritner, who used satellite temperature measurements to suggest that the California Current system was a very dynamic system filled with eddies and meanders. They backed up this suggestion by showing that in situ measurements of the ocean corresponded quite well with what had been observed by satellite. Remotely

Courtesy of Dr. Mark Abbott, Oregon State University



A satellite-derived image of sea surface temperature, representing July 18, 1988. The lighter shades represent cold water, and the darker shades represent warmer water.

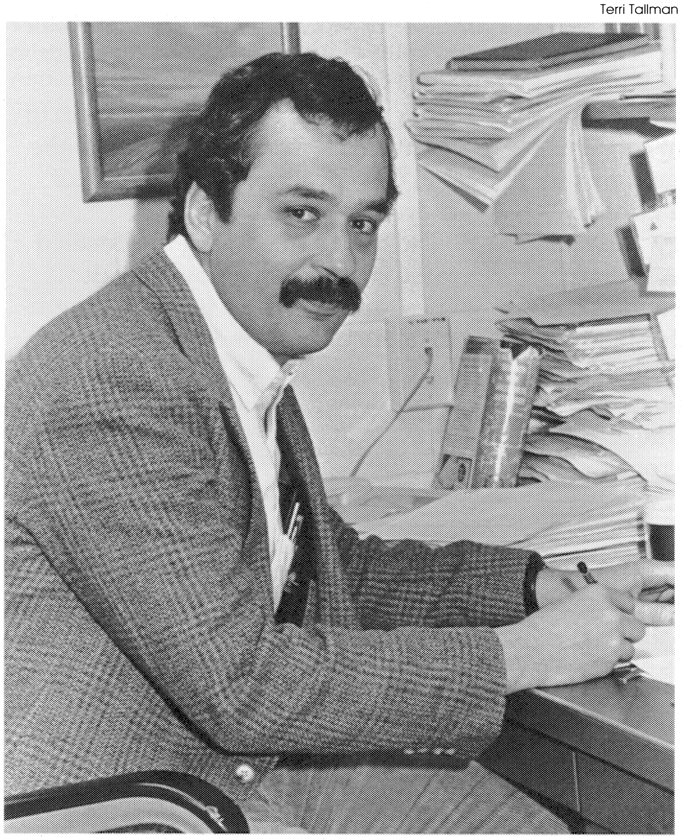
sensed data could no longer be dismissed as simply superficial noise. While these findings were very important, most oceanographers were familiar with eddies and meanders, so that no new oceanographic features were exposed by their initial study.

New structures were not long in coming, however. Several investigators noticed narrow (20 to 40 kilometer), long (200 to 400 kilometer) structures of cold water which often extended from the coast of California offshore (figure at left). Since then, similar features have also been observed in such diverse locations as the western coast of South Africa, and off Portugal. These cold features seem to draw cold upwelled water from near the coast to great distances offshore. Nothing about these features, now commonly called "filaments," was familiar to oceanographers. They seemed to concentrate the cold, nearshore waters into a thin jet in a way that no one could explain. At first, it was tempting to dismiss the cold filaments as a superficial artifact of the satellite sea surface temperature measurements. A major step was made, though, by Traganza, Conrad and Breaker, who in 1981 published the results of a preliminary ship-based survey of one of the satellite-observed filaments. They found that the filament was not at all superficial, and that it was accompanied by important biological and chemical signals. The filament appeared to be more biologically productive than its surrounding warmer waters. The stage had now been set: filaments had been recognized as a real, albeit completely unexplained, aspect to the ocean.

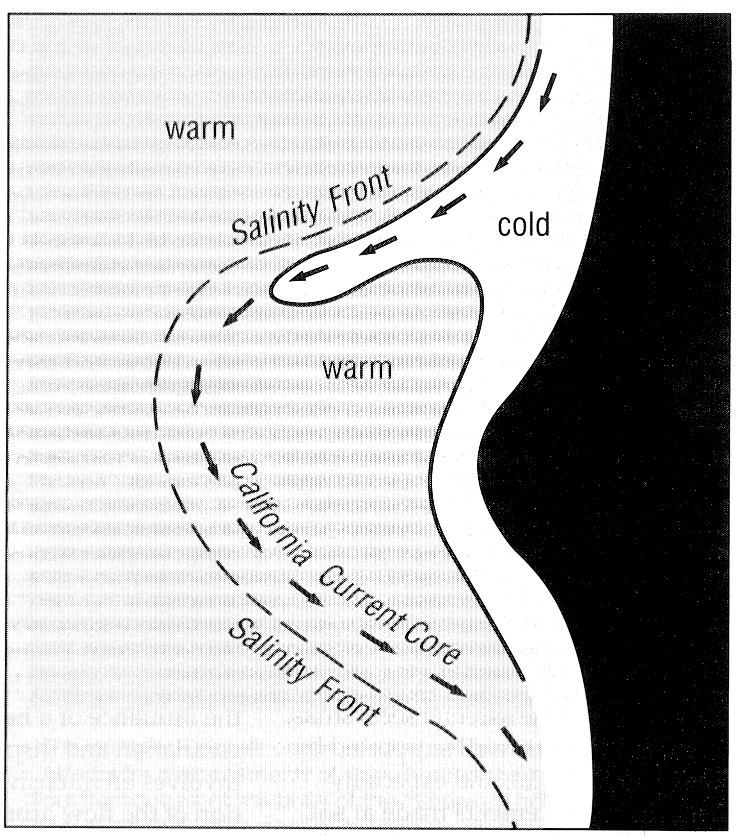
During the early 1980s, some detailed surveys of filaments were made through such large programs as CODE (Coastal Ocean Dynamics Experiment), OPUS (Organization of Persistent Upwelling Structures), and also by independent investigators. These surveys did much to sharpen up our understanding of the structure of filaments. It was found that, generally, there is an energetic current flowing seaward in the core of the filament. Speeds are typically 1 to 2 knots, and the currents extend down to depths of 100 to 200 meters, at least. Also, the filaments usually had very well-defined temperature fronts along their southern edges. These results served mainly to emphasize that filaments are important oceanographic structures, and to refine our ideas about their typical behavior. Very little could be learned from these "shapshot" observations about the evolution and causes of these features.

In the mid 1980s, the Office of Naval Research decided to concentrate resources on the issue of cold filaments. This encouragement led to the creation of the Coastal Transition Zone (CTZ) program, an interdisciplinary group of about 25 scientists from several institutions dedicated to understanding filaments. The general goal of the program is to characterize

Terri Tallman



Ken Brink is one of the organizers of a developing program of study known as CoPo (Coastal Physical Oceanography).



Cartoon shows the basic features of our current understanding of the cold filaments off California.

filaments and their variability and to understand the mechanisms that lead to their existence. Although the program includes a vigorous modeling effort, most of its resources are dedicated to observational efforts, which were concentrated in a 1987 pilot effort and in a 1988 main program. The diverse observational techniques include satellite remote sensing, drifter deployments, water sampling (for temperature, salinity, nutrients, and microscopic plants), moored current measurements, turbulence measurements, and sampling zooplankton (small, drifting animals). The two field years were both quite successful, in that 1) cold filaments were "captured" both times, and 2) the rate of data return was excellent.

It is too early to state any final results from the CTZ program, but the 1987 pilot measurements did lead to a preliminary explanation for filamentary structures (second figure). The core of the California Current is a narrow (about 30 kilometers wide) southward jet. As it proceeds southward, it meanders in much the same way the jet stream does in the atmosphere (thus giving rise to changes in the weather). When the current reaches close to shore, it entrains some of the cold, dense surface waters which arise from coastal upwelling. These cold surface waters are then carried offshore with the current core when the meander turns westward. This explanation so far leaves open the question of why it is that, when the current again meanders shoreward, we do not see it in satellite images as the cold filament turning shoreward also. The answer, which was completely unanticipated before the 1987 field work, is that the cold surface waters sink as they move offshore with the current, and they are replaced by warmer, less dense ambient waters. Thus, the current is well-behaved, but the water (which is what the satellite sees) sinks. This explanation is well supported by physical, biological, and especially chemical measurements made at sea.

All told, the Coastal Transition Zone program shows a nice example of the interplay of satellite oceanography with more traditional techniques. Remote sensing pointed out that there was an interesting phenomenon to be studied, but it gave a very incomplete picture. A thorough seagoing study filled in many of the holes, and led to further surprises. It is still too early to say whether our preliminary synthesis, presented above, is the complete answer to the filament problem, but as we analyze the more complete 1988 data set, we have a good deal of optimism that we will understand the basic processes involved.

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Circulation and Dispersion in Bays and Estuaries

Rocky Geyer

CONCERN for careful management of our coastal resources is broadly recognized as one of our nation's high priorities. In the oceanographic research community, there is an increasing focus on basic research issues that will help meet the management needs of the coastal environment in the coming years. Among fundamental scientific problems relating to research and management concerns are nearshore circulation and mixing of water, which influence virtually every facet of local ecology as well as sediment distribution, transport of toxic materials, and dispersion of sewage effluent. Our understanding of circulation and mixing is still very limited, due in large part to the overwhelming complexity of the response of coastal waters to numerous forcing variables, including tides, winds, runoff, and atmospheric heat exchange.

To address one of these issues, the effect of tides on horizontal exchange in embayments, several WHOI scientists in Ocean Engineering and Physical Oceanography have investigated the influence of a headland on tidal circulation and dispersion. The study involves an intensive field investigation of the flow around Gay Head, a promontory at the mouth of Vineyard Sound in southeastern Massachusetts, where tidal currents sweeping around the headland generate energetic eddies, which in turn have a profound influence on the mixing of water parcels. A satellite image of surface water temperature in Vineyard Sound and Buzzards Bay (opposite page, at right) provides evidence of numerous tide-generated eddies throughout the region, including a prominent swirl of warm water (arrow) extruding off the tip of Gay Head into the entrance of Vineyard Sound.

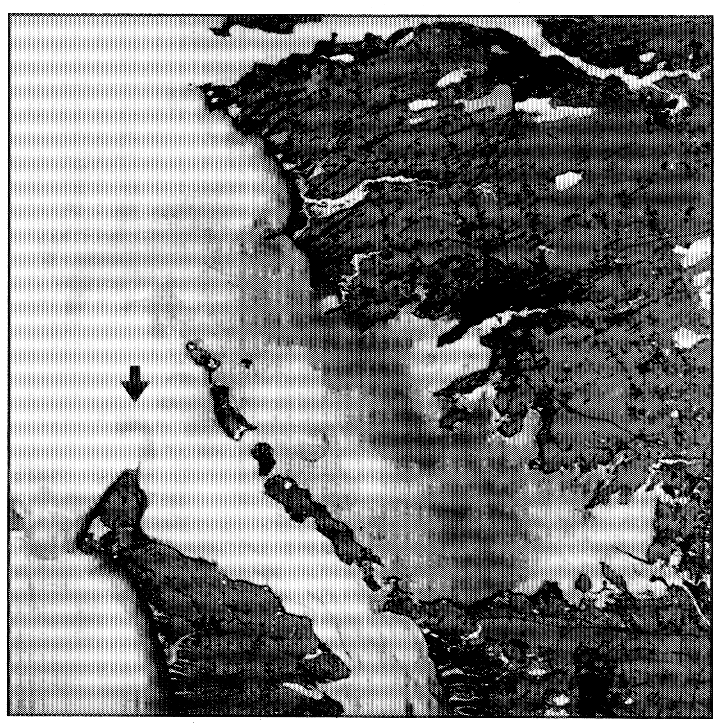
The task of measuring the detailed spatial structure of a flow that also varies rapidly in time is beyond the capability of such traditional oceanographic instruments as moored current meters, which provide detailed information at a few descrete points but tell little of the spatial variability. A relatively new type of current measuring device, the acoustic Doppler current profiler, or ADCP, provides a means of obtaining a virtually continuous record of the spatial structure of the currents from a moving ship. The drawing at right provides a schematic of the ADCP operation on WHOI's coastal research vessel, R/V *Asterias*. The instrument sends acoustic pulses down 4 separate beams, then receives the energy that echoes off small particles in the water column. A combination of analog and digital processing equipment in the instrument precisely measures the frequency shift (or Doppler shift) of backscattered sound resulting from the relative motion of the particles to the instrument. Since on average the particles are carried at the speed of the fluid, the Doppler shift provides a measure of the relative speed of the water to that of the ship. The speed of the ship is obtained by the Doppler shift of the bottom echo, which is then subtracted to obtain the true speed of the water.

The measurement program at Gay Head involved 8 cruises, each extending over a complete tidal cycle during which R/V *Asterias* repeated a closed track once per hour. Compiling the results of all of these cruises, a map of the current structure could be generated for any phase of the tidal cycle, indicating the structure of the currents at horizontal scales of several hundred meters to ten kilometers. One such map of the currents (top figure overleaf) indicates the current vectors at the time of maximum flood into Vineyard Sound. The current sweeps strongly past the tip of the headland and is carried by the inertia of the fluid toward the interior of the channel, producing an eddy on the downstream side of the headland. The point at the tip of the headland where the eddy meets the outer flow is a point of flow separation, where fluid that originates near the shore is carried into the interior of the flow. The influence of the flow separation on transport is clearly evident in the satellite image, which shows a dark patch of fluid being extruded off the tip of Gay Head.

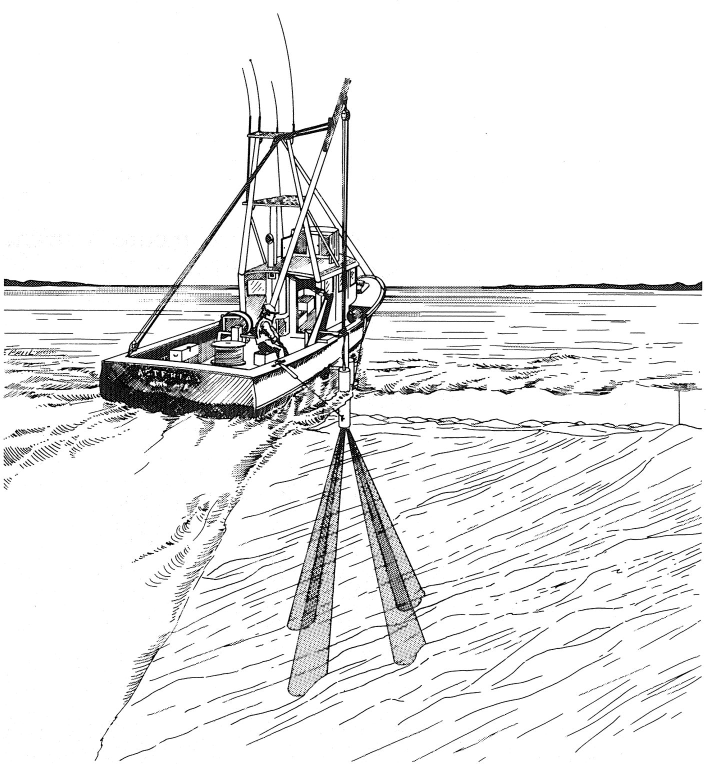
The mechanism for formation of these eddies is similar to separation in steady flows, such as the stall phenomenon with airplane wings. However, the time dependent nature of tidal flow brings additional complexity to the problem, as does the spatially varying bathymetry. This study addressed the mechanism of eddy formation in order to determine the important physical mechanisms responsible for the evolution of the rotational flow. We found that bottom frictional effects near the tip of the headland generate the "spin," but overall tidal characteristics determine the dimensions and structure of the eddies.

To further investigate the dynamics and the detailed nature of the flow field, we have developed a numerical model of tidal flow around a headland, using a CRAY supercomputer to provide the computational power required to handle the large range of spatial scales influencing the flow. This model allows us to test our hypotheses about the processes responsible for eddy formation at the headland, and to extend the results of the Gay Head study to idealized headlands and other case studies.

A further application of this model is the investigation of dispersion resulting from the complex flow around the headland. Performing



>Satellite image of surface water temperature in Vineyard Sound and Buzzards Bay shows evidence of eddies induced by tidal flow. Arrow points to a water parcel that has been carried by the tidal current off the tip of Gay Head and is being wrapped into an eddy.



<The acoustic Doppler current profiler is mounted on the side of *Asterias* for measurements of velocity structure in nearshore waters. Four transducers at the base of the instrument transmit narrow acoustic beams and receive the backscattered signal. The instrument converts the frequency of the backscattered signal to velocity, and a shipboard computer then stores and displays the data.

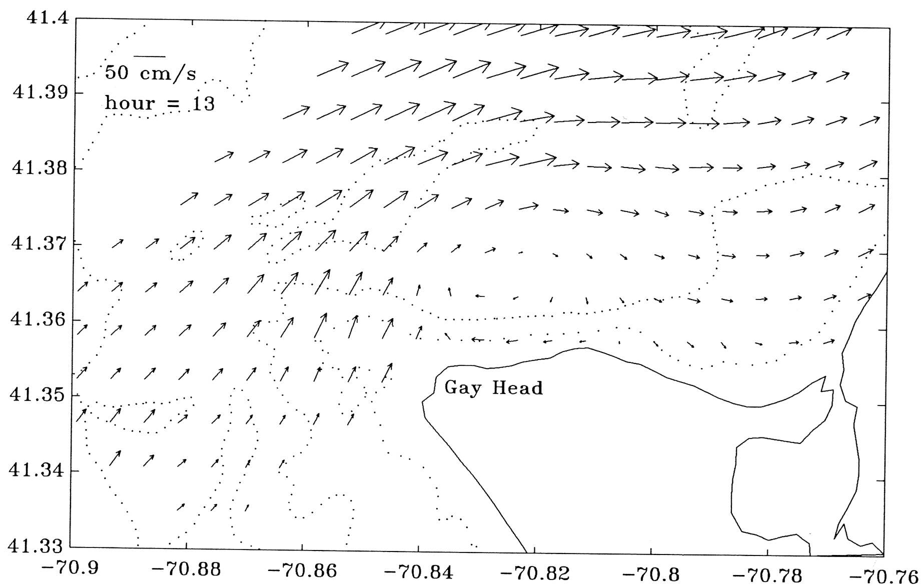
dispersion "experiments" in a numerical model has decided advantages over attempting the same experiment in a real system, since one can track virtually unlimited numbers of particles for many tidal cycles in a numerical model, while tracking real drifters in a tidal flow is a laborious and expensive undertaking. Figure 4 shows one such numerical drifter release. It illustrates the complex variations in distribution of particles subjected to tidal flow around a headland. Two patches of particles are introduced to the fluid at the same time, one just off the tip of the headland, and the other several kilometers further seaward. After six tidal cycles, the seaward patch has stretched slightly and has been carried a few kilometers from its release point. In contrast, the patch that started just off the headland has spread into many filaments that extend throughout the region of the eddies. The dramatic difference in the fate of these two patches is a consequence of flow separation, which provides a very efficient mixing mechanism to flow passing close to the tip of the headland. Patches of fluid that avoid the straining influence of flow separation may remain intact for many tidal cycles, while those that pass close to the headland may be stretched and folded across a broad spatial area.

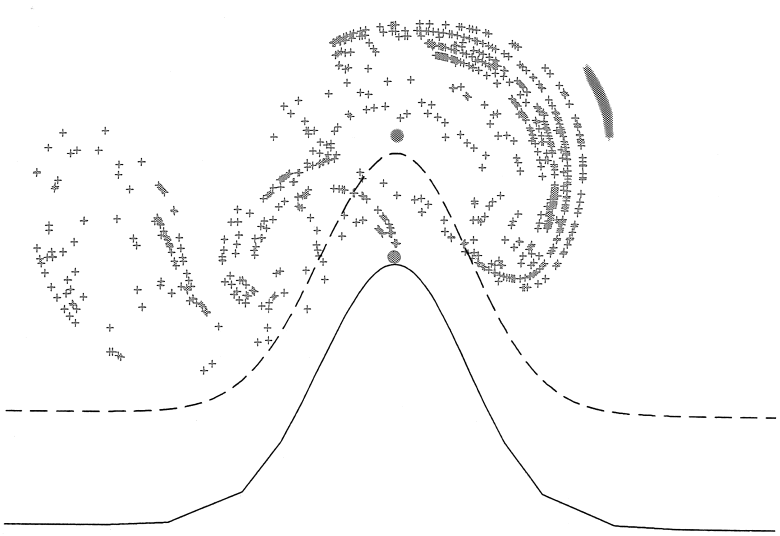
Tidal flow around headlands provides an interesting example of how physics may influence the fate of waterborne contaminants, and how one's intuition about the nature of transport processes may not reckon well with the complex distributions actually resulting from these deceptively simple flows. While our primary interest is in basic research questions involving the dynamics and kinematics of these flows, this research should provide a better understanding of the physical processes responsible for mixing and transport of pollutants in the nearshore environment.

