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About the covers:

Research Specialist Keith von der Heydt of the Ocean Engineering Department, one of the authors in this report, has captured some beautiful scenes in the Arctic during his many trips north for acoustic research. The front cover, looking through ice on the surface, was taken during the FRAM-II experiment in 1980. The inside front cover is a close-up of an icy brine finger. The inside back cover, showing polar bear tracks, was taken during MIZEX '83 (Marginal Ice Zone Experiment, 1983). The bear, incidentally, was never seen.

Annual Report 1987

Shelley M. Lauzon, *Editor & Designer*
Reynolds-DeWalt Printing, Inc., *Typographer & Printer*

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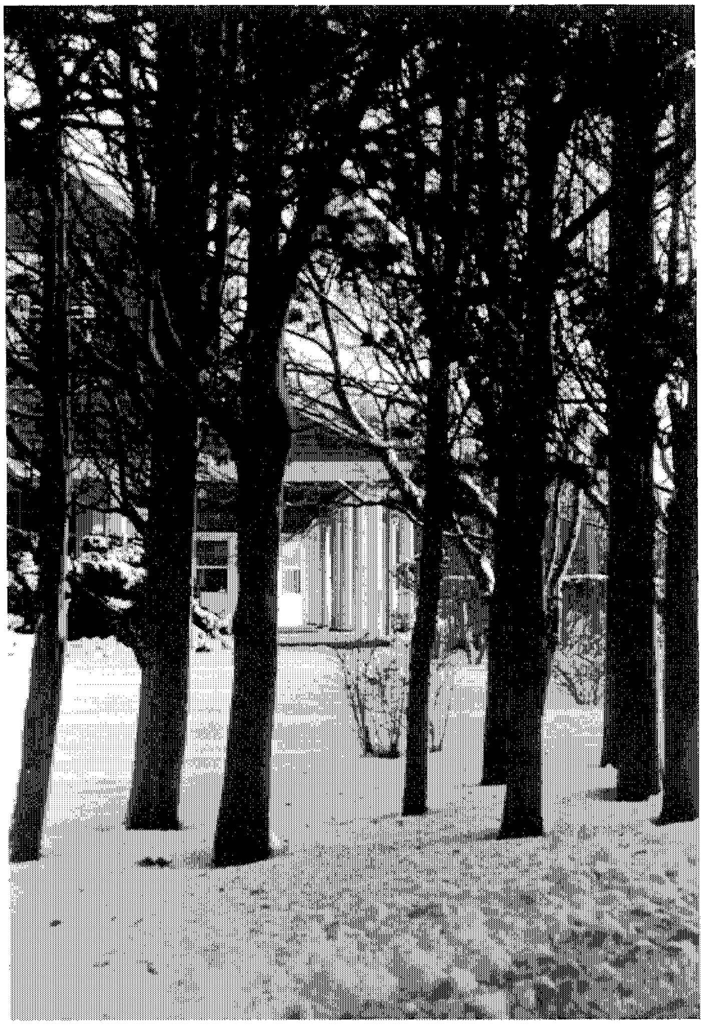
WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930