Right: Current vectors one hour after maximum flood in Vineyard Sound were determined by compiling shipboard data from 8 cruises. Strong flood currents are evident in Vineyard Sound, but the current actually reverses in the nearshore region north of Gay Head due to the eddy generated behind the headland.

Below left: In this numerical simulation of dispersion at the tip of a headland, two patches of particles are released, one just off the tip, and the other offshore. After five tidal cycles, the offshore patch of particles has been stretched slightly and carried to the east, but the inshore patch has been dispersed througout the region with a complex, filamentous distribution.

Below right: Rocky Geyer stands near R/V *Asterias* at the WHOI pier.





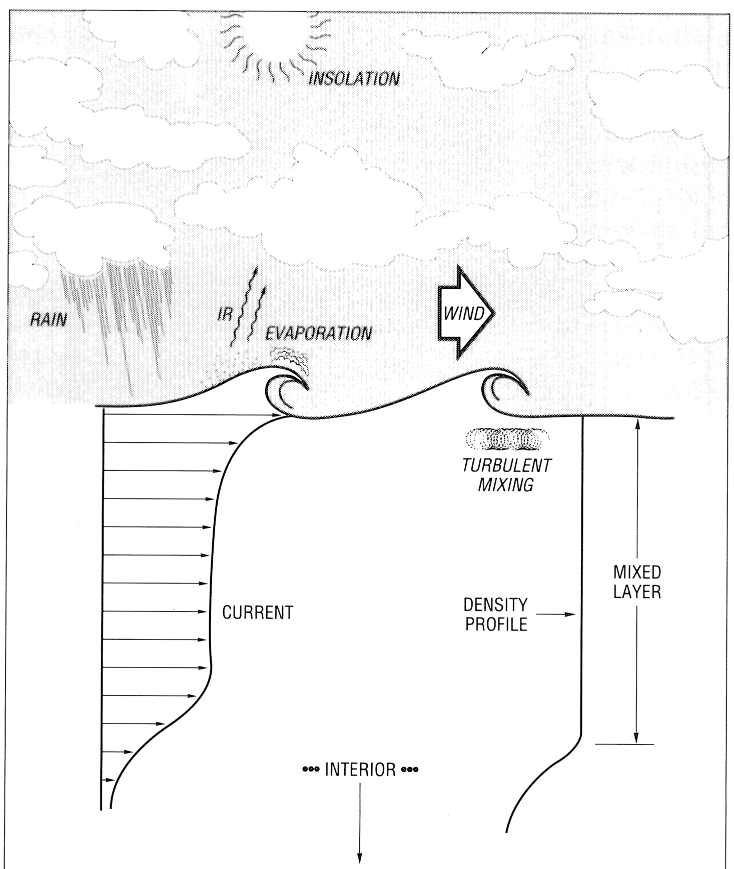
Rob Brown

The Surface Boundary Layer Over the Continental Shelf

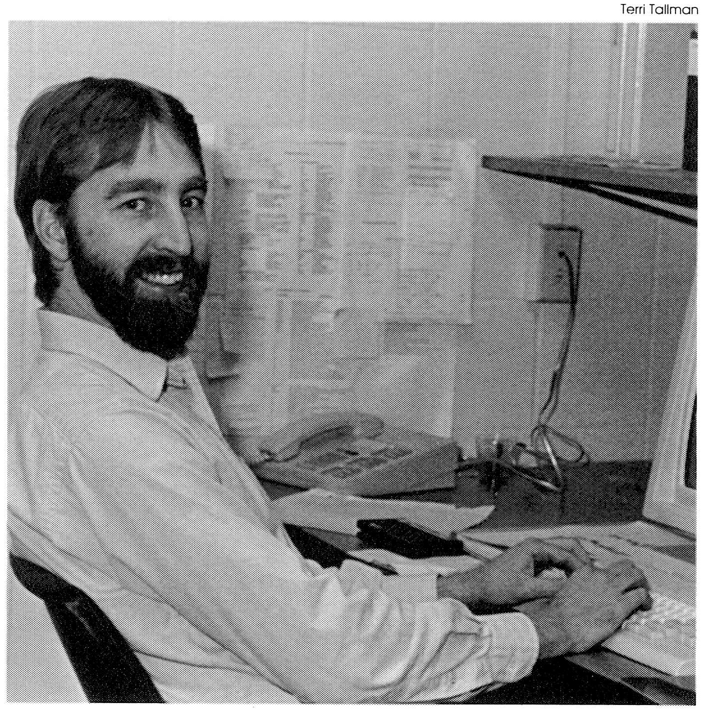
Steven J. Lentz

THE surface boundary layer can be defined as the portion of the ocean that responds quickly and directly to the input of momentum and energy from the atmosphere. Several components of this atmospheric forcing are shown schematically below. Momentum and turbulent energy from the wind generate currents, waves, and mixing in the surface boundary layer which is also heated and cooled by solar radiation (insolation), evaporation, precipitation, and infrared radiation (IR). This atmospheric forcing, transmitted through the surface boundary layer, is ultimately responsible for much of the interior circulation in the ocean and hence is an important process to oceanography in general. However, because of the winds, currents, and waves, the surface boundary layer is a difficult environment in which to make measurements, and it has only been in the last decade or so that instrumentation capable of making accurate measurements of the relevant oceanic and atmopheric variables has been available. This advance in measurement techniques has resulted in a number of experiments which have improved our understanding of the surface boundary layer over the deep ocean.

Relative to the deep ocean, our understanding of the surface boundary layer over the continental shelf is poor. Yet, the surface boundary layer plays an even more important role in the physics of the continental shelf than in the deep ocean. The surface boundary layer is typically a few tens of meters thick. While this is a relatively small fraction of the water column in the deep ocean, which is typically 4,000 meters deep, it comprises a substantial fraction of the water column over the continental shelf, which is typically less than 100 meters deep. The surface boundary layer is also a very important pathway for cross-shelf exchange over the continental shelf. Because of the Coriolis force (due to the earth's rotation), an alongshore wind tends to drive an onshore or offshore flow in the surface boundary layer over the continental shelf. Both of these aspects can be seen in the left figure on page 24 which shows wind vectors from a meteorological buoy and cross-shelf currents (color) from current meters at various depths below the meteorological buoy. These instruments were



Terri Tallman



Steve Lentz describes research in the surface boundary layer.

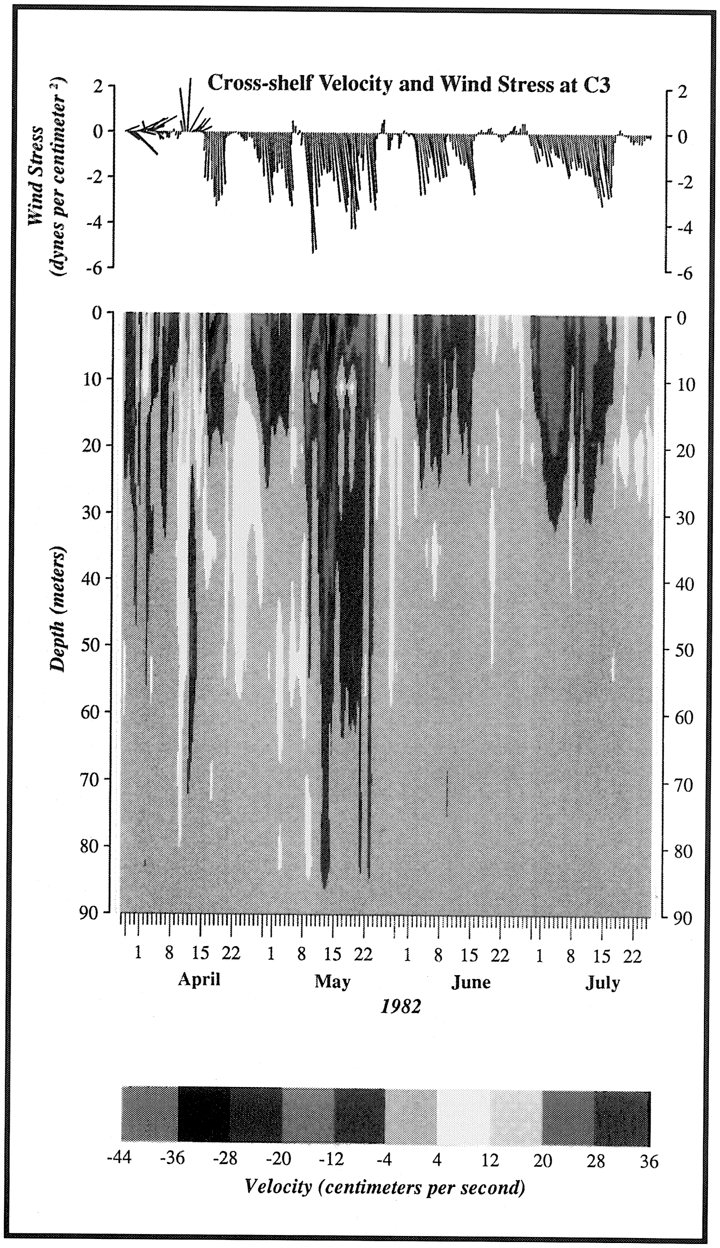
Schematic of various components of atmospheric forcing that influence the surface boundary layer.

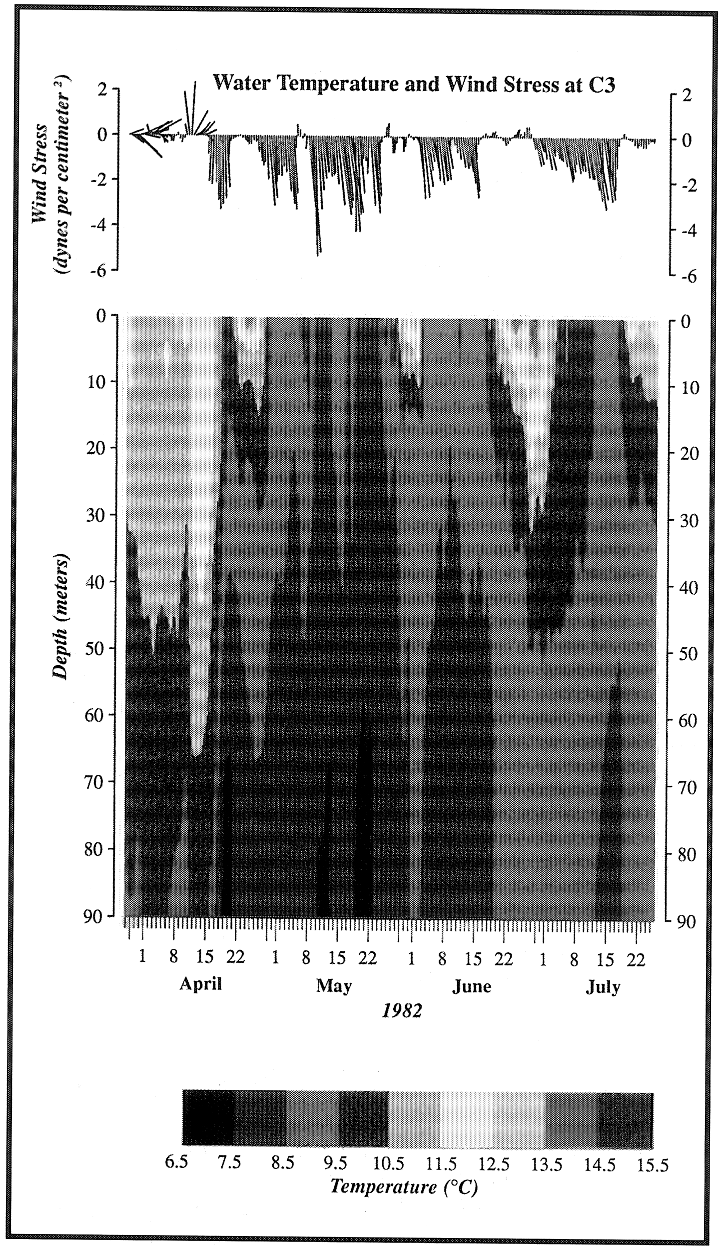
deployed over the northern California continental shelf (in 90 meters of water) during the summer of 1982 as part of the Coastal Ocean Dynamics Experiment conducted by a multi-institutional group of scientists and engineers. Note the strong offshore currents (dark green and blue) during winds toward the south and the

This figure shows a time series plot of the wind stress (vector stick plot at top) and cross-shelf current as a function of depth (color plot) from a mid-shelf mooring deployed over the northern California shelf during the summer of 1982 as part of the Coastal Ocean Dynamics Experiment. The orientation of wind vectors (stick plot) indicates the direction of the wind – vectors pointing toward the top of the page correspond to northward alongshore winds. The length of the vectors indicates the strength of the wind. Color contours of cross-shelf velocity are generated from instruments at depths of 5, 10, 15, 20, 35, 53, 70, and 83 meters. Yellows and reds signify onshore flow (downwelling) while dark green and blues signify offshore flow (upwelling). Note that the strong cross-shelf currents occur primarily in the upper 20 to 30 meters of the water column and correspond to wind events.

This is a time series plot of the wind stress (vector stick plot at top) and water temperature as a function of depth (color plot) from a mid-shelf mooring deployed over the northern California shelf during the summer of 1982 as part of the Coastal Ocean Dynamics Experiment and displayed in the same fashion as the adjacent figure. Color contours of water temperature are generated from instruments at depths of 1, 5, 10, 15, 20, 35, 53, 70, 83, and 90 meters. Yellows and reds signify warmer water while dark green and blues signify colder water. Notice the tendency for the near-surface water to warm due to solar heating when the upwelling favorable winds cease, and the correponding presence of colder water near the surface during upwelling favorable winds.

(Color contour plots prepared by Carol Alessi)





onshore currents (orange and red) during the northward wind event at the beginning of the time period shown. Also notice that the strong cross-shelf flows are generally concentrated in the upper 20 to 30 meters, about 30 percent of the water column, which corresponds roughly to the depth of the surface boundary layer.

Near the coast, water being carried offshore in the surface boundary layer is replaced by the upwelling of deeper water. Similarly, onshore flow of surface water results in downwelling. Upwelling is of particular importance biologically because it brings deep nutrient-rich water into the euphotic zone (the near surface region where there is enough light for photosynthesis) where it can be used by phytoplankton. This process is evident in the right-hand figure on page 24, which shows the temperature through the water column in the same fashion as the cross-shelf velocity is shown in the companion figure. During the southward wind (and offshore current) events, the water is relatively cold (blue). This is a signature of upwelling since the deep upwelled water tends to be colder than the near surface water. When the wind and offshore flow cease for a period, the near surface water temperatures begin to rise (green to red) due to solar warming. This solar warming is always present, and only the continual upwelling during southward wind events keeps the near surface water cold in the face of this heating. The enhanced productivity associated with coastal upwelling is evident in the fact that many of the world's major fisheries are located in coastal upwelling regions such as those off Peru and the west coast of the United States. However, the importance of the surface boundary layer over the continental shelf extends beyond coastal upwelling. For example, the cross-shelf currents shown are much stronger in the surface boundary layer than in the rest of the water column indicating that the surface boundary layer plays an important role in the dispersal of oil spills, sewage ou-falls, and other contaminants dumped over the continental shelf either intentionally or unintentionally.

These issues, and a general perception that our poor understanding of the surface boundary layer was a limiting factor in our understanding of the coastal ocean, led a group of us at Woods Hole Oceanographic Institution, including Robert Beardsley, Sandy Williams, Eugene Terray, Richard Limeburner, and myself, to propose to the National Science Foundation a field study focusing specifically on the surface boundarylayer over the continental shelf. The study, called the Shelf MIxed Layer Experiment (SMILE), includes a field experiment over the northern California shelf from November 1988 to May 1989. As part of SMILE, a variety of atmospheric and oceanic instruments were deployed over the continental shelf to measure the important components of the atmospheric forcing and the oceanic response. Observations from these instruments, complemented by both shipboard and aircraft surveys of the study region, will aid us in ultimately understanding the surface boundary layer response to atmospheric forcing over the continental shelf.

STRESS, a Sediment Transport Study on the Shelf

Albert J. Williams 3rd

SEDIMENT on the continental shelf is subject to fluid stress from currents and long period waves. If the stress exceeds the strength of the sediment, material is suspended and then carried along by the current until it settles out again where the stress is low. This sediment transport process also occurs in rivers, on beaches, and in the deep sea. In the deep sea, the wave stress can be neg1ected, but on the shelf, in 90 meters depth for example, long period waves penetrate to the bottom. The oscillatory currents, reversing every 8 to 10 seconds (16 to 20 second waves) create a thin wave boundary layer (10 centimeters thick) which enhances the stress and makes the bottom appear rough to the current due to turbulent eddies spawned by the high stress region. In boundary layer models, waves increase the effective surface roughness.

A decade ago it was hypothesized that waves would increase the effective stress on the sediment, lowering the threshold for erosion, and this was tested in the Coastal Ocean Dynamics Experiment (CODE) in 1981 and 1982. Sediment at the CODE site, on the northern California shelf, is silt from the Russian river 20 miles southeast. Its presence at the CODE site implies there is sediment transport along the shelf. A number of investigators including Dave Cacchione at USGS in Menlo Park, Arthur Nowell at University of Washington, and the late Bill Grant at WHOI postulated that the sediment moved during winter storms when the long period waves were exceptionally high. An ONR sponsored experiment, STRESS (Sediment Transport Events on the Shelf and Slope), was devised to test this hypothesis and to determine precisely the conditions responsible for this transport. The experimental phase began in November 1988 when 6 tripods and two current meter moorings were placed on the bottom to measure current and waves, bottom stress, concentration and distribution of suspended sediment, and flow structure. All of the measurements were recorded internally in some form but some were transmitted ashore for interactive control of the measurement program and to obtain higher frequency detail in the data. The figure below shows this scheme with acoustic links from tripods to surface buoys and radio links from the buoys to the shore station.

Telemetry of data ashore is possible in the coastal zone using VHF or UHF radio because the distances are line of sight with an elevated receiver on shore. STRESS included a test of this combined acoustic telemetry and radio telemetry link. Half hourly reports of average quantities such as current, stress, turbulence levels, optical turbidity, temperature, pressure spectrum, and velocity spectrum were transmitted by the tripod to the buoy and relayed ashore for recording on a computer at the shore station. These data were reviewed by the operator, and based on the concentration of suspended sediment, current, and wave velocities, the operator could send a radio command to the buoy for relay as an acoustic command to the tripod to transmit raw data for 30 minutes. Only 90 hours of such transmission was possible before replacing the batteries in the buoy, so it had to be judged carefully. However, during a storm event, the data could be acquired ashore for high frequency analysis.

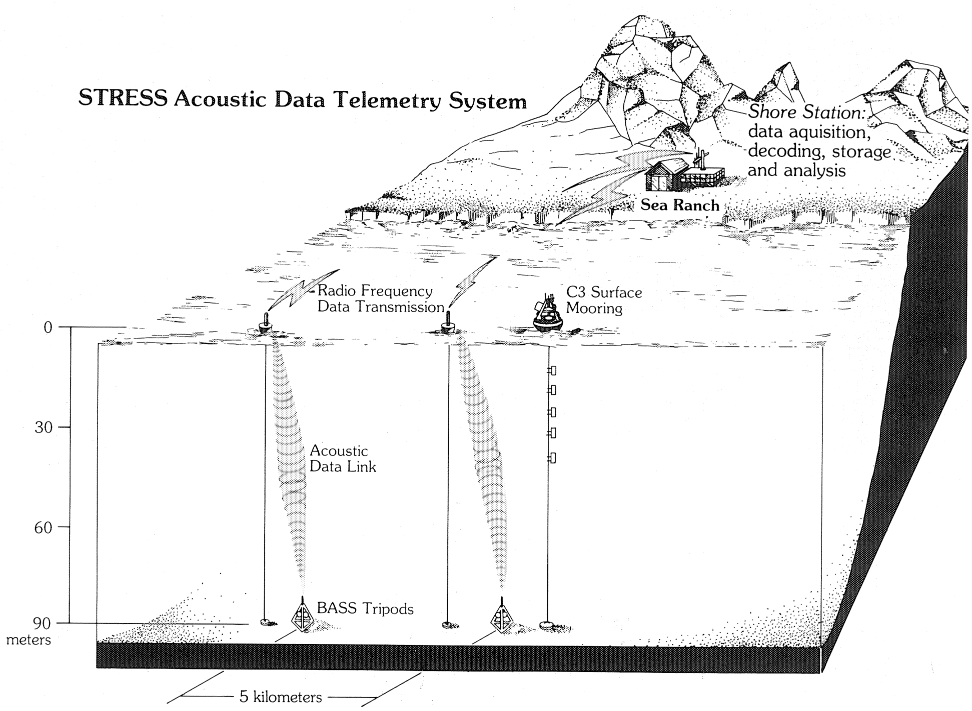
The open coastal regime differs from the deep sea in several important ways besides depth. The boundary supports "edge waves," for example. These are experienced as currents that rotate in direction at a fixed location but propagate along the coast. Moored arrays can resolve these edge waves and their propagation can be predicted. Another difference is upwelling. The boundary at the shore forces subsurface water or even bottom water to upwell when there is offshore surface wind stress, that is, when the wind is in the northern sector between northwest and east. While these distinctions are important for transport of material in suspension, they are only indirectly of consequence to the bottom stress that suspends sediment. There, it is the magnitude and frequency of the waves and the angle between the current and the waves on the bottom that is significant. Existing models of the wave/current interaction do not consider this angle, but this is an oversimplification, and angle as well as the actual mix of waves is probably significant. Stratification of the boundary layer by sediment in suspension influences the bottom stress by providing a mechanism for dissipation of turbulence; the sinking of dense particles removes from the boundary layer energy that was put into it by turbulence derived from velocity shear. Thus there are effects not now considered that are important when modeling boundary layer stress under waves with suspended sediment. These will be studied in the data sets from STRESS.

Silt, the fine noncohesive material carried down the Russian River, is found in a band along the shelf centered at 90 meters depth. However, the band does not extend as far north as Point Arena – the silt is building up, not moving, or going offshore before reaching Point Arena. Its fate depends on the current conditions after it is eroded. If winter storms put the silt into suspension, and if these storms are generally associated with alongshelf currents, the silt should move

Ellyn Montgomery

Joint Program Student Markuu Santala prepares a tripod for the STRESS experiment.

E. Paul Oberlander



The acoustic data telemetry system for the STRESS experiment includes acoustic links from tripods to surface buoys and radio links from the buoys to the shore station.

along the shelf. It is not the principal goal of STRESS to track the motion of sediment on the California coast – rather, it is to discover the correlation of erosion with current during winter storms and the correlation of erosion with storm waves.

The STRESS array of instruments and tripods reflects the measurements required for boundary layer studies. There is an acoustic current meter array, BASS (see glossary below), to measure stress, current, and waves in the bottom 5 meters. A model for most of the STRESS tripods, the BASS tripod is 18 feet tall and 12 feet on a side. There is an acoustic backscatter sensor, ABSS, to measure the distribution of suspended sediment in the bottom 20 meters. This is mounted on a separate tripod. There are three instruments measuring suspended particle properties on the ABSS tripod: ROST, LISST, and OBS. ROST captures a sample of water once a day and tracks the rate at which particles settle out of the captured volume; this gives the concentration weighted settling velocity, the quantity needed for the sediment stratified boundary layer model. LISST obtains the particle size distribution by the angular spread of scattered laser light. OBS pumps a water sample into a plastic bag for later analysis when the turbidity (measured optically) exceeds a threshold. A third tripod carries a laser Doppler velocimeter (LDV) for turbulence and stress measurements within a few centimeters of the bottom. This is the only velocity sensor that has a chance of making measurements in the wave boundary layer. For reasons of greater water clarity, so the laser beam can penetrate to the bottom, the LDV tripod is deployed at 50 meters depth, closer to shore, on a sand patch. On a fourth tripod, Geoprobe, the optical turbidity, a measure of suspended particle concentration at a single level, is correlated with the current measured from an array of four electromagnetic current sensors. This gives a direct sediment flux measurement. A scanning SONAR is mounted to a fifth tripod to correlate acoustic backscatter from the bottom with sediment transport events. This takes advantage of the observations of benthic storms made by all the instruments to support the acoustic measurements. A stereo camera on a sixth tripod documents the gain or loss of sediment and the bedforms in which the sediment is formed during storms.

Terri Tallman

Sandy Williams works on a Benthic Acoustic Stress Sensor (BASS) in his laboratory.

Currents are excited by wind set up and tides; internal waves and edge waves propagate into the area from the greater coastal region. Moorings, with current meters spanning the entire water column, complete the set of STRESS sensors. The layers, fronts, and edge waves responsible for inhomogeneity in the currents will be sorted out with the observations from the moored arrays.

The five tripods and two moored arrays were placed in November 1988 for recovery in March 1989 with a turnaround cruise in January to change batteries, tapes, and films. The results of the first STRESS experiment will be analyzed in the next year and a second deployment of the STRESS instruments, modified by the understanding gained from the first deployment, is planned for the winter of 1990-91.

STRESS is an example of coastal work undertaken by the marine community after first addressing a simpler problem in the deep sea. The High Energy Benthic Boundary Layer Experiment, HEBBLE, obtained similar measurements, except for waves, in the mid 1980s at 4800 meters depth off the Nova Scotian rise. Our experience there indicated that sediment transport was highly intermittent and occurred in response to benthic storms, times when the stress and current were extreme. However, the picture was complicated by horizontal structure in the storms, The boundary layer behaved well locally and could be predicted from velocity and bed roughness, but the concentration of suspended sediment depended on depositional history and what the stress was off stage, where it was not being measured. Moving the experiment to the shelf added a different complexity but addressed a need, the understanding of how waves and current combine to generate the stress and other conditions that erode and transport sediment.

Glossary

ABSS: Acoustic Backscatter Sensor
BASS: Benthic Acoustic Stress Sensor
CODE: Coastal Ocean Dynamics Experiment
HEBBLE: High Energy Benthic Boundary Layer Experiment
LDV: Laser Doppler Velocimeter
LISST: Light In Situ Scattering Transmissometer
OBS: Optical Backscatter Sensor
ROST: Remote Optical Settling Tube
STRESS: Sediment Transport Events on the Shelf and Slope

Generation of Coastal Seiches by Deep-Sea Internal Waves

Graham S. Giese and David C. Chapman

MANY harbors around the world experience sea-surface oscillations with frequencies intermediate between those of the astronomical tides (1 or 2 oscillations per day) and wind-produced swell (say 2 to 10 oscillations per minute). These intermediate-frequency sea-surface oscillations, which may occur from less than once to as many as 10 times per hour, are known as coastal (or harbor) seiches. They result from the sloshing back-and-forth of harbor water in a manner similar to the sloshing of water in a lake or soup in a bowl. Large seiches can result in severe damage to harbor facilities, and occasionally loss of life, due to unexpected and rapid changes in water level. But their greatest potential for destruction lies in the swift and presently-unpredictable currents they can induce in the often-restricted waters at the harbor entrance. Such unanticipated "rogue" currents can wrest control from the most cautious harbor pilot and set a heavily-laden ship drifting towards shoals or submerged reefs.

Almost all harbors experience seiching to a degree, but in some the sea-surface oscillations due to seiches can exceed those produced by ordinary tides. Seiches ranging in height between 2 and 3 meters have been reported in recent years from the western Mediterranean, the Gulf of Bohai in China, and the Sea of Japan. Because of their destructiveness, the waves are often identified by special names, such as "seebär" in the Baltic, "resaca" in the Mediterranean, and "abiki" in Nagasaki Harbor, and much effort has been devoted to their prediction. Most researchers believe that large harbor seiches are excited by the arrival of long deep-sea surface waves generated by such meteorological processes as storm winds or sharp, rapidly-moving atmospheric pressure jumps.

In contrast to this prevailing view, we have evidence that large coastal seiches are excited by deep-sea internal waves generated by tidal currents. Our evidence has been derived in part from measurements made along the Caribbean coast of Puerto Rico and the Sulu Sea coast of Palawan Island in the Philippines, and in part from theoretical studies that provide a dynamical mechanism for the transfer of energy from deep-sea internal waves to coastal seiches. Based on our results, we expect that practical seiche predictions will be a reality in the near future.

The basic mechanisms involved in our model of seiche generation in Puerto Rico are illustrated in Figure 1. As tidal currents flow over seamounts on Aves Ridge, part of their energy is used in the formation of internal lee waves (A) which, after the tide turns, propagate northwestward (B) across the ridge toward Puerto Rico. As they travel, the waves form into packets of "solitary waves" (C) that maintain their form with little change over time . After about 5 days of travel, the packets reach the island slope south of Puerto Rico (D) where they break. Part of their energy is reflected seaward, part is dissipated as turbulence, and part is transferred to oscillations – seiching – of the island shelf water.

The instrument stations used for measurements of various phenomena related to this process are depicted in Figure 2. Expendable bathythermographs (XBTs) deployed 5 kilometers off the shelf edge were used to record the solitary waves, while a moored array of thermistors closer to the shelf was employed to measure the turbulence created by wave breaking. At the shelf edge, a current meter recorded the seiche-induced cross-shelf currents, while the sea-surface oscillations produced by seiching were recorded on a tide gauge at the shoreline.

The cross-shelf currents recorded at the shelf edge and the coastal sea-surface oscillations observed during a period of particularly active seiching are shown in Figure 3. The dashed line in Figure 3 (lower) shows the cross-shelf currents that theoretically would be expected to be produced by the observed coastal sea-surface oscillations. While the match between the two lines is sufficiently close to confirm that the cross-shelf currents are primarily due to seiching, other factors

Terri Tallman

Graham Giese is at left, and Dave Chapman is at right.

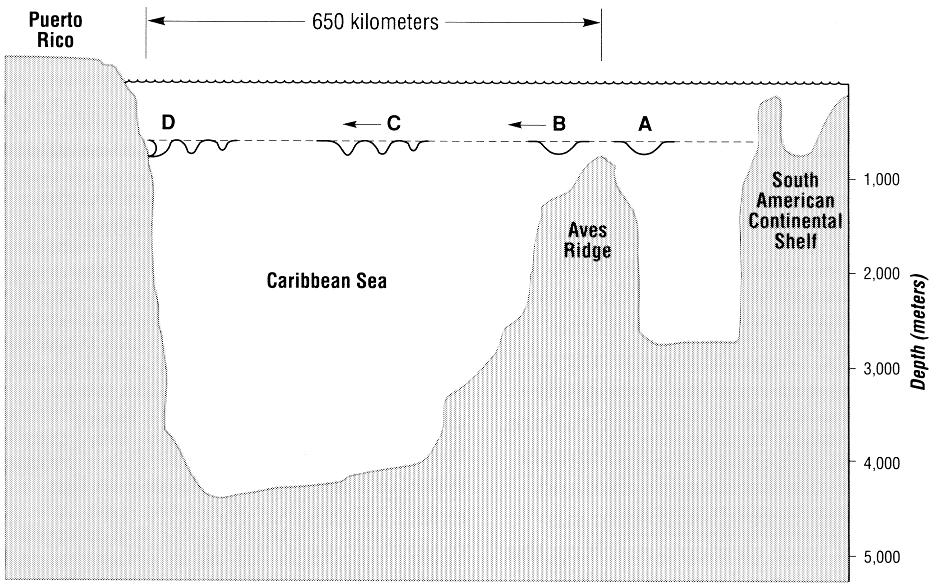
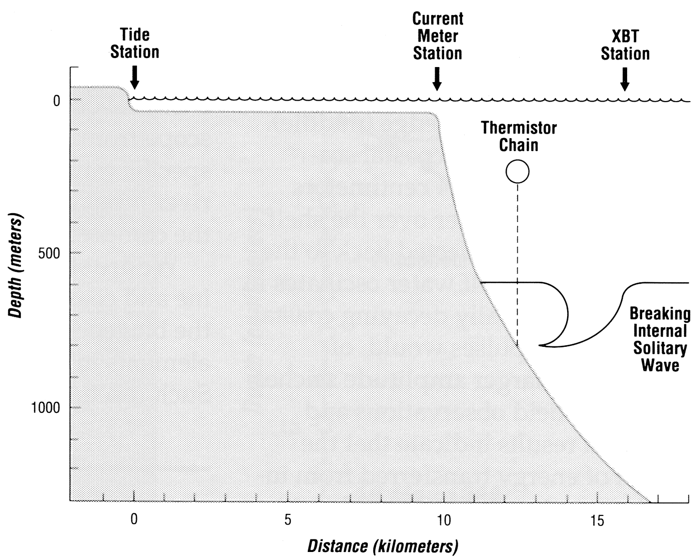


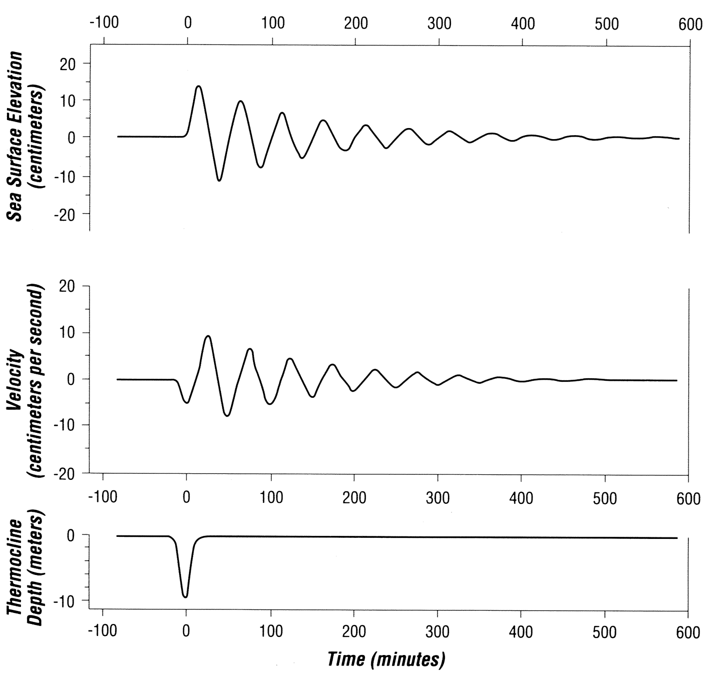
Figure 1 (above): Tidal currents over Aves Ridge produce internal lee waves (A) that propagate northwestward when the tide turns. Five days later the internal waves break (D) on the island slope south of Puerto Rico and produce coastal seiching.

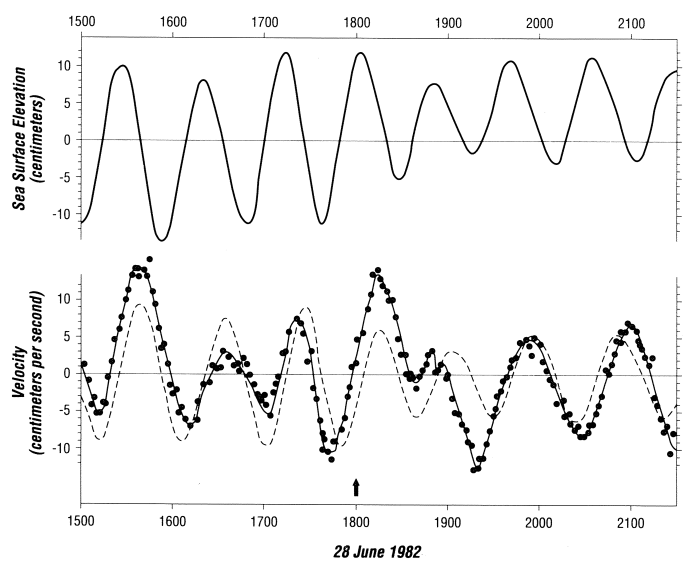
Figure 2 (right): Instruments were deployed on the shelf and slope south of Puerto Rico to record the relationship between incoming internal waves and coastal seiches.

Figure 3 (below right): Fifty-minute sea-surface oscillations (top curve) recorded at the coastal tide station, and cross-shelf current oscillations (bottom solid-line curve) recorded at the shelf edge are 2 manifestations of the seiches generated by Caribbean internal waves.

Figure 4 (below left): Results of theoretical modeling demonstrate that a deep-sea internal wave (bottom) arriving at the shelf south of Puerto Rico can produce 50-minute sea-surface oscillations (top curve) and cross-shelf current oscillations (middle curve) similar to those observed (Figure 3).







influence currents at the shelf edge. For example, the arrow at 1800 hours indicates the time at which a large internal wave was observed at the XBT station (Figure 2), and the flow disturbance at the shelf edge shortly after was probably caused by its arrival.

Our idealized theoretical model shows that the observed deep-sea internal waves can efficiently transfer enough energy into coastal seiches to account for the observed shelf-edge currents and coastal sea-surface oscillations. An example, representative of the Puerto Rican case, is shown in Figure 4. A single internal wave pulse with an amplitude of 10 meters (somewhat small compared to observed solitary waves) impinges upon the continental slope at time zero (bottom). The water above the pulse is pushed onto the shelf creating a shoreward velocity of 5 centimeters per second at the shelf edge (middle). Shortly thereafter, the coastal sea-surface rises (top) to 14 centimeters due to the excess water over the shelf. After the pulse is reflected back to the deep ocean, the shelf water oscillates in the form of gradually decaying coastal seiches. Larger pulses would, of course, excite larger amplitude seiches.

Both our field observations and theoretical results indicate that the amount of energy transferred from internal waves to seiches depends critically on the geometry of the shelf and slope and on the density stratification characteristics of the seawater. Some of our effort in1989 will be devoted to a cooperative study with Philippine scientists to develop a better understanding of these energy-transfer mechanisms at Puerto Princesa on Palawan Island. We will also expand our theoretical model to include a better representation of the complexities of realistic coastal form and water density characteristics, and we will continue our analysis of seiche data from harbors around the world. Our recent results indicate that seiching in Los Angeles and other major harbors also is forced by internal waves, and we anticipate soon applying the results of our research in these areas.

Estuarine Chemistry of Trace Elements

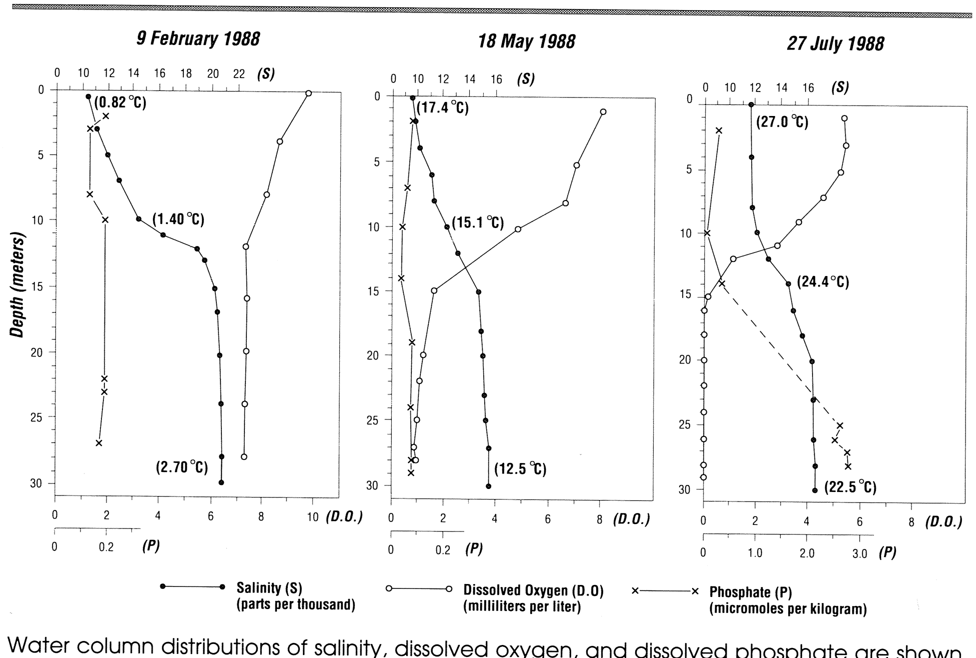
Edward R. Sholkovitz

RIVERS are important to the chemistry of the ocean because they provide large – in many cases, the major – flux of chemicals to the ocean. Both natural processes, such as mechanical and chemical weathering of continental rock, and anthropogenic activities, such as industry, agriculture, and sewage, introduce trace elements into rivers. The net riverine flux and the chemical form (dissolved or suspended) of trace elements reaching the oceans can be greatly modified by chemical and biological reactions operating in estuaries. Hence, estuarine chemistry, as a subdiscipline of chemical oceanography, ranges in scope from pollution studies of a specific estuary to the influence of river input and estuarine reactions on the composition of the global ocean.

We are studying the role of estuarine and coastal processes in regulating the biogeochemical cycles of trace elements in the marine environment. Such reactions include coagulation, adsorption, oxidation and reduction, and diagenetic (post depositional) mineral formation in sediments.