Photo by Terri Tallman



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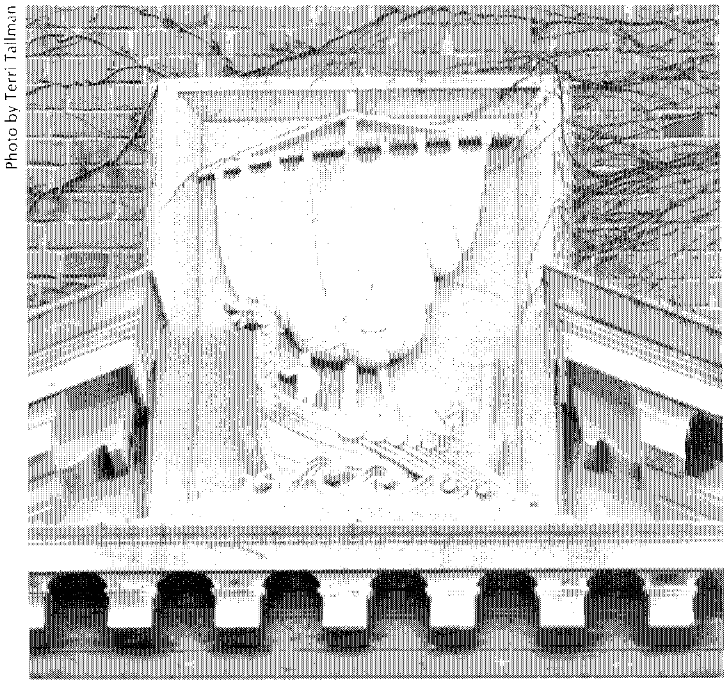

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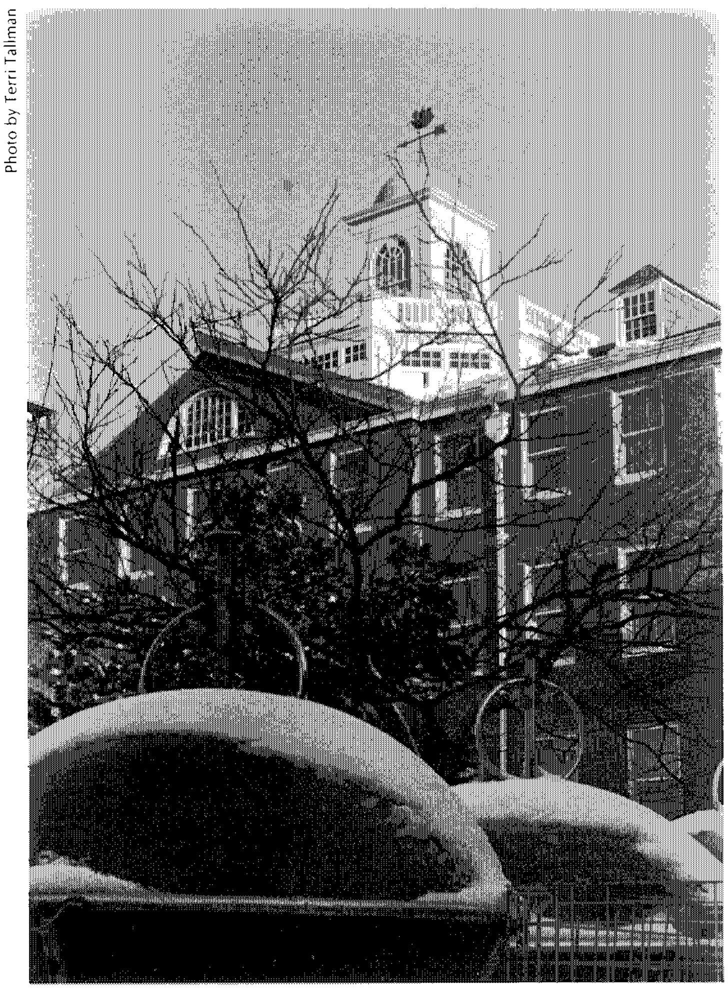


Clockwise from top left: Fenno House; the frieze over the main entrance to Bigelow Laboratory; the cupola of Bigelow Laboratory as seen from the Iselin Mall; and Meteor House, home of Director and Mrs. John Steele.

DIRECTOR'S COMMENTS

John H. Steele

Photo by Shelley Lauzon

Historically the Arctic Ocean has been relatively unknown except for the explorers — Peary on the ice, Byrd above it and the submarine *NAUTILUS* below. In 1977 the Russian icebreaker, *ARCTICA*, made a surface passage to the North Pole. Though few in number, research expeditions have been conducted in the Arctic. Notable among the early ventures was that by the Norwegian scientist Fram, who drifted round the Pole, locked in the ice to demonstrate the general circulation of the area. In recent years, we have constructed stations on ice islands such as T3. All of these efforts demonstrate the hazards of working and living in this environment. And this, perhaps, was the challenge as much as research results.