Chesapeake Bay, the site of some of our work, is the object of considerable scientific study because the "health" of the Bay has declined over the past decade. Reduced catches in major fisheries (crabs, clams, oysters, certain types of fish) and an increase in the extent of seasonal anoxicity (lack of oxygen) in deep waters are of major concern. It is generally accepted that increased riverine input of nutrients (nitrogen and phosphorus) from agriculture and sewage have made the Bay more eutrophic. This higher productivity in plankton and algae drives more extensive retention and recycling of nutrients within the Bay which, in turn, results in more extensive loss of oxygen from the deep waters.

The seasonality in the oxygen concentration of the upper Bay's deep basins is a major biogeochemical



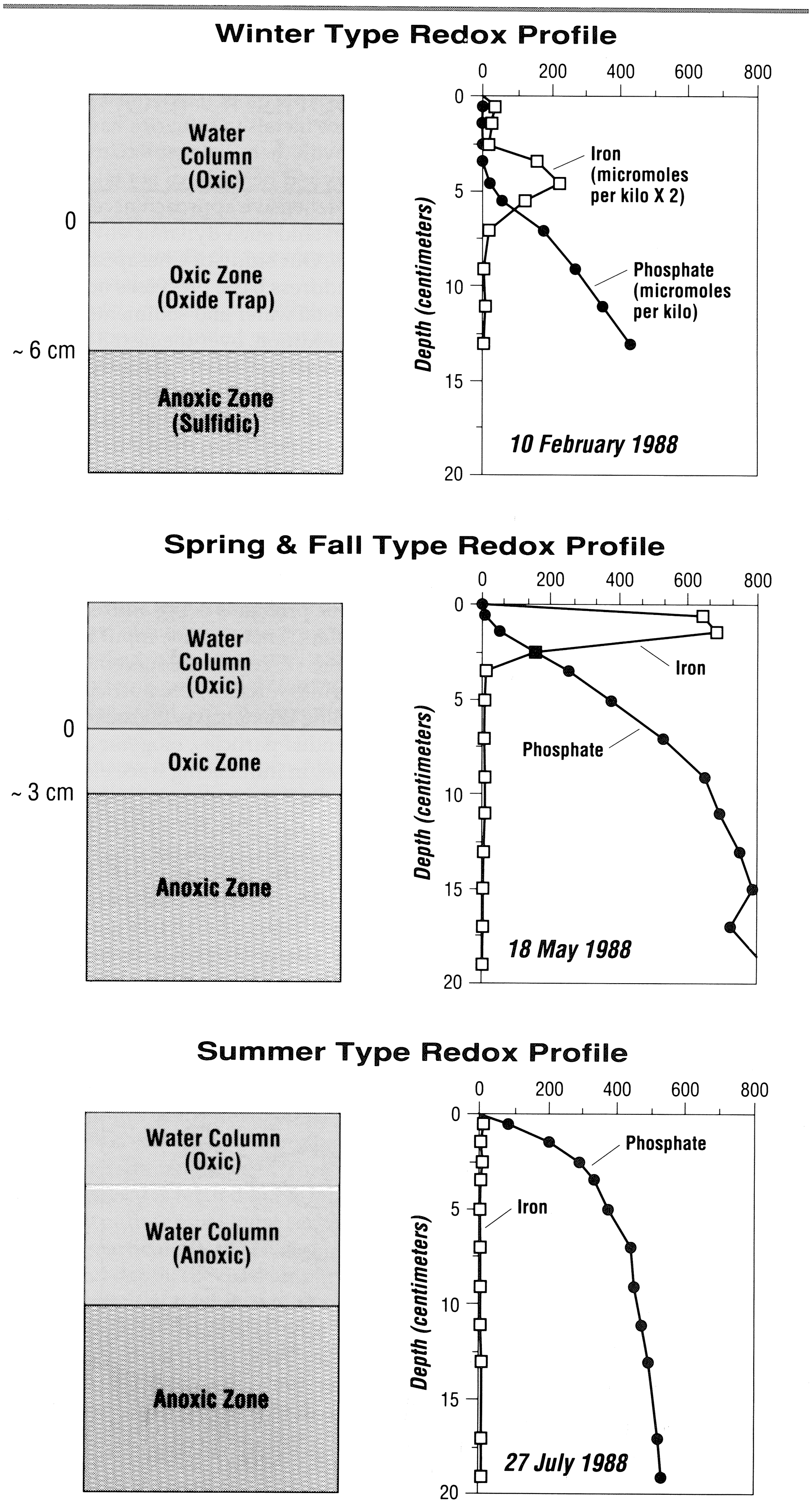
Water column distributions of salinity, dissolved oxygen, and dissolved phosphate are shown for a northern basin of Chesapeake Bay near Annapolis, MD. These three profiles from February, May, and July 1988 are typical of different seasons.

feature. It is driven by the coupling of density stratification and decomposition of oxygen-consuming organic matter. Oxygen depletion begins with salt stratification caused by the spring increase in water discharge from the Susquehanna River. As deep waters warm with the season, there is an increase in the rate of oxygen consumption. The deep basin waters become increasingly depleted in oxygen and finally anoxic during the summer. Beginning in early fall and continuing through the winter, the deep basin waters are again oxygenated.

Along with WHOI Postdoctoral Investigator Timothy Shaw, my laboratory is studying the coupling of this seasonal reduction-oxidation (redox) cycle and the cycling of trace elements. While our main focus will be on the rare earth elements (lanthanum through lutetium in the periodic table), we also intend to study more common trace elements – copper, nickel, cobalt, chromium, molybdenum.

To track the large-scale seasonal variations in the Bay, we sampled the water column and sediments from two deep (30 meter) upper Bay basins on 12 cruises from February 1988 to January 1989. Profiles of dissolved and particulate phases were obtained from the water column while pore water (water contained in the sediments) profiles were obtained from the upper 20 centimeters of sediment cores. With these profiles we are now in a position to follow the cycling of trace elements in the upper Bay.

The figures at right and left illustrate some of the major seasonal variations in the water column and pore waters from our north basin site



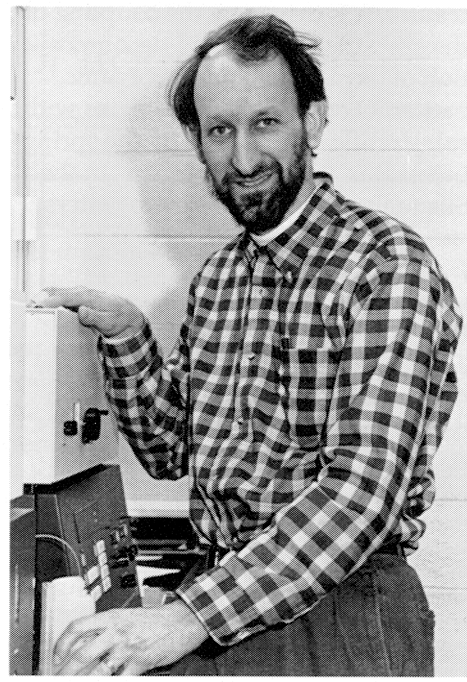
>This figure shows oxidation conditions and pore water composition typical of different seasons in the north basin of Chesapeake Bay. The left side shows thinning of oxidized (brown) surface sediment and development of anoxic (black) sediment and bottom waters. The right side shows pore water profiles of iron and phosphate indicating the removal of iron (when sulfides are generated) and upward migration of high phospate concentration in spring and summer.

off Annapolis, Maryland. Increases in phosphate and ammonia concentrations accompany the development of anoxia in the deep waters. The upper 10 centimeters of the sediments undergo dramatic color changes and chemical pore water cycles (figure page 31). In February, the upper 6 centimeters of sediments are brown in color; these oxic sediments overlay black anoxic sediments. During the spring, the brown color of sediments thins upward until the sediments are black at the sediment-water interface in June. The sediments remain black (from iron sulfides) throughout the summer, and then the brown (from iron oxides) layer thickens as the bottom waters become oxygenated in the fall. The transition from oxic to anoxic (sulfidic) conditions in the upper sediments plays a critical role in the recycling of nutrients (phosphate and ammonia) back to the water column. The "oxide trap" near the interface is very effective in limiting or stopping the transport of phosphate from the sediments to the bottom water. Our pore water profiles of iron and phosphate confirm this point. During a seasonal cycle, the oxide trap in the sediments thins, vanishes, and then reforms and deepens. In the summer, bright red iron oxide particles are observed in the water column near the salt gradient; hence the oxide trap moves into the water column as the bottom waters become increasingly reducing to ferric iron in the summer.

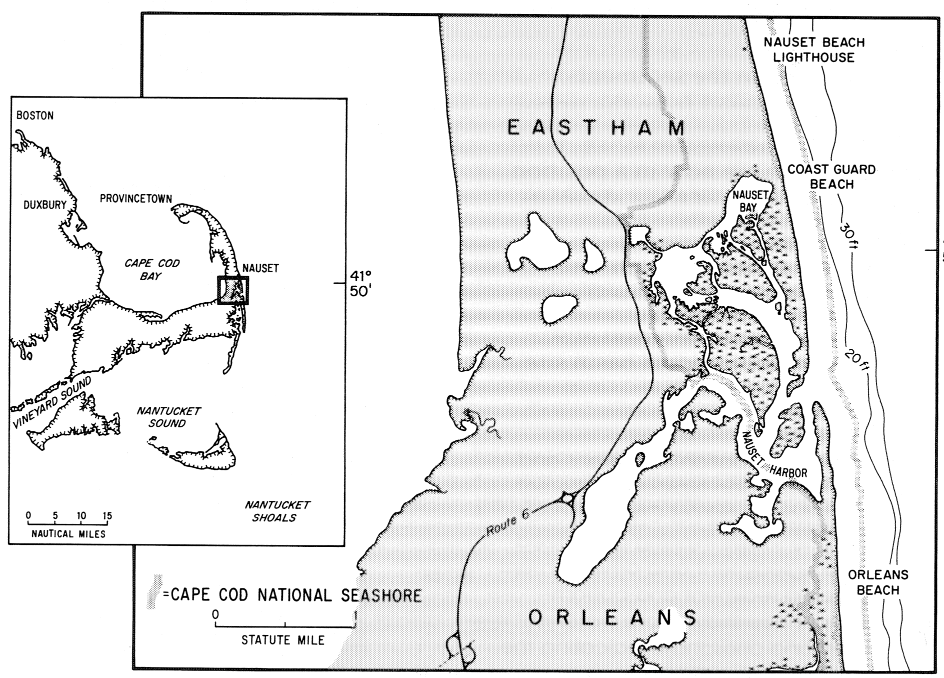
The concentration and flux of trace elements will certainly respond to the redox cycles operating in Chesapeake Bay. Many trace elements, such as copper, nickel, cobalt, and molybdenum, form insoluble sulfides and are adsorbed onto iron oxides. Rare earth elements, for example, have extremely high concentrations in anoxic pore waters, form complexes with phosphate and adsorb onto iron oxides. With samples covering a year, we should be able to follow the biogeochemical cycles of many trace elements and identify the water column and sedimentary processes regulating the concentration and fluxes of trace elements. At present, trace metals do not represent an environmental problem in the main part of Chesapeake Bay. On the other hand, most studies of trace metals in estuaries have dealt only with their distribution in surface waters and hence have not taken the comprehensive approach necessary to understand such dynamic environments. Our study of Chesapeake Bay will address basic processes occurring in coastal water and sediments.

In addition, over the next 3 years, my laboratory will be involved in a study of trace elements (rare earth elements, in particular) in the Amazon River estuary. Data from 3 to 4 "AmasSeds" Project cruises in the estuary of the world's biggest river (with respect to water discharge) should enhance our understanding of trace metal cycles at a globally important level. Specific problems being addressed include: (1) net riverine input to the Atlantic, (2) regeneration in the deep estuarine waters where nutrient recycling is extensive, (3) role of suspended particles, biogenic and detrital, in influencing trace element cycles, and (4) pore water profiles and regeneration near the sediment-water interface. This study will be tied closely to sedimentological and physical oceanographic investigations of the Amazon estuary and shelf region.

Terri Tallman



Ed Sholkovitz at the atomic absorption spectrometer in his Redfield Laboratory.



Nauset Inlet on Cape Cod, MA, is representative of the small coastal systems being studied by the authors of the article that begins at right.

Research on Nearshore Process: Eroding Shorelines and Global Changes

David G. Aubrey and Graham S. Giese

CONSIDERABLE research at the Woods Hole Oceanographic Institution has been conducted in shallow nearshore waters, the critical interface between land and oceanic processes. Freshwater runoff, sediments, and pollutants are transferred to the deep ocean primarily through the coastal zone. These exchange processes, and the interaction between the deep oceans and the continents, form the basis for our nearshore studies.

Because the processes occurring at this interface have such a rich spectrum of space and time scales, quantitative models of nearshore processes are difficult to derive with much accuracy. For instance, sediment transport along a beach may involve the interaction of breaking waves with tides, storm surge, and wind. Water motion that moves sediment responds in a complex fashion to these different time scale events, ultimately decaying to turbulence that itself is responsible for maintaining sediments in suspension. Our theoretical and experimental knowledge of the interaction of these different forcing functions is incomplete and is likely to remain so for the next decade and more unless study of these processes receives significant national focus.

The complexity of the nearshore environment mandates use of many different approaches, including field observations, laboratory experimentation, and a multitude of theoretical avenues. The examples presented below illustrate some of the diverse means used to study complex nearshore phenomena. The specter of global climate change and its impact on the densely inhabited coastal zone argues strongly for increased emphasis on this research area.

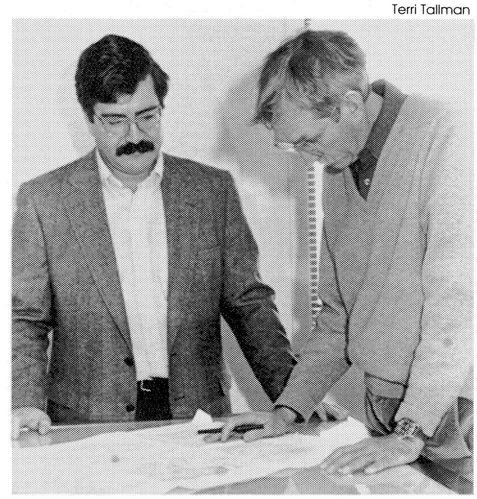
Our work has largely focused on three areas over the past decade. These are tidal inlets and estuaries, shoreline erosion, and climate change impacts on the coastal zone.

Tidal inlets and estuaries: While most of the nationally-funded estuarine research effort in the United States has centered on large scale systems such as Chesapeake Bay and Puget Sound, most of the lagoons and estuaries found along our shorelines have lengths on the order of 10 kilometers or less, and depths of less than 10 meters. To help bring some balance into the science, our research group has focused on these smaller systems that are at the heart of many resource management problems plaguing small coastal communities. Nauset Inlet (figure at left) on Cape Cod, which separates two barrier beaches that protect a productive salt marsh from the open Atlantic, is representative of the scale of the systems we have studied.

These shallow systems can export or import sediment from the nearshore zone and deeper continental shelf. Large estuaries are thought to be sources of continental shelf sediment, while shallow systems tend to remove sediment from the nearshore, increasing the coastal sediment deficit. Large shoals both within and just outside the inlet result from trapping of sediment in the confines of the inlet and estuary system, thus removing it from the nearshore sediment budget. This trapping efficiency is related in part to the geometry of the embayment served by the inlet, particularly the channel length and depth, the tidal amplitude, and the extent of tidal flats in the system. Estuaries having shallow depths compared to the tidal amplitude tend to import sediment more efficiently than do systems with greater water depths compared to tidal amplitude, and those having extensive tidal flats. This geometry causes tide distortion, so the duration of flood tide and ebb tide no longer are equal (as they are on the continental shelf). This tidal distortion may be: 1) flood dominant, wherein the flood tide has a shorter duration but stronger currents than the ebb tide, or 2) ebb dominant, wherein the ebb tide has a shorter duration but stronger currents than the flood tide. This distinction is an important one for evaluating the sediment trapping efficiency of an inlet as well as for predicting its future evolution.

One of the authors (DGA) was involved in a recent study on estuarine evolution that focused on the effects of climate change on sedimentation in these shallow estuarine systems. As climate changes, sea level is expected to rise (how much or when is a subject of intense debate and little consensus). One impact of climate change may be a change in the way an estuary evolves, or how it affects the sediment budget. The study described two types of systems that are distinguished by their geometry: one type tends to evolve more quickly and experience increased sedimentation, thereby dying earlier. The second type becomes a more efficient bypasser of sediment, and its channels will scour deeper and export sediment to the nearshore area. This distinction is critical for proper management of our shorelines and estuar-

Terri Tallman



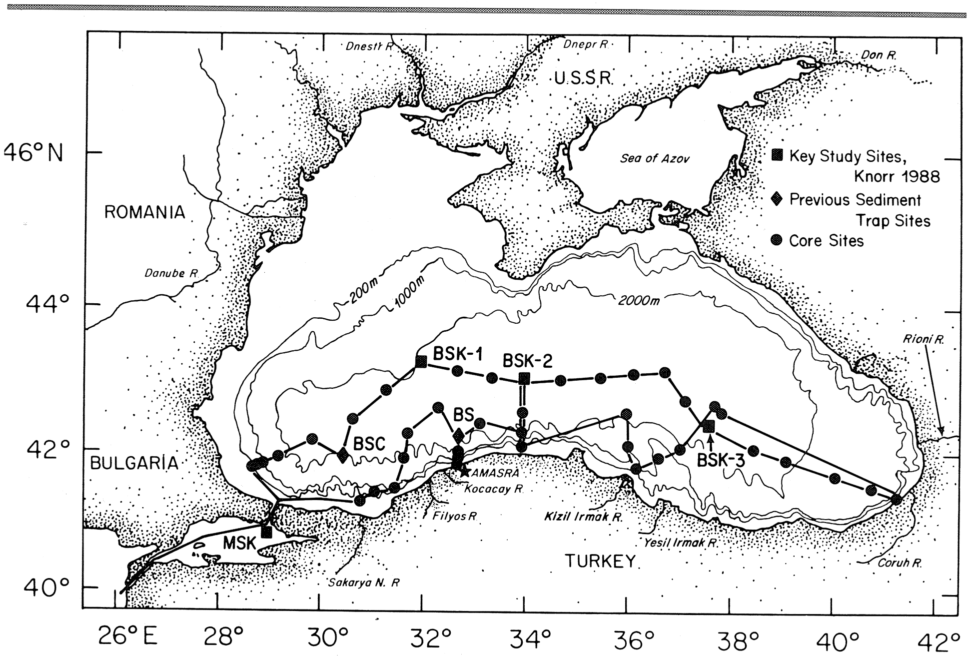
Authors Dave Aubrey, left, and Graham Giese, discuss their work at the Coastal Research Center.

precise chronological study ever made of the Black Sea's several thousand years of anaerobic history.

Many intact sediment cores were required for this study. To relate the bottom sediment correctly to such Black Sea variables as productivity and the rate of land erosion over the past few thousand years, we must study the particles which settle through the present day water column. An understanding of the qualitative and quantitative relationship between present settling particles and the sediment below is the best key for deciphering the useful signals hidden in the varves covering the anaerobic Black Sea floor. Among the new tools developed for this work since the 1969 *Atlantis II* cruise are advanced deep ocean sediment traps to collect settling particles and measure fluxes in a time series, sophisticated optical tools for precise characterization of particles in the water column, and improved technology for bottom sediment coring.

The international scientific staff consisted of 7 Turkish, 4 German, 1 Canadian, and 14 American scientists with many specialities and varied expertise. This group worked together extremely well during the 3-week cruise, accomplishing all the goals set for this leg and more. In addition the *Knorr* officers and crew did everything possible to make this research cruise successful. We traversed almost the entire length of the Black Sea and made three subtransects in a north-south direction along the Turkish Antolian coast (see figure).

First, we deployed a total of 4 mooring arrays with 8 time-series sediment traps at 4 locations best representing the Black Sea's sedimentary environment. The sediment traps were synchronized for a year's worth of sampling from 1 August 1988 to 1 August 1989, with individual sampling periods set at one month. At station BSK2, gigantic Mark 5-12 traps with 1.2-meter-square openings were deployed at two depths and set to collect sediment for 12 sampling periods over three months. This array was recovered in August, and samples collected were shared among U.S. and Turkish scientists. R/V *K. Piri Reis*, the flagship of the Marine Science and Technology Center, Izmir, will recover all Black Sea moorings in September 1989. The successful recovery of these large mooring systems will make a significant contribution to the work of Black Sea researchers.



Cruise track for Leg 1 of R/V *Knorr* Voyage 134 shows sediment trap, coring, and key study sites undertaken toward reconstructing the environmental evolution of the Black Sea.

On this leg we collected 30 box cores and 62 giant gravity cores up to 5.2 meters long. The soupy pelagic Black Sea sediment, in particular in the upper 50 centimeters of varved sediment, which is known as "Unit l" and represents the last 110 centuries, is difficult to collect. Use of newly designed gravity and box corers yielded a core recovery rate as great as 92 percent. This heralds a new era in marine geological studies of the Black Sea.

These first successful recoveries of the intact water-sediment interface by a box corer provided detailed observation of the surface "fluffy" layer and annual varve formation. The fluffy layer, seen for the first time on this cruise, was several millimeters thick. In a few box cores in which the water-sediment interface was extraordinarily well preserved, continuous formation of varves within the fluffy layer and uppermost Unit 1 sediment was observed. Thicker and less clearly defined laminae on the top gradually turned to thinner, well-demarcated black-and-white couplets which continued into Unit 1. Comparison of the fluffy material with time-series sediment trap material will contribute to an understanding of processes affecting the fate of particles settling to the seafloor.

The continuity of Black Sea sediment deposited over the past 10 centuries is extraordinary. Distinctive light and dark varve packages were used to correlate Unit 1 sediments across the entire Black Sea basin for a distance of more than 1,400 kilometers. Local disturbances caused by occasional turbidite intrusions expanded the sequences, but they apparently were "inserted" with little, if any, erosion of the varve sequence. This continuity of Unit 1 varve sequences from the western to the eastern extremes of the basin is indeed surprising in light of the heterogeneous sources of Black Sea sediment. This is the first time that modern or ancient varves have been correlated over such a great distance.

The apparent onset of calcareous

nannoplankton deposition at the very end of Unit 2 suggests that a coccolith-tolerant environment did become established as one sharp event but there were some reversals to more sapropelic mud deposition before calcareous nannoplankton and chalks finally became dominant in the Black Sea. Preliminary counts of varve couplets by X-radiography indicates the onset of coccolith sedimentation 1,075 years ago. We will seek confirmation of this through carbon-14 dating in varved sediment.

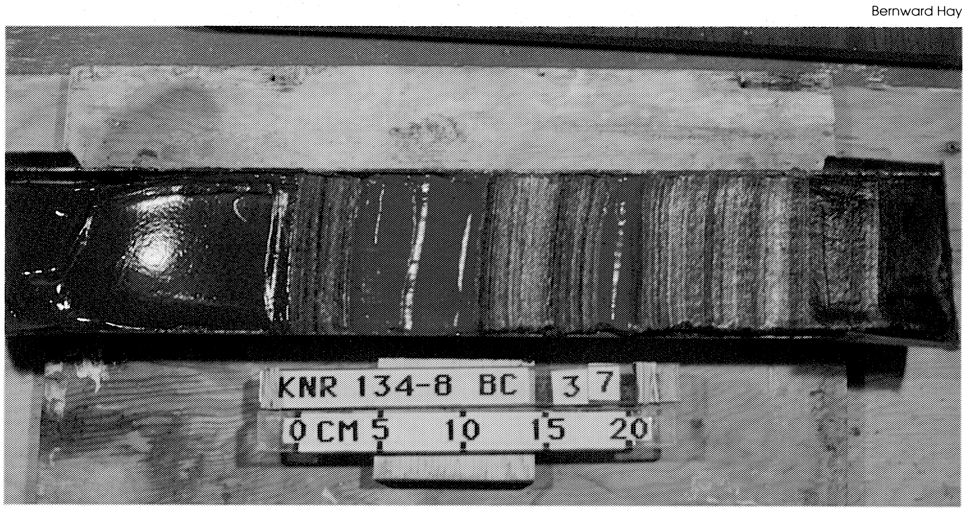
Coccoliths, microscopic shields produced by plant plankton, are especially important in light of concern about the global fate of carbon. In order to make them, coccolithophores turn carbon dioxide gas into insoluable calcium carbonate through photosynthesis. Then they descend through the water layers, and finally settle at the anaerobic bottom. Hence, coccoliths buried in the Black Sea sediment are a permanent sink of carbon dioxide, and much can be learned about the oceanic absorption of modern day fossil fuel carbon dioxide by studying them. As the photo shows, some parts of Unit 1 are clearly lighter in color than others, although fine varve sequences occur throughout the unit. The lightness of color indicates a portion of sediment rich in coccoliths. For example, around 350 A.D., when Byzantium was at its maxim prosperity, there were many more coccoliths blooms than now.

An onboard extruded and split gravity core recovered from a water depth of 411 meters on a slope near the Caucasus coast allowed us to estimate the time at which the oxic interface rose to approximately 400 meters in the far-eastern part of the Black Sea. The upper 170 centimeters of the core is laminated, with no manganese oxide deposition indicating anoxia. Preliminary laminae counting showed that the estimated beginning of anoxia was 2,040 years ago. This exceeds the age estimated for the base of Unit 1 in the deep basin and suggests that the initiation of anoxia at 400 meters occurred during the latter part of Unit 2 sapropel deposition. Below this laminated sequence is a well-bioturbated zone followed by extensive deposition of manganese oxide minerals.

We suspect that occurrences of unconsolidated sediment under layers in Unit 1 are closely related to earthquakes in the Anatolian and Caucacus region. Thus the turbidites may prove to be indicators of ancient earthquakes. Turkish scientists are studying the details of turbidite distribution in time and space in the Black Sea. Preliminary conclusions were: (1) turbidite layers are more abundant on the Anatolian side of the Black Sea, (2) turbidite layers in Unit 1 occur in different stratigraphic horizons at different locations that may be closely spaced, suggesting highly random formation in time and space; (3) turbidites are exposed (under the surface fluff) at all Amasra and Sakarya transect stations. This suggests very recent turbidite intrusion into this area.

The most significant collective accomplishment of this cruise was that we greatly increased the sample and the sediment and water column chemistry data bases available to international research communities interested in Black Sea studies. Intensive laboratory studies and discussions will continue for many years to come not only among the Woods Hole Oceanographic Institution researchers, but also among their colleagues all over the world.

Bernward Hay



Susumu Honjo

Above: Round subcore from a 1988 box core shows finely-layered upper sediments from the Black Sea interlayered with turbidites (shiny material). The box core was taken at a site that was well documented in 1969 during an *Atlantis II* Black Sea research cruise.

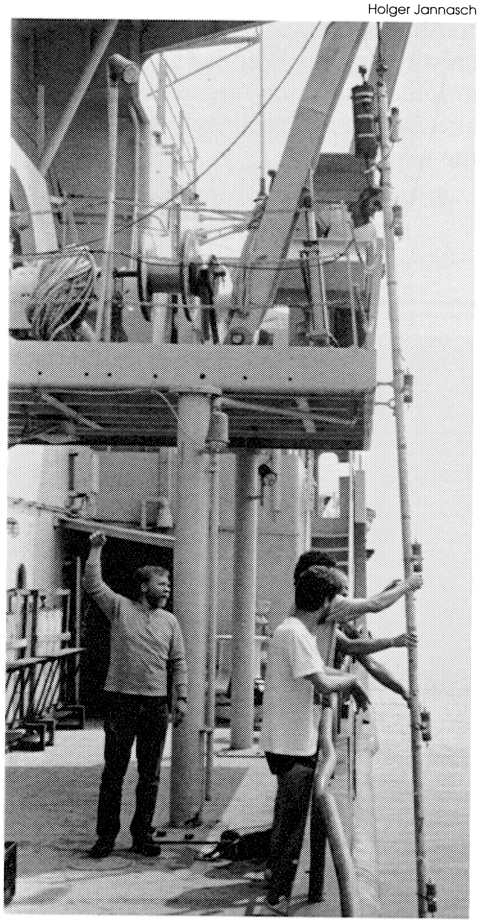
Right: Photo of R/V *Knorr* fantail shows 7 of the 8 sediment traps deployed in pairs during Voyage134. Some were recovered after three months, and others will be recovered after a full year of collecting samples in the Black Sea and in the Sea of Marmara.

Microbiological Studies in the Black Sea

Holger W. Jannasch

THE Black Sea is an *eldorado* for microbiologists. Indeed, the peculiar conditions of the world's largest anoxic basin are primarily generated by oxygen-consuming bacteria in the absence of efficient mixing of the water column. Once the dissolved oxygen is respired during the bacterial decomposition of organic matter, other microorganisms capable of "anaerobic respiration" of sulfate take over. As a result, hydrogen sulfide is produced. It is a powerful reductant and adds to the stability of the oxic/anoxic interface in the uppermost layers of the 2,000 meter water column in the center of the Black Sea. At this interface, the sulfide can be re-oxidized to sulfate by certain chemoautotrophic bacteria capable of synthesizing organic matter in the absence of light. These microbial processes, the cycling of carbon and sulfur compounds, are well known from their occurrence in shallow marine waters and their sediments. But here in the Black Sea they occur on the oceanic scale and interlink biological, chemical, and physical oceanography as nowhere else in offshore waters.

Holger Jannasch

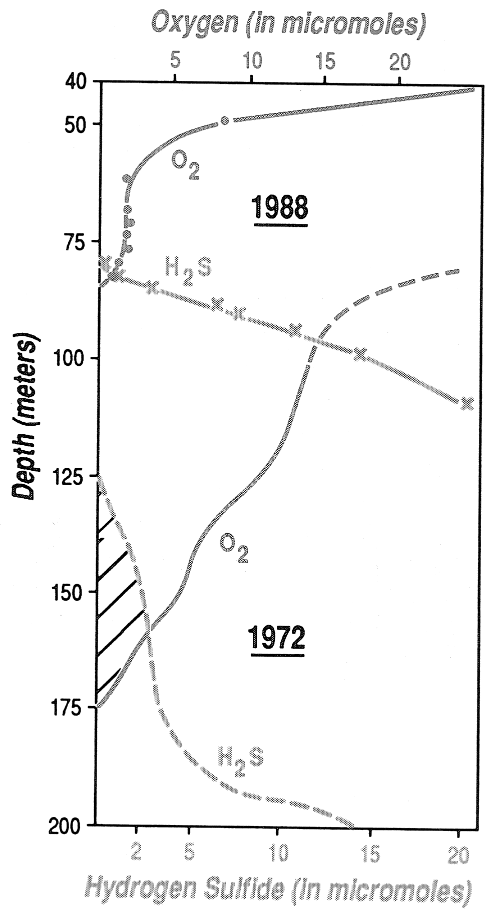


Carl Wirsen directs a launch of the 10-meter long multiple interface sampler newly constructed for work aboard R/V *Knorr* during the 1988 Black Sea cruise.

On two previous Black Sea cruises, aboard R/V *Atlantis II* in 1969 and R/V *Chain* in 1975, we found the oxic/anoxic interface approximately 125 to 150 meters below the surface as a very stable phenomenon – or so we thought. We also observed, and Russian oceanographers reported as well, that the borderline between the upper oxygenated layer of water and the deeper sulfide-containing water is by no means sharply defined. In fact, an overlap of these layers, where oxygen and sulfide occur side by side, may be up to 30 meters thick, a remarkable fact considering the spontaneous reaction between these two compounds. It was exactly the well known kinetics of this chemical reaction that we wanted to use for determining the rates of biological sulfide production and oxygen consumption. Because of our primary interest in this unique feature of the Black Sea, we were equipped to sample vertical profiles through the oxic/anoxic interface as accurately as possible in three ways: with CTD bottles, a submersible pump system, and the newly devised interface sampler.

We were in for a great surprise. Not only had the interface – or more exactly, the depth where sulfide first appears – risen from below 125 meters to about 90 meters, but the large overlap of oxygen and sulfide had virtually vanished. Instead, a suboxic zone, containing only traces of oxygen, separated the oxygenated from the sulfide-containing layers. This discovery raised the immediate question: how is the sulfide oxidized anaerobically? There were a number of possibilities: nitrate, carbon dioxide, or metal (iron/manganese)-oxides may replace oxygen as alternative "electron acceptors" in the microbial utilization of hydrogen sulfide.

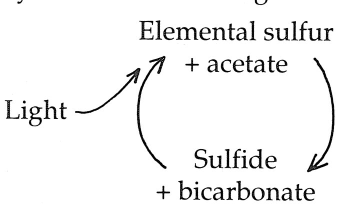
We were able to deal with the former two potential electron acceptors immediately. Dennis Bazylinski found active bacterial reduction of nitrate (denitrification) in the zone just above the appearance of sulfide in the water column. At the same time Dan Repeta and Dan Simpson made a significant observation. While looking for plant



Change of the oxic/anoxic interface in the Black Sea water column (western central basin) between 1972 (data from Sorokin) and 1988 (R/V *Knorr* Black Sea Cruise, Leg 2).

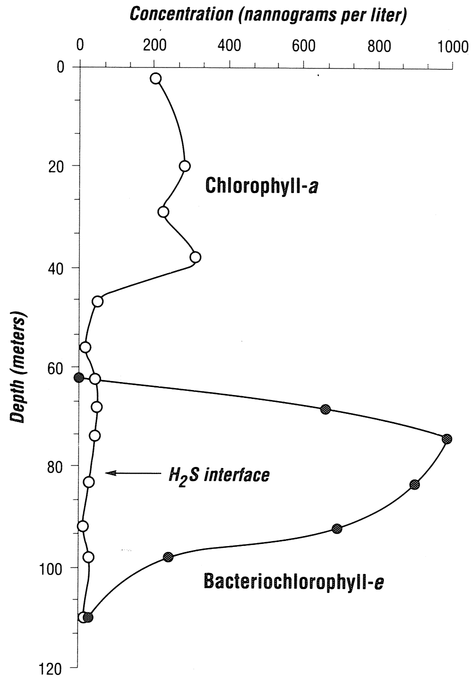
pigments, they found, in addition to the expected chlorophyll-*a* of the surface water phytoplankton, high levels of bacteriochlorophyll-*e* which indicates the presence of *Chlorobiaceae*, a group of photosynthetic sulfur-oxidizing bacteria.

These organisms are able to photosynthesize at extremely low light levels and contain, in addition to bacteriochlorophyll-*e*, characteristic carotenoids. These red-to-brown pigments aid in the absorption of the long-wave length light that penetrates to the depth at which these organisms occur. An extensive search for such bacteria during our 1975 cruise had been unsuccessful, except for one positive isolate from a sediment sample. Now it appears, however, that the sulfide layer has risen to a zone that can just be reached by enough light to allow the anaerobic photosynthetic bacteria to grow. The *Chlorobiaceae* are known to live in "syntrophy" with a number of heterotrophic sulfur-reducing bacteria linking the carbon and sulfur cycles in the following manner:



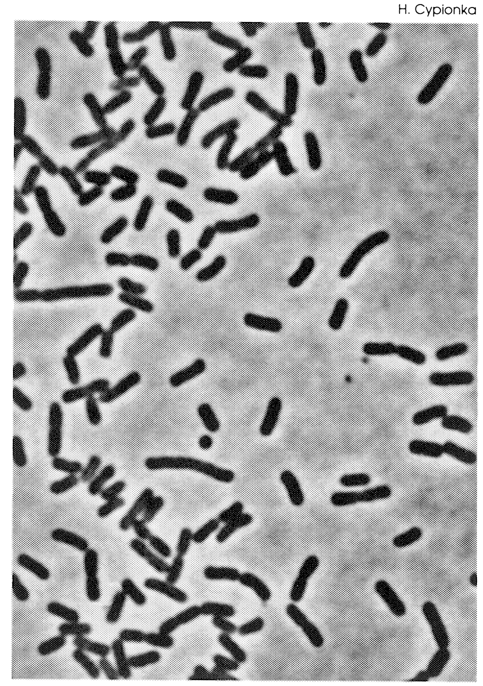
This time we also found high numbers of photosynthetic bacteria in the so-called "fluffy layer" using microscopes and pigment extraction. The "fluffy layer" of sedimentary material can be several inches thick and floats just on top of the more solid Black Sea sediment. This phenomenon occurs frequently in larger anoxic bodies of water and is primarily caused by the absence of zooplankton-feeding in the overlying anoxic water column, and by a much slower microbial degradation than found in oxic top sediments.

Above the zone of anaerobic phototrophic production of organic matter, we found another zone of aerobic chemoautotrophic production, or dark fixation of carbon dioxide. From this layer, at a depth of approximately 70 meters, several interesting bacteria were isolated that turned out to be obligate chemoautotrophs, the first organisms of this metabolic type to be found in the Black Sea. Furthermore, measurements of in situ rates of bacterial sulfate reduction during Leg 2 of the R/V Knorr Black Sea cruise resulted in much more realistic data



A strong peak of bacteriochlorophyll-*e* distinctly below the phytoplankton chlorophyll-*a* and just at the oxic/anoxic interface suggests anaerobic microbial oxidation of hydrogen sulfide.

H. Cypionka



The photosynthetic bacteria*Chlorobium phaebacterioides* shown here have been isolated from the upper anoxic Black Sea water column (ca. 90 m). The cell width is 0.7-0.9 µm.

Author Holger Jannasch, left, and his son Hans, a graduate student at the University of Washington, participated in successive legs of the Black Sea cruise aboard R/V *Knorr*. They are shown here on the fantail of the ship between Legs 2 and 3 of the cruise.

than obtained from indirect laboratory studies in earlier attempts.

Additional information is needed in order to decide whether the upward movement of the oxic/anoxic interface is a temporary or permanent phenomenon. We hope to receive necessary data on changes of freshwater inflow, for instance, through cooperation with scientists of countries bordering the Black Sea. Our new microbiological data have already aroused much interest, and they will be discussed at the International Symposium on Environmental Biogeochemistry in Moscow in September 1989. We are also looking forward to a workshop on Black Sea oceanography to be held in Turkey in October 1989.

Holger Jannasch

Steve Molyneaux and Dennis Bazylinski inject freshly sampled Black Sea water into anoxic tubes, while Dan Repeta handles a line behind them.

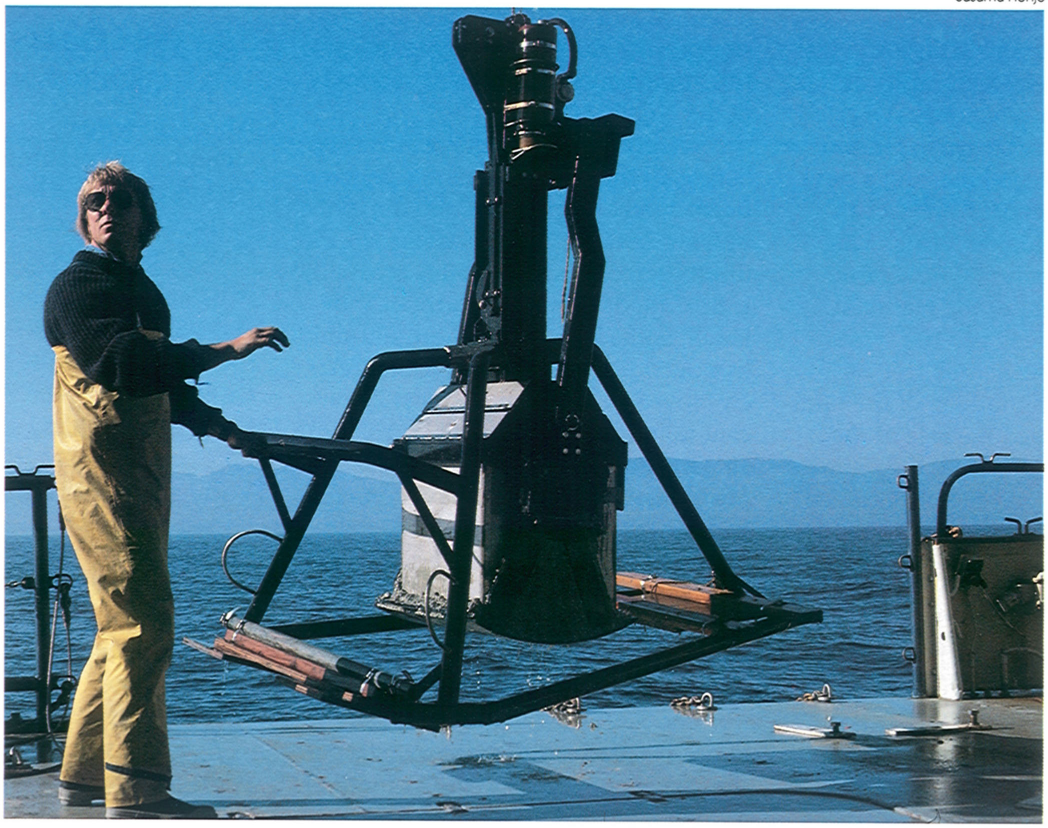
Jim Broda

An excited scientific party gathers around the box corer to see the first "fluffy" layer sediment samples from the Black Sea.

Holger Jannasch

Small sediment traps are brought aboard R/V *Knorr* after several days of drfiting to collect a Black Sea sample set.

Susumu Honjo



Jim Broda directs retrieval of a box corer specially modified for the work in the Black Sea.

Bernward Hay

Subsamples of sediment collected with the box corer above are being taken here for a variety of research programs conducted both aboard R/V *Knorr* and in U.S. and European research labs.

THIS year marked the 20th anniversary of the MIT/WHOI Joint Program in Oceanography and Oceanographic Engineering. We celebrated with several parties including a clambake at Woods Hole and a day-long symposium at MIT on "Ocean Sciences and Technology: Preparing for the Next Millenium." Dr. Frank Press, the president of the National Academy of Sciences and the symposium's keynote speaker (as well as one of the founding fathers of the Joint Program), addressed the role of the executive branch in setting the nation's scientific agenda, and the importance of maintaining scientific leadership in the U.S. Other speakers included Rear Admiral Craig Dorman, USN, (Joint Program graduate, Ph.D., 1972) who spoke of the need to develop new technologies for extracting information from the oceans; Dr. William R. Holland, Senior Scientist from the National Center for Atmospheric Research who focused on new advances in addressing the ocean component of the climate system with powerful computers and realistic models; MIT Department Chairman of Earth, Atmospheric and Planetary Sciences Tom Jordan who presented new techniques for quantifying seafloor shape ; WHOI Senior Scientist and Chemical Oceanographer Peter Brewer, who reviewed the global ocean flux program and other experiments being planned to address greenhouse warming and climate change; and WHOI Director John Steele, who concluded with remarks about new mathematical models to integrate the impact of global change across the land/sea boundary.

The symposium ended with the presentation of a plaque engraved with: "For twenty years of dedicated service in helping to make the Joint Program what it is today – the best" to WHOI Assistant Dean A. Lawrence Peirson III.

The year also saw a change in the Joint Program's MIT directorship. Professor Sallie "Penny" Chisholm, a biological oceanographer in MIT's Civil Engineering Department, succeeded Dr. Arthur Baggeroer, professor of electrical and ocean engineering, who stepped down after 5 years to focus full attention on his acoustic research in the Arctic.

We also issued our first directory listing all the Joint Program's 246 graduates, who are spread across the globe in New Zealand and Australia, the Philippines, Hong Kong, Korea, Japan, the U.S., Canada, northern Europe, and Israel. Some 16 percent of our alumni live outside the U.S., 60 percent are employed in academia, almost 20 percent in industry (primarily petroleum), 10 percent hold government research positions, 6 percent are Naval officers, and the remainder have left the field. Nineteen Joint Program graduates are currently on our scientific staff.

This year the first degrees were awarded in our new Joint Master's degree program with MIT.

The 3-year old Ocean Ventures Fund reached a milestone by passing the quarter of a million dollar mark of total monies raised from the private sector for Joint Program student research. This would not have been possible without the substantial help of Terry Brown of San Diego, Frank and Lisina Hoch of New York, Dee Hubbard of Ft. Worth, Don Koll of Newport Beach, Edgar Kaiser of Van-couver, and Fred Rentschler of Scotts-dale. The work of one of our Ocean Ventures awardees, Cindy Lee Van Dover, was described in the *Los Angeles Times*, the *New York Times*, and *Nature*.

This year we were able to expand our Postdoctoral Scholar Program from an average of 7 to 10 Institution-funded fellowship awards, an important asset for us, as 25 of our current staff members first came to the Institution as postdoctoral scholars.

Charles D. Hollister

1988 Ocean Ventures Fund Awardees

Alan J. Lewitus
"Regulation of Autotrophy and Heterotrophy in Two Microalgae in the Response of the Photosynthetic System"

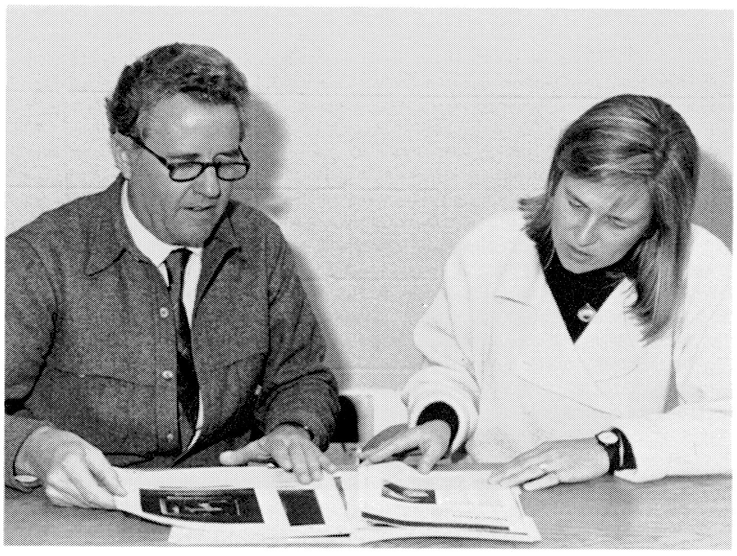
Michael J. Moore
"Growth Modulation and Disease in the Life Cycle of the Winter Flounder, *Pseudopleuronectes americanus*"

Laela S. Sayigh
"A Comparison of Whistle Vocalization Repertoires of Two Populations of Bottlenose Dolphins, *Tursiops truncatus*"

Elisabeth L. Sikes
"Development of a New Paleotemperature Estimation Technique"

D. Andrew Trivett
"Monitoring Heat Flux at a Hydrothermal Vent"

Terri Tallman



WHOI Dean Charley Hollister and new MIT Joint Program Director Penny Chisholm discuss education matters.

1988 DEGREE RECIPIENTS

Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Oceanography/Oceanographic Engineering

Doctor of Philosophy

John A. Barth
Special Field: Physical Oceanography
Dissertation: Stability of a Coastal Upwelling Front Over Topography

Sara L. Bennett
B.S. Colorado State University
Special Field: Physical Oceanography
Dissertation: Where Three Oceans Meet: The Agulhas Retroflection

Gaboury Benoit
B.S. Yale University
S.M. Massachusetts Institute of Technology
Special Field: Chemical Oceanography
Dissertation: The Biogeochemistry of ^{210}Pb and ^{210}Po in Freshwaters and Sediments

Carol E. Diebel
B.A., M.A., M.S. Humboldt University
Special Field: Biological Oceanography
Dissertation: The Sensory Mediation of Symbiosis between Hyperiid Amphipods and Salps

Cynthia J. Ebinger
B.S. Duke University
Special Field: Marine Geology and Geophysics
Dissertation: The Thermal and Mechanical Development of the East African Rift System

Elisabeth S. Gray
A.B. Washington University
Special Field: Biological Oceanography
Dissertation: Sexual Patterns of Monooxygenase Function in the Liver of Marine Teleosts and the Regulation of Activity by Estradiol

Janet G. Hering
A.B. Cornell University
Special Field: Chemical Oceanography
Dissertation: Kinetics and Thermodynamics of Copper Complexation in Aquatic Systems

John P. Jasper
B.A. University of Chicago
Special Field: Chemical Oceanography
Dissertation: An Organic Geochemical Approach to Problems of Glacial-Interglacial Climatic Variability

John P. Jemsek
B.S. Notre Dame University
Special Field: Marine Geology and Geophysics
Dissertation: Heat Flow and Tectonics of the Ligurian Sea Basin and Margins

Michael A. Kaminski
B.A. Rutgers University
Special Field: Marine Geology and Geophysics
Dissertation: Cenozoic Deep-water Agglutinated Foraminifera in the North Atlantic

Sarah A. Little
B.S. Stanford University
Special Field: Marine Geology and Geophysics
Dissertation: Fluid Flow and Sound Generation at Hydrothermal Vent Fields

Lorenzo M. Polvani
B.Sc., M.Sc. McGill University
Special Field: Physical Oceanography
Dissertation: Geostrophic Vortex Dynamics

Rui V. Ponte
B.Sc. University of Rhode Island
Special Field: Physical Oceanography
Dissertation: Observations and Modelling of Deep Equatorial Currents in the Central Pacific

Stephen R. Rintoul
B.A. Harvard University
Special Field: Physical Oceanography
Dissertation: Mass, Heat and Nutrient Fluxes in the Atlantic Ocean Determined by Inverse Methods

Kevin G. Speer
B.S. University of California, Santa Barbara
Special Field: Physical Oceanography
Dissertation: The Influence of Geothermal Sources on Deep Ocean Temperature, Salinity, and Flow Fields

W. Kenneth Stewart
B.S. Florida Atlantic University
Special Field: Oceanographic Engineering
Dissertation: Multisensor Modeling Underwater with Uncertain Information

M. Ross Vennell
B.E. University of Auckland, New Zealand
Special Field: Physical Oceanography
Dissertation: The Influence of a Steady Baroclinic Deep Ocean on the Shelf

Sophie Wacongne
B.S., M.S. Pierre and Marie Curie University
Special Field: Physical Oceanography
Dissertation: Dynamics of the Equatorial Undercurrent and Its Termination

John L. Wilkin
B.E. University of Auckland, New Zealand
Special Field: Oceanographic Engineering
Dissertation: Scattering of Coastal-trapped Waves by Irregularities in Coastline and Topography

Joanne M. Willey
R.N., B.A. University or Pennsylvania
Special Field: Biological Oceanography
Dissertation: Characterization of Swimming Motility in a Unicellular Cyanobacterium

20 Ph.D., 3 Engineer's, and 8 Master's (SM) Joint Degrees were awarded in 1988 bringing the total of Joint Degrees awarded since the program's founding in 1968 to 246: 188 Ph.D.s, 24 Sc.D.s, 26 Engineer's, and 8 Master's degrees.

Ocean Engineer

Kevin D. Casey
B.S. United States Naval Academy
Special Field: Oceanographic Engineering
Dissertation: A Modal/WKB Inversion Method for Determining Sound Speed Profiles in the Ocean and Ocean Bottom

John W. Nicholson
B.S. United States Naval Academy
Special Field: Oceanographic Engineering
Dissertation: Registration and Variability of Side Scan Sonar Imagery

Gregory M. Vaughn
B.S. United States Naval Academy
Special Field: Oceanographic Engineering
Dissertation: Hybrid State Estimators for the Control of Remotely Operated Vehicles

Master of Science

Jeffrey W. Campbell
B.S. United States Naval Academy
Special Field: Physical Oceanography
Dissertation: Evaluation of Geosat Data and Application to Variability of the Northeast Pacific Ocean

Joon Won Choi
B.S. Seoul National University
Special Field: Biological Oceanography
Dissertation: The Effects of Algal Density on Growth of Heterotrophic Micro-flagellates

David M. DiPietro
B.S. Massachusetts Institute of Technology
Special Field: Oceanographic Engineering
Dissertation: Development of an Actively Compliant Underwater Manipulator

Clark B. Freise
B.S. United States Naval Academy
Special Field: Physical Oceanography
Dissertation: A Comparison of Cross-Stream Velocities and Gulf Stream Translations Utilizing in-situ and Remotely-Sensed Data

Kristine Holderied
S.B. United States Naval Academy
Special Field: Physical Oceanography
Dissertation: Comparison Study of SEASAT Scatterometer and Conventional Wind Fields

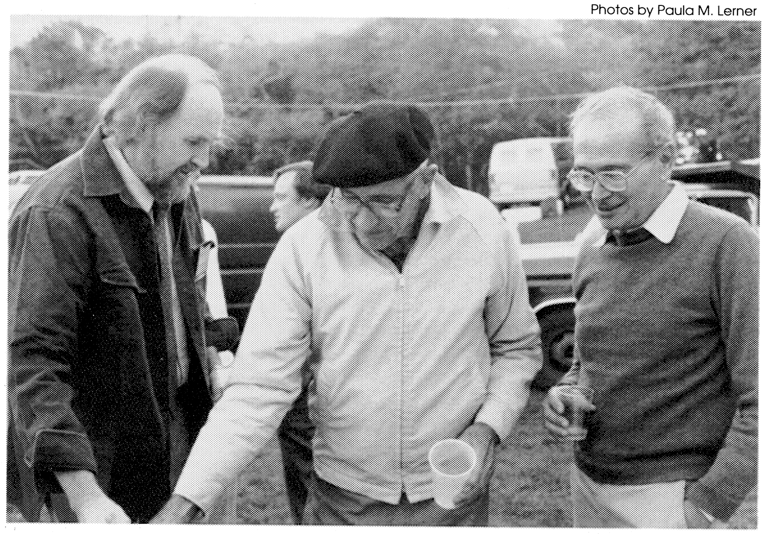
Wendy B. Lawrence
B.S. United States Naval Academy
Special Field: Oceanographic Engineering
Dissertation: Measurements of a Barotropic Planetary Vorticity Mode in an Eddy-Resolving Quasi-geostrophic Model Using Acoustic Tomography

Elizabeth A. Rowe
B.S. United States Naval Academy
Special Field: Oceanographic Engineering
Dissertation: Improvement of Three Dimensional Acoustic Field Estimation Using Tomographic Reconstructions of the Ocean

Padmaraj Vengayil
B.Tech. Indian Institute of Technology
M.S. University of Florida
Special Field: Oceanographic Engineering
Dissertation: Similarity Relations of Wind Waves in Finite Depth

Photos by Paula M. Lerner


Graduates and guests line up for the clambake held in Woods Hole as part of the Joint Program's 20th anniversary celebration.


Early Joint Program Graduate Bill Fitzgerald, First Dean K.O. Emery, and Frank Presss, a Joint Program founding father, gather at the clambake.

Accomplishments

PEOPLE continued to be the emphasis of WHOI's Development Program in 1988. Providing alternatives to the federal funding system is essential to allow scientists the freedom and means to take the risks that are an essential ingredient in any truly original initiative in science. Through this freedom, our scientists preserve the Institution's independence. Two milestones in continuing efforts to raise sufficient endowment monies to meet these needs adequately and permanently were achieved in 1988.

In December, The Andrew W. Mellon Foundation Challenge Grant to endow the Joint Initiative Awards was completed 4months ahead of schedule. In total, $2.5 million was raised. One major award of $100,000 or more will be made each year to support WHOI scientists in establishing the type of unconventional interdepartmental partnerships in research that are necessary to take totally new approaches to understanding complex oceanic processes. Through these initiatives, WHOI hopes to seed the federally supported programs of the future.

A second milestone was the establishment of the Stanley W. Watson Chair for Excellence in Biological Oceanography, endowed through a generous gift by one of WHOI's own Biology Department staff members, Dr. Stanley W. Watson, Scientist Emeritus. The Chair was awarded to Biochemist John J. Stegeman, Senior Scientist in the Biology Department.

Institutional unrestricted funding is one of the primary means through which WHOI's Director can encourage specific new initiatives. Relatively small amounts of money, strategically placed, can act as a rudder and exert great influence over the future course taken by the federally funded "hull" of the Institution. Realizing this and in anticipation of the arrival of a new Institution Director in early 1989, the J. Unger Vetlesen Foundation very generously award WHOI a $250,000 unrestricted grant in December to be used at the Director's discretion.

Gifts and Grants from Private Sources

Foundations	$1,782,538
Corporations	237,252
Trustees	44,700
Honorary Trustees	218,502
Corporation Members	55,147
Honorary Corporation Members	11,598
Associates	359,579
Oil Industry Program	90,000
General Donors	82,775
Total	**$2,882,091**

Associates

At the Annual Meeting of the Corporation in June the duties of the President of the Associates were transferred from James S. Coles, who had held the office since 1982, to Charles A. Dana, III. One of the first steps taken by Mr. Dana was to form an ad hoc committee to assess the program and establish goals for the future.

Another change in the Associates Program was the redesigning and renaming of *Woods Hole Notes*, the newsletter sent to all members. Written specifically for the Associates, *Ocean Views* will focus on research topics of interest to the members and will feature articles on Associates themselves.

During 1988, the Associates once again served the Institution by providing their time and talents as volunteers. In addition to staffing the Exhibit Center and the Public Information Office, volunteers worked at the Archives/Data Library, on a Pond Study Project, and at the cetacean lab. Once a month volunteers were invited to luncheons where they met infomally with members of WHOI's staff and enjoyed a special insight into their research projects.

The travel program saw more than 35 Associates join an expedition to Antarctica aboard the *Society Explorer*, which included stops at research stations of many nations. Plans were finalized for the November 1989 trip to the South Pacific, which will retrace the voyage of H.M.S. *Bounty*.

The Boston Associates Dinner unofficially kicked off celebrations commemorating the 25th Anniversary of the commissioning of *Alvin*. Barrie Walden, Manager, Submersible Engineering and Operations, provided highlights of the sub's achievements and plans for future operations.

In Addition...

Membership in the Ocean Industry Program currently consists of 5 companies, Amoco, Exxon, Mobil, Standard Oil/BP, and Texaco. Sun and EG&G discontinued their participation. Cutbacks, resulting from the petroleum industry recession, continue to be felt.

Major support for the work of the Marine Policy Center came from The Pew Charitable Trusts in support of "Changing Global Processes and Ocean Conservation," a two part project studying sea level rise and marine biological diversity.

The Florence and John Schumann Foundation continued to provide support for the study of brown tides, red tides, and toxic algae in the ocean. Other organizations that have generously contributed to WHOI are listed in the "Sources of Support for Research and Education" section of this report.

Committee Members

Charles F. Adams, Chairman
James M. Clark
James S. Coles
Charles A. Dana, III
Joel P. Davis
Kenneth S. Safe
John A. Scully
Walter A. Smith
Marjorie von Stade

Ex-officio

Paul Dudley Hart
Guy W. Nichols
John H. Steele

Publications of record as of February 1, 1989. Entries are listed by department. Institution contribution number appears at the end of each entry. 1987 publications not listed in the 1987 Annual Report are included here.

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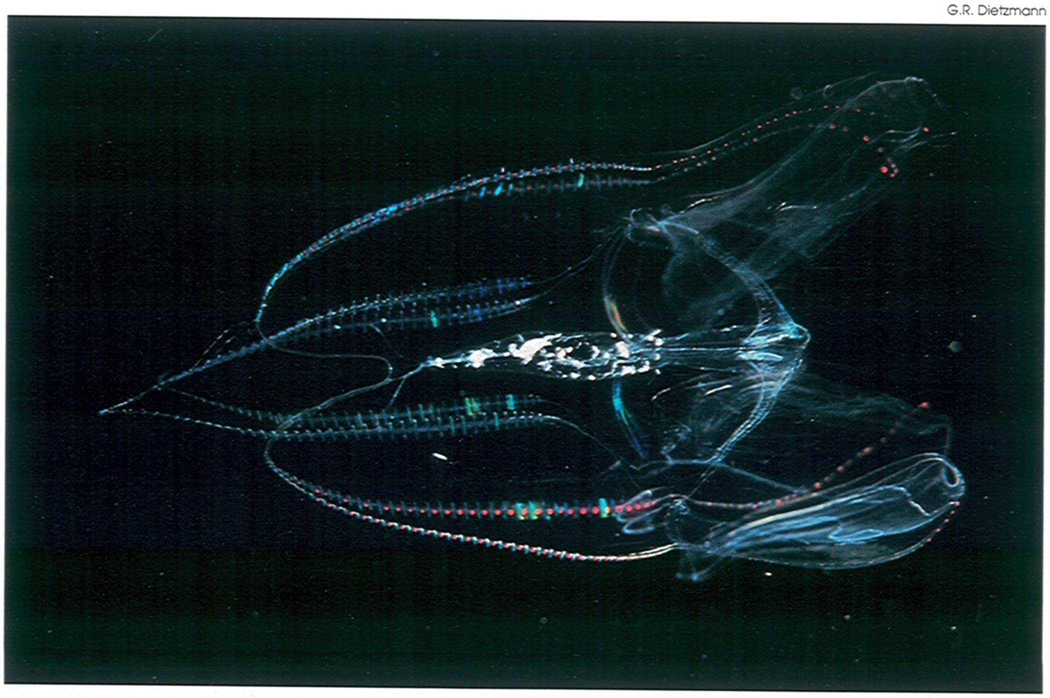
G.R. Dietzmann



This night photograph of a ctenophore *(Eurhamphaea vexilligera)* feeding on copepods was taken for research in the biological oceanography laboratory of Larry Madin.

Jerry Dean

Dave Simoneau, right, and Rick Trask wind wire on the fantail of R/V *Knorr* for FASINEX (Frontal Air-Sea Interaction Experiment) buoy work during a port call in Bermuda in 1986. R/V *Oceanus* , in the background, happened to be calling in Bermuda at the same time.

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George Tupper

Captain Richard Bowen executes a pirouette in Nantucket Sound using R/V *Knorr*'s fore and aft cycloids.

George Tupper

R/V *Oceanus* steams toward the Gulf Stream to set moorings for SYNOP, the SYNoptic Ocean Prediction experiment

R/V Atlantis II & DSV Alvin

Total Nautical Miles for 1988 – 19,746
Total Days at Sea -- 293
Total Dives – 200

Voyage	Cruise Period	Principal Objective, Area of Operations	Ports of Call	Chief Scientist
118-IIV	5 Jan-15 Jan	Catalina Basin, 10 dives, emplacement of benthic flux chambers and measurement of zooplankton food responses	San Diego, CA	D. Hammond (USC)
118-XXVI	19 Jan-23 Jan	Transit to Guaymas, Mexico	San Deigo, CA	
118-XXVII	25 Jan-30 Jan	Guaymas Basin, 4 dives, geochemistry and benthic ecology at hydrothermal vent sites	Guaymas, Mexico	F. Sayles F. Grassle
118-XXVIII	31 Jan-8 Feb	Guaymas Basin, 7 dives, microbiological studies of Guaymas vent system	Guaymas, Mexico	H. Jannasch
118-XXIX	10 Feb-19 Feb	Guaymas Basin, 9 dives, continuation of Leg XXVII investigations	Guaymas, Mexico	F. Sayles F. Grassle
118-XXX	20 Feb-24 Feb	Guaymas Basin, 4 dives, studies of molluscan shells, geochemistry, and interstitial water at hydrothermal vents	Guaymas, Mexico	B. Simoneit (OSU) R. Lutz (Rutgers) F. Sayles
118-XXXI	27 Feb-29 Feb	Transit to Manzanillo, Mexico		
118-XXXII	4 Mar-29 Mar	East Pacific Rise, 20 dives, axial geological process studies (*Alvin*'s 2,000th dive)	Manzanillo, Mexico	W. Bryan G. Thompson
118-XXXIII	4 Apr-7 May	Galapagos Rift, 28 dives, coordinated study of water chemistry and biological communities at "Rose Garden" vent sites	Puerto Quetzal, Guatemala	R. Hessler (SIO) J. Childress (UCSB) R. Lutz (Rutgers)
118-XXXIV	11 May-18 May	Transit to San Diego, CA		
118-XXXV	31 May-14Jun	Escanaba Trough, 10 dives, investigation of hot spring chemistry in a hydrothermal vent system	San Deigo, CA	J. Edmond (MIT)
118-XXXVI	18 Jun-2 Jul	Oregon Margin, 13 dives, study of subduction processes in a heavily sedimented trench	Astoria, OR	L. Kulm (OSU)
118-XXXVII	6 Jul-27 Jul	Endeavor Ridge, 19 dives, acoustic imaging of a hydrothermal system; temporal and spatial variability studies	Astoria, OR	J. Delaney (UWash) B. Lewis (UWash)
118-XXXVIII	1 Aug-23 Aug	Juan de Fuca Ridge, 20 dives, buoyant plume sampling and geological mapping in conjunction with NOAA VENTS Programs	Astoria, OR	R. Embley (NOAA)
118-XXXIX	28 Aug-14 Sep	Endeavor Ridge, 16 dives, multidisciplinary study of archaebacteria from a hydrothermal vent area	Seattle, WA	J. Baross (UWash) R. Spindel (UWash)
118-XL	18 Sep-2 Oct	Endeavor Ridge, 11 dives, thermal and chemical output measurements from high temperature vent fields	Newport, OR	M. Mottl (UHawaii)
118-XLI	6 Oct-16 Oct	Side-scan sonar and deep-towed magnetometer study of Juan de Fuca Ridge	Seattle, WA	H.P. Johnson (UWash)
118-XLII	18 Oct-1 Nov	Monterey Canyon, 10 dives, study of benthic drifting algae and geologic processes, IMAX filming	Astoria, OR	R. Embley (NOAA) E. SClark (UMaryland)
118-XLIII	4 Nov-11 Nov	Catlaina Basin, 7 dives, organism, particle, and flow interactions, bioturbation and sedimentation studies	San Deigo, CA	C. Smith (UWash) P. Jumars (UWash) A. Nowell (UWash) S. Emerson (UWash)

118-XLIV	15 Nov-19 Nov	Transit to Manzanillo, Mexico		
118-XLV	21 Nov-5 Dec	Volcano 7, 12 dives, ingestion rate and trophic relationships of deep sea boundary layer zooplankton	San Deigo, CA	K. Wishner (URI) L. Levin (NC STate)
118-XLVI	7 Dec-20 Dec	Transit to Woods Hole	Manzanillo, Mexico Woods Hole	

R/V Knorr

Total Nautical Miles for 1988 – 29,034
Total Days at Sea – 256

Voyage No.	Cruise Period	Principal Objective, Area of Operations	Ports of Call	Chief Scientist
134-IV	18 Dec–23 Jan	SAVE (South Atlantic Ventilation Experiment) work including measuring chlorofluoromethanes, Kr-85, Ar-39, oxygen, carbon, helium isotopes, and tritium in the South Atlantic	Abidjan, Ivory Coast	W. Smethie (LDGO)
134-V	28 Jan–7 Mar	SAVE investigations of rates of mixing, ventilation, interocean exchange, and circulation, and studies of carbon, oxygen, and nutrient cycling on ocean basin scale	Rio de Janeiro, Brazil	W. Jenkins
134-VI	11 Mar–23 Mar	Transit to Spain to embark personnel and equipment for Black Sea Expedition	Abidjan, Ivory Coast	
134-VII	29 Mar–10 Apr	Collect sediment samples for studies of oxygen depletion in deep waters of the the Eastern Mediterranean 9,000 years ago	Cadiz, Spain	E. Boyle (MIT)
134-VIII	16 Apr–7 May	Investigate the sedimentary evolution of the Black Sea by examining particle fluxes and sediment cores	Izmir, Turkey	S. Honjo
134-IX	14 May–28 May	Microbiological studies in the surface layer, at the oxic/anoxic interface, and in the water column and sediments of the western basin of the Black Sea	Istanbul, Turkey	H. Jannasch

Holger Jannasch

John Bouthilette

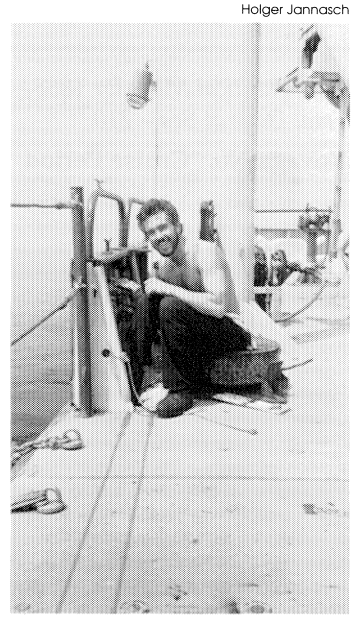
Shelley Lauzon

R/V *Knorr* at the pier

Rob Brown

R/V *Oceanus* in Woods Hole

Holger Jannasch



Don Cook

134-X	3 Jun–16 Jun	Work on the distribution and cycling of trace metals, oxygen, sulfide, and nutrients across the anoxic interface and in the deep water of the Black Sea	Istanbul, Turkey	J. Murray (UWash)
134-XI	21 Jun–8 Jul	Collect hydrographic tritium, C-14, dissolved gases, freon, cesium-137, and other tracer data to model their input, mixing rates, and circulation in the Black Sea	Istanbul, Turkey	Z. Top (UMiami) R. Anderson (LDGO)
134-XII	13 Jul–29 Jul	Investigate methane and organic geochemical cycles in the oxic/anoxic transition zone of the Black Sea	Istanbul, Turkey	W. Reeburgh (UAlaska)
134-XIII	3 Aug–5 Aug	Studies of the sedimentary history of the Sea of Marmara and the exchange of water between the Sea of Marmara and the Black Sea	Istanbul, Turkey	G. Grice
134-XIV	5 Aug–9 Aug	Transit to Naples, Italy	Izmir, Turkey	
134-XV	11 Aug–18 Aug	Testing of dynamic positioning system in conjunction with a towed vehicle and operational testing of new fiber optic cable	Naples, Italy	R. Ballard
134-XVI	20 Aug–24 Aug	Work on oxygen depletion in the Mediterranean 9,000 years ago	Cagliari, Italy	E. Boyle (MIT)
134-XVII	28 Aug–5 Sep	Transit to Bergen, Norway	Cadiz, Spain	
134-VIII	8 Sep–6 Oct	Deploy 6 subsurface acoustic transceiver moorings for studies of the formation of Greenland Sea deep water in winter and to measure the response of the Greenland Sea gyre to changes in the applied wind ice zone	Bergen, Norway	W. Munk SIO)
134-XIX	6 Oct–10 Oct	Recovery of R-Team buoy	Longyearbyen, Norway	E. Mellinger
134-XX	11 Oct–18 Oct	Transit to Iceland	Longyearbyen, Norway	
134-XXI	19 Oct–29 Oct	Tripod recovery operations	Reykjavik, Iceland Woods Hole	R. Chandler

R/V Oceanus

Total Nautical Miles for 1988 – 30,133
Total Days at Sea – 210

Voyage No.	Cruise Period	Principal Objective, Area of Operations	Ports of Call	Chief Scientist
	1 Jan-5 Apr	Maintenance at WHOI Pier	Woods Hole	
197-I	6 Apr-11 Apr	Engineering tests of CTD Fast Profiler and collecting samples for study of the distribution and transport of particulate trace metals in the Sargasso Sea	Woods Hole	A. Bradley
197-II	15 Apr-25Apr	Investigate the spatial variability in chemical gradients at the sediment-water interface using benthic lander southeast of Bermuda	St. George, Bermuda	F. Sayles
198	29 Apr-3 May	Recover surface mooring at 33°57' N, 69°46'W and STEM engineering test mooring at 39°10'N, 70°01'W	Woods Hole	G. Tupper
199	12 May-16 May	Engineering tests of and measurements with Deep Towed Explosive Sound Source	Woods Hole	G. M. Purdy

200-I 200-II	20 May-2 Jun 4 Jun-18 Jun	Deploy array of instrumented moorings for studies of the dynamic and energy balances in Gulf Stream meanders and interactions with surrounding rings and eddies	Woods Hole Woods Hole	D. R. Watts (URI) D. R. Watts (URI)
201	21 Jun-4 Jul	Study of shear wave propagation in shallow water marine sediment using sound sources and sensing arrays at 3 locations	Woods Hole	J. Ewing
202-I	11 Jul-20 Jul	Deploy HEBBLE tripod and Free Vehicle Stereo Camera tripod, test freon sampling devices	Woods Hole	R. Chandler
202-II 202-III	23 Jul-7 Aug 10 Aug-1 Sep	Closely spaced hydrographic section of CTD profiles and water samples in the north and equatorial Atlantic along 20° W from the Icelandic Continental Shelf to 5°S	Reykjavik, Iceland Funchal, Madeira	M. McCartney M. McCartney
202-IV	4 Sep-19 Sep	Study of the structure and modifications of Mediterranean Sea water exiting through the Strait of Gibraltar and flowing down steep channels into the Atlantic Ocean	Funchal, Madeira	T. Sanford (UWash)
202-V	21 Sep-28 Sep	Study of the structure and dynamics of the Mediterranean outflow plume, the isolated eddies that form the plume, and flows around Ampere Seamount.	Cadiz, Spain	T. Sanford (UWash)
202-VI	29 Sep-9 Oct	Transit to Woods Hole	Cadiz, Spain	
203	15 Oct-26 Oct	Deploy Severe Environment Surface Mooring and also an array of 5 instrumented subsurface moorings for a tomography experiment	Cadiz, Spain	S. Worrilow
204	31 Oct-4 Nov	Engineering tests of and measurments with Deep Towed Explosive Sound Source	Woods Hole	G.M. Purdy
205-I	12 Nov-27 Nov	Hydrographic section across the Gulf Stream at 26° N for measurements of carbon dioxide properties of seawater	Woods Hole	P. Brewer
205-II	2 Dec-18 Dec	Collection of sediment cores from the margin of Little Bahamas Bank for reconstruction of the glacial-interglacial history of temperature and water chemistry in the upper water column of the western North Atlantic	Fort Lauderdale, FL	W. Curry
205-III	24 Dec-30 Dec	Transit to Bridgetown, Barbados	Fort Lauderdale, FL	

Rod Catanach

DSV *Alvin* is lifted aboard R/V *Atllantis II* following a dive. The yellow drogue helps prevent the sub from colliding with the mother ship during recovery operations.

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The Institution gratefully acknowledges the service and support of George H. A. Clowes, Jr., Paul M. Fye, Hollis D. Hedberg, Joseph V. McKee, Jr., Raymond B. Montgomery, Richard S. Morse, and James R. Shepley who passed away in 1988, and George Nichols, Jr., who passed away in early 1989.

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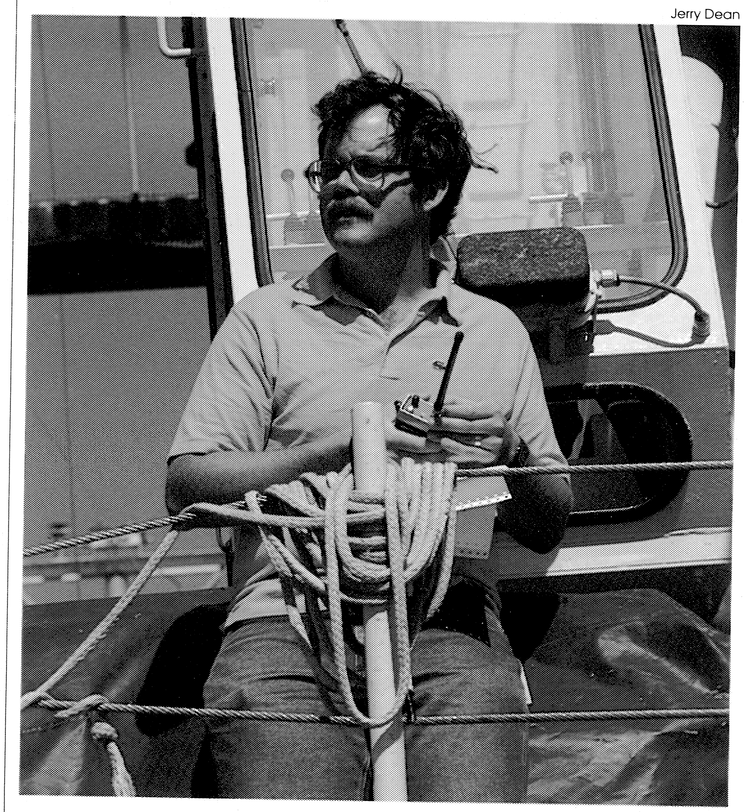

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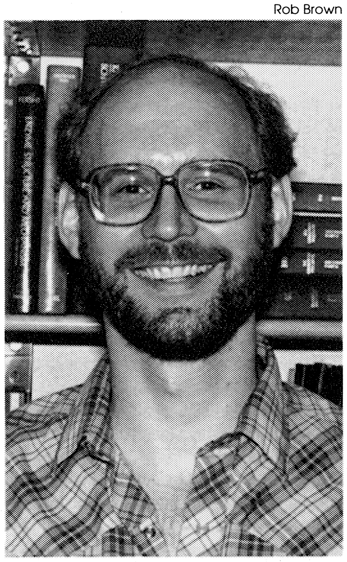
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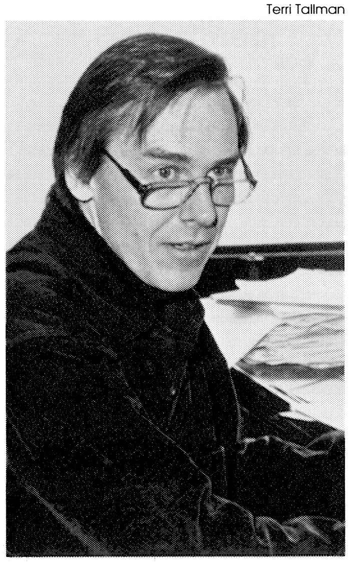
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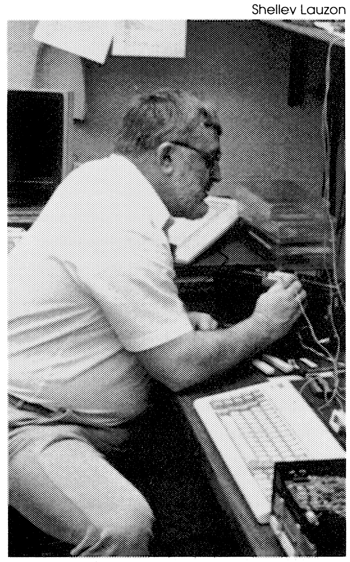
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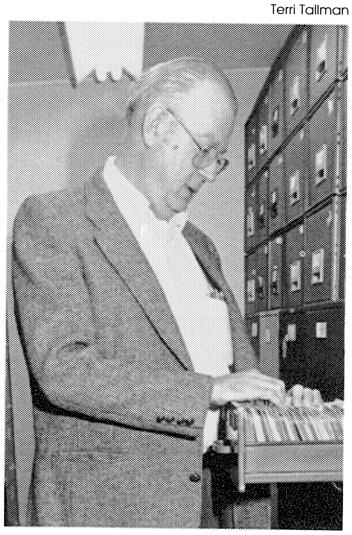
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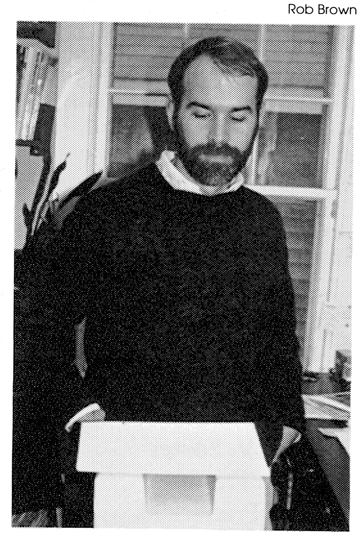
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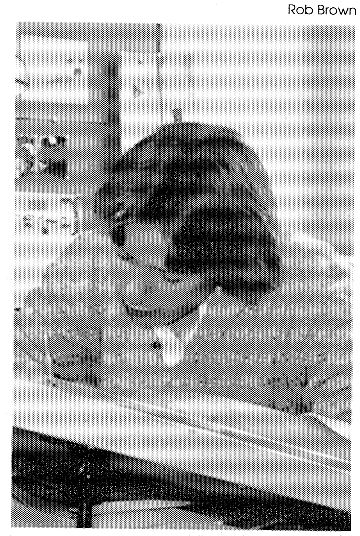
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Arthur D. Colburn, Jr. .... Boat Operator, *Asterias*
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Ralph M. Hollis .... Chief Pilot, DSV *Alvin*
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Geophysical Fluid Dynamics Summer Seminar Fellows:

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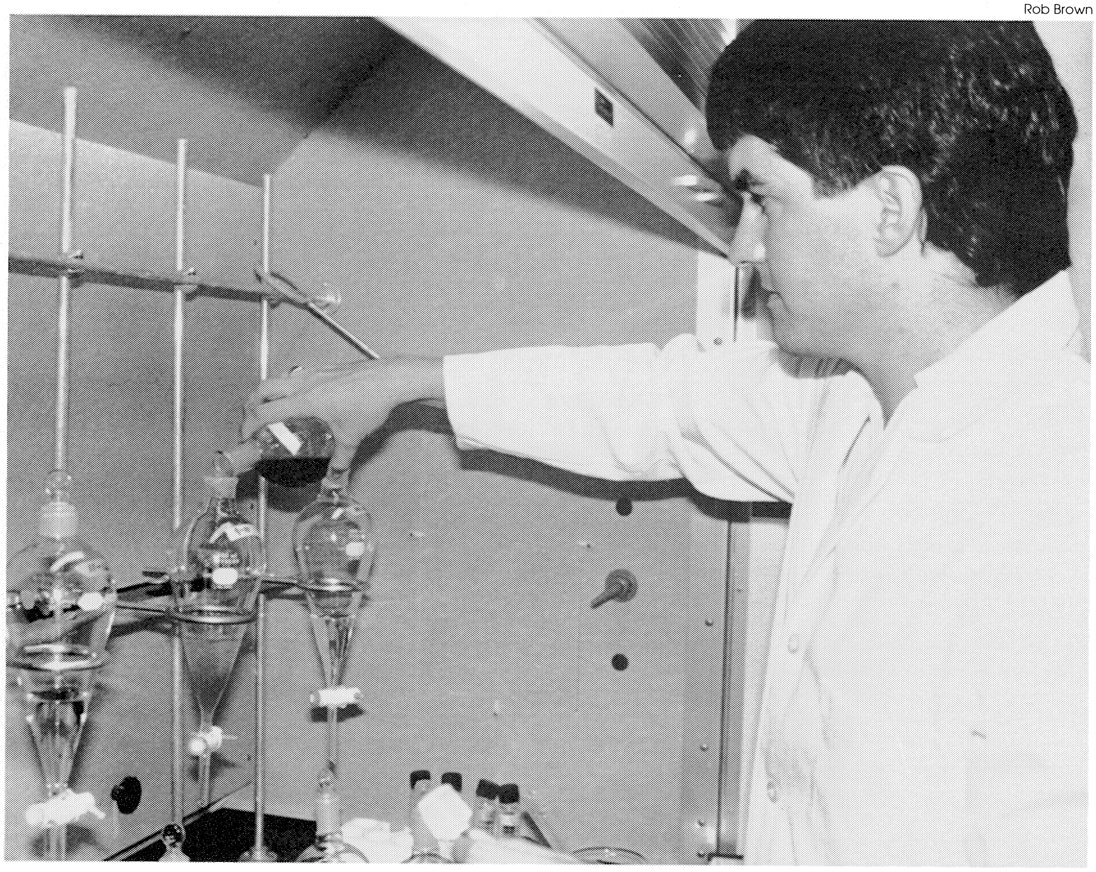

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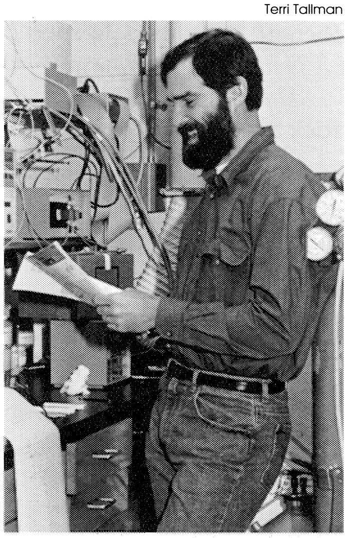

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Asterias is tied to the WHOI pier as the sun sets over Woods Hole harbor.

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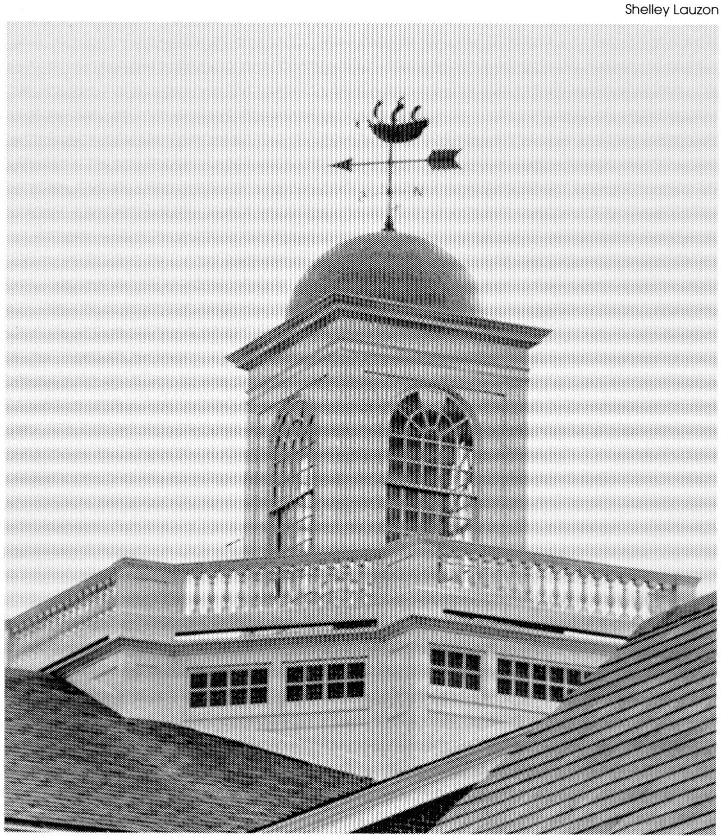

Sailing ship weathervane sits atop the Bigelow Lab cupola.

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FINANCIAL STATEMENTS

Highlights

The Institution's financial results depict a very successful year. In 1988, total revenues increased by 21% to $65,356,152 from $53,844,403, an increase of $11,511,749.

Increases in government and nongovernment sponsored research of $7,224,853 and $3,371,899 respectively accounted for $10,596,752 of the yearly change and represented increases of 17% and 66% respectively over the previous year. This increase occurred principally in the Physical Oceanography, Geology and Geophysics and Ocean Engineering departments and also included $2,264,991 for the *Knorr/Melville* refit. For government research, the National Science Foundation showed a $4,886,814 increase, up 21%. Research funding from the United States Navy decreased slightly by $357,353 excluding the *Knorr/Melville* refit which commenced during the year. Other government funding advanced by $430,401, an increase of 12%. The increase of $3,371,899 from nongovernment sources was principally from subcontracts and universities. The backlog of sponsored research excluding the vessel refit at year end increased by $2,066,000 to $26,681,000. Increases for other income of $764,215 and $150,782 for the education program accounted for the remainder of the total increase.

Total expenses increased $10,941,315 to $62,872,056 from $51,930,741, an increase of 21% from 1987. Costs of sponsored research, excluding the *Knorr/Melville* refit, increased by $8,344,461, up 18%. Education expenses increased 4% while other expenses increased by 12%.

Excess current unrestricted funds totalling $2,484,096 were allocated as follows: $800,000 to the unexpended plant fund, $581,979 to the endowment fund for the Iselin Chair, $500,000 to replenish the Director's Innovative Fund, and the balance net of other transfers to working capital.

Gifts and grants from private sources decreased slightly by $108,025 to $2,804,423 from $2,912,448 as noted below:

	1988	1987
Restricted:		
Endowment	$1,135,526	$1,597,916
Research	916,999	989,300
Education	71,300	22,000
Plant	10,207	–
	2,134,032	2,609,216
Unrestricted	670,391	303,232
	$2,804,423	$2,912,448

The market value of the endowment increased by $5,349,609 including new gifts of $1,135,526 to $89,648,872 from $84,299,263. During the year, the Investment Committee voted to alter the investment and income allocation policies of the endowment fund. The new long term goal is to maintain the purchasing power of the endowment while at the same time providing for a predictable stream of income to be available for the Institution's research and education programs.

Capital expenditures totalled $2,019,398 in 1988, an increase of $383,544 over 1987 which includes $603,566 for the Clark and $171,025 for the Fye laboratory additions. Funds for capital expenditures are provided from depreciation recoveries and unrestricted income.

The number of employees at year end increased by 34 to 811 principally as a result of additional positions in the research programs.

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

Gary B. Walker
Assistant Director for Finance & Administration
Kenneth S. Safe, Jr.
Treasurer
George A. Smith
Controller

Balance Sheets December 31, 1988 and 1987

ASSETS	1988	1987
Current fund (Note A):		
Cash	$ 6,620,237	$ 6,405
Short-term investments, at cost which approximates market	18,196,388	16,794,495
Accrued interest and dividends	872,880	665,759
Reimbursable costs and fees:		
Billed	1,436,724	1,125,917
Unbilled	1,489,989	638,672
Other receivables	357,194	787,312
Inventories	326,154	315,118
Deferred charges and prepaid expenses	190,938	411,889
Deferred fixed rate variances	470,768	(438,744)
Due to other funds	(9,885,113)	(8,983,739)
	20,076,159	**11,323,084**
Endowment fund (Notes A and B):		
Investments, at market	52,624,756	70,720,967
Cash and cash equivalents	35,560,206	12,704,369
Pooled income investments, at market	163,803	154,964
Due from current fund	1,158,348	581,983
	89,507,113	84,162,283
Annuity investments, at market	141,759	136,980
	89,648,872	**84,299,263**
Plant fund (Note A):		
Land, buildings, and improvements	25,685,973	25,062,278
Vessels and dock facilities	7,410,793	7,432,532
Laboratory and other equipment	4,836,566	4,380,001
Work in process	1,008,389	132,632
	38,941,721	37,007,443
Less: accumulated depreciation	(17,700,548)	(15,989,654)
	21,241,173	21,017,789
Due from current fund	8,726,765	8,401,756
	29,967,938	**29,419,545**
Total all funds	**$139,692,969**	**$125,041,892**

LIABILITIES AND FUND BALANCES	1988	1987
Current fund:		
Liabilities:		
Accounts payable and other liabilities	$ 2,325,353	$ 2,350,404
Accrued payroll and related liabilities	4,517,497	2,783,078
	6,842,850	5,133,482
Fund balances:		
Restricted-unexpended:		
Sponsored research	8,602,677	2,824,501
Education program	1,235,334	809,850
Designated	942,067	1,030,914
Unrestricted	2,453,231	1,524,337
	13,233,309	6,189,602
	20,076,159	**11,323,084**
Endowment fund:		
Endowment:		
Income restricted	53,060,909	49,863,091
Income unrestricted	1,016,244	955,767
Quasi-endowment:		
Income designated	11,829,734	12,244,647
Income unrestricted	23,600,226	21,098,778
	89,507,113	84,162,283
Annuity	141,759	136,980
	89,648,872	**84,299,263**
Plant fund:		
Invested in plant	21,241,173	21,017,789
Unexpended	8,726,765	8,401,756
	29,967,938	**29,419,545**
Total all funds	**$139,692,969**	**$125,041,892**

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

Statements of Current Fund Revenues, Expenses and Transfers for the years ended December 31, 1988 and 1987

	1988	1987
Revenues:		
Sponsored research:		
Government	$49,456,286	$42,231,433
Nongovernment	8,471,356	5,099,457
	57,927,642	47,330,890
Education funds availed of	2,238,671	2,087,889
Total restricted	60,166,313	49,418,779
Unrestricted:		
Fees	497,682	438,021
Endowment income	1,260,688	964,968
Gifts	670,392	303,232
Tuition	1,111,089	1,189,051
Investment income	1,113,560	991,104
Oceanus subscriptions	238,165	270,544
Other	298,263	268,704
Total unrestricted	5,189,839	4,425,624
Total revenues	**65,356,152**	**53,844,403**
Expenses:		
Sponsored research:		
Salaries and fringe benefits	15,690,678	14,202,927
Ships and submersibles	8,947,175	7,718,893
Knorr/Melville refit	2,252,291	–
Material and equipment	9,267,937	6,635,030
Subcontracts	4,065,538	2,500,674
Laboratory overhead	4,734,575	4,308,591
General and administrative	5,255,907	4,928,575
Other	7,713,541	7,036,200
	57,927,642	47,330,890
Education:		
Faculty expense	1,147,741	1,093,867
Student expense	1,018,212	937,712
Postdoctoral programs	328,845	331,732
Other	299,417	319,103
	2,794,215	2,682,414
Unsponsored research	798,037	730,214
Oceanus magazine	397,312	376,808
Other activities	954,850	810,415
Total expenses	**62,872,056**	**51,930,741**
Net increase before transfers	**2,484,096**	**1,913,662**
Transfers - (to) from:		
Director's Innovative Fund	(500,000)	(500,000)
Designated reserves	326,777	63,855
Endowment fund	(581,979)	(741,605)
Plant fund	(800,000)	(800,000)
Total	**(1,555,202)**	**(1,977,750)**
Net increase (decrease)-unrestricted current funds	**$ 928,894**	**$ (64,088)**

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

Statement of Changes in Fund Balances for the year ended December 31, 1988

	Current Funds					Plant Fund		Total All Funds	
	Restricted	Designated	Unrestricted	Total	Endowment Fund	Invested in Plant	Unexpended	1988	1987
Increases:									
Gifts, grants and contracts									
Government	$54,271,651			$54,271,651				$54,271,651	$40,876,863
Nongovernment	8,813,283		$670,392	9,483,675	$1,135,526		$10,207	10,629,408	6,515,936
Endowment and similar funds	3,233,066		1,260,688	4,493,754				4,493,754	3,332,634
Net increase (decrease) in realized and unrealized appreciation				–	3,370,896			3,370,896	(538,422)
Other	45,473		3,258,759	3,304,232	5,638			3,309,870	3,212,931
Total increase	66,363,473		5,189,839	71,553,312	4,512,060		10,207	76,075,579	53,399,942
Decreases:									
Expenditures	(60,166,313)		(2,705,743)	(62,872,056)				(62,872,056)	(51,930,741)
Depreciation (Note A)				–		$ (1,796,014)	1,534,200	(261,814)	(261,814)
Plant asset additions				–		2,019,398	(2,019,398)	–	–
Other				–				–	(173,492)
Total (decrease) increase	(60,166,313)		(2,705,743)	(62,872,056)		223,384	(485,198)	(63,133,870)	(52,366,047)
Net change before transfers	6,197,160		2,484,096	8,681,256	4,512,060	223,384	(474,991)	12,941,709	1,033,895
Transfers-additions (deductions):									
Current revenues to:									
Plant funds			(800,000)	(800,000)			800,000	–	–
Endowment funds			(581,979)	(581,979)	581,979			–	–
Director's Innovative Fund		$500,000	(500,000)	–				–	–
Other		(326,777)	326,777	–				–	–
		173,223	(1,555,202)	(1,381,979)				–	–
Director's Innovative Fund to endowment		(255,570)		(255,570)	255,570			–	–
Other	6,500	(6,500)		–				–	–
Total transfers	6,500	(88,847)	(1,555,202)	(1,637,549)	837,549		800,000	–	–
Change in fund balance	6,203,660	(88,847)	928,894	7,043,707	5,349,609	223,384	325,009	12,941,709	1,033,895
Fund balance, December 31,1987	3,634,351	1,030,914	1,524,337	6,189,602	84,299,263	21,017,789	8,401,756	119,908,410	118,874,515
Fund balance, December 31, 1988	**$9,838,011**	**$942,067**	**$2,453,231**	**$13,233,309**	**$89,648,872**	**$21,241,173**	**$8,726,765**	**$132,850,119**	**$119,908,410**

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:

We have audited the accompanying balance sheet of Woods Hole Oceanographic Institution as of December 31, 1988 and the related statements of changes in fund balances, and of current fund revenues, expenses and transfers for the year then ended. We previously audited and reported upon the financial statements of the Institution for the year ended December 31, 1987; totals for that year are shown for comparative purposes. 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 in accordance with generally accepted auditing standards. Those standards require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements. An audit also includes assessing the accounting principles used and significant estimates made by management, as well as evaluating the overall financial statement presentation. We believe that our audit provides a reasonable basis for our opinion.

In our opinion, the financial statements referred to above present fairly, in all material respects, the financial position of Woods Hole Oceanographic Institution as of December 31, 1988, the changes in its fund balances, and its current fund revenues, expenses and transfers for the year then ended, in conformity with generally accepted accounting principles.

Boston, Massachusetts
March 31, 1989

Coopers & Lybrand

Notes to Financial Statements

A. Summary of Significant Accounting Policies:

Fund Accounting
The accompanying financial statements have been prepared on the accrual basis. In order to comply with the internal designations and external restrictions placed on the use of the resources available to the Institution, the accounts are maintained in accordance with the principles of fund accounting. This procedure classifies resources into various funds in accordance with their specified activities or objectives.

Cash
Included in cash at December 31, 1988 and 1987 is $5,061,364 and $676,897, respectively, representing advances received from the United States Navy. Such amounts are restricted in use to certain vessel refit and other research programs. Interest earned on unspent funds reverts to the federal government.

Investments
Investment securities held by the Endowment Fund are carried at market value determined as follows: securities traded on a national securities exchange are valued at the last reported sales price on the last business day of the year; securities traded in the over-the-counter market and listed securities for which no sales prices were reported on that day are valued at closing bid prices. Purchases and sales of investment securities are recorded on a trade date basis. Realized gains and losses are computed on a specific identification method.

Investment income, net of investment expenses, is distributed on the unit method. Unrestricted investment income is recognized as revenue when earned and restricted investment income is recognized as revenue when it is expended for its stated purpose. Realized and unrealized gains and losses are recognized on a specific fund basis.

Contracts and Grants
Revenues earned on contracts and grants are recognized as related costs are incurred. The Institution has negotiated with the federal government fixed rates for the recovery of certain indirect costs. Such recoveries are subject to carryforward provisions that provide for adjustments to be included in the negotiation of future fixed rates. The deferred fixed rate variance account represents the cumulative amount owed to or from the federal government.

Gifts
Unrestricted gifts are recognized as revenue when received and restricted gifts are recognized as revenue as they are expended for their stated purposes.

Noncash gifts are generally recorded at market value on the date of gift, although certain noncash gifts for which a readily determinable market value cannot be established are recorded at a nominal value until such time as the value becomes known.

Plant
Plant assets are stated at cost. Depreciation is provided on a straight-line basis at annual rates of 2% to 12 1/2% on buildings and improvements, 3 1/2% on vessels and dock facilities and 20% to 33 1/3% on equipment. Depreciation expense on plant assets purchased by the Institution amounting to $1,534,200 in 1988 and $1,465,951 in 1987, has been charged to operating expenses. Depreciation on certain government funded facilities (*Atlantis II*, the Laboratory for Marine Science and the dock facility, amounting to $261,814 in each year) is accounted for as a direct reduction of the plant asset and invested in plant fund. Title to the research vessel *Atlantis II* is contingent upon its continued use for oceanographic research.

The Institution consolidates available cash from the plant fund with other cash in the current fund for investment purposes.

Reclassifications
Certain amounts in the 1987 presentation have been reclassified to conform with the 1988 presentation.

B. Endowment Fund Investments:

The cost and market value of investments held at December 31, 1988 and 1987, are as follows:

	1988		1987	
	Cost	Market	Cost	Market
Government and government agencies	$19,305,864	$19,188,872	$18,951,382	$19,252,899
Convertible bonds	337,795	278,438	282,969	253,688
Corporate bonds	8,907,202	8,745,226	5,658,389	5,413,084
Municipal bonds	–	–	250,000	238,750
Common stocks	19,869,737	23,079,219	39,384,883	43,145,739
Other	1,357,733	1,333,001	2,478,124	2,416,807
Total investments	**$49,778,331**	**$52.624,756**	**$67,005,747**	**$70,720,967**

C. Investment Units:

The value of an investment unit at December 31, 1988 and 1987 was $1.7596 and $1.6900, respectively. The investment income per unit for 1988 and 1987 was $.0901 and $.0682, respectively.

	1988	1987
Unit value, beginning of year	$1.6900	$1.7144
Unit value, end of year	1.7596	1.6900
Net change for the year	.0696	(.0244)
Investment income per unit for the year	.0901	.0682
Total return per unit	**$ .1597**	**$ .0438**

D. Endowment Income:

Endowment income consisted of the following:

	1988	1987
Interest and dividends	$4,845,424	$3,758,835
Investment management costs	(351,670)	(426,201)
Net endowment income	**$4,493,754**	**$3,332,634**

E. Retirement Plans:

The Institution maintains two noncontributory defined benefit pension plans covering substantially all employees of the Institution. Pension benefits are earned based on years of service and compensation received. The Institution's policy is to fund pension cost accrued.

Combined net pension expense for two plans consisted of the following for 1988:

Service cost	$2,321,584
Interest cost	3,599,781
Actual return on plan assets	(5,248,951)
Net amortization and deferral	874,647
Net pension expense	**$1,547,061**

Below is a reconciliation of the combined funded status of the plans at December 31, 1988:

Accumulated benefit obligation:	
Vested benefits	$35,670,545
Nonvested benefits	3,922,972
Total accumulated benefit obligation	**39,593,517**
Projected benefit obligation	55,616,960
Market value of plan assets	59,161,847
Plan assets in excess of the projected benefit obligation	3,544,887
Unrecognized net transition asset	(6,731,586)
Unrecognized prior service costs	768,125
Unrecognized net loss	1,444,390
Accrued pension cost	**$ 974,184**

In addition to the $59,161,847 of plan assets listed above, the Institution has approximately $1,100,000 available at December 31, 1988 to fund certain benefits.

The discount rate and rate of increase in future compensation used to determine the projected benefit obligation as of December 31, 1988 were 7.25% and 7.0%, respectively. The expected return on plan assets was 8.0%.

F. Post-Retirement Health Care Benefits:

In addition to providing pension benefits, the Institution provides certain health care benefits for retired employees and their spouses. Substantially all of the Institution's employees may become eligible for the benefits if they reach normal retirement age (as defined) or elect early retirement with certain time in service limitations. The cost of retiree health care is recognized as an expense when paid. These costs amounted to $193,301 in 1988 and $169,359 in 1987.