Now, however, there is a rapidly increasing need to study this area for commercial as well as scientific reasons. The exploitation of oil reserves off the North Slope raises questions about the "fragility of Arctic ecosystems". Fish stocks at high latitudes are over-exploited in the Bering and Norwegian Seas. These and other regional problems are coming together as a concern for the Arctic as a whole physical, chemical, and biological system.

There is a further need for more research in this demanding environment. Our interest in global climate change focuses on the oceans as the flywheel that can determine the nature and magnitude of the effects we may experience over the next several decades. Our present preliminary concepts indicate that such changes may be most marked at high latitudes. The ocean plays a major role in these polar regions where deep water is formed. We now believe that critical parts of this process occur in the Arctic Ocean, where the water is cooled and made more salty by the cascading of brine from the Siberian Shelf. Thus, our understanding of the processes producing climate change requires more study of the dynamics of northern waters, particularly in the Norwegian and Greenland Seas.

What are the difficulties in carrying out such research? They are partly technical and partly political. Technically, the problems of working in these areas in all seasons are obvious. Satellite measurements enable us to overcome some of these problems. The changing distribution of ice, for example, can be mapped regularly in this way. We can also put instruments under the ice for long periods and recover the data by transmission to satellite. Despite these sophisticated methods, we still need to have ships which can work in the ice itself. At present, the only suitable ships are Canadian, Russian and German. Much of the work described in this report was carried out on the *POLARSTERN*, a superb ship which was specially designed for polar research by West Germany. Future U.S. polar programs require us to have our own research vessel capability.

Politically, the United States interest in the Arctic has focused explicitly on Alaska and its offshore waters, where there are critical interactions between conservation and exploitation of resources. The strategic importance of the Norwegian and Greenland Seas now brings us into much wider context. There is a diverse mix of scientific, economic, and political reasons for carrying out research in Arctic waters. Scientifically, we need to have extensive collaboration with other countries. One major reason is the full and efficient use of the limited technical resources such as ships like West Germany's *POLARSTERN* capable of working in these regions. A second and possibly more significant reason is the importance of processes occurring within each nation's terrestrial waters — particularly true for the Russian shelf.

Work in the Arctic and adjacent seas poses problems which are not so different from those in other regions of the oceans: the relevance to global issues, the management of natural resources, international cooperation — or lack of it. But the Arctic is unique in the importance and in the sensitivity of these issues. No matter how technically advanced we may be compared with the early explorers, it remains the most demanding and hazardous for our human commitment.

AREAS OF INTEREST

DEPARTMENTS

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, planktonology, ichthyology, benthic biology, physiology, biogeochemistry and animal behavior. Work on marine pollution includes research on the effects of hydrocarbons and the biochemical responses of animals to these and other pollutants. The "patchy" distribution of many marine animals is under investigation as are the physiological adaptations of deep sea organisms to sparseness of food, low temperatures, high pressures, and deep sea thermal 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 and the behavior of large marine animals followed by tagging are being studied. Other work concentrates on salt marsh ecology and conservation, and nutrient cycling in coastal waters. The symbiotic relationships between marine microbes and other organisms (including wood-borers) are a recent focus. Gelatinous organisms of the plankton (salps, ctenophores, and jellyfish) are being studied with new techniques that finally allow us to properly evaluate the roles of these organisms in the oceans.

Chemistry

Chemical oceanographers are concerned with the composition of the ocean environment. They seek to understand the processes that have brought seawater and sediments to their present composition and that contribute to the observed variability. They also seek understanding of the extent to which the environment may be changed by both natural and man-made phenomena operating on a variety of time scales. Input from rivers and reactions at the air-sea, seawater-sediment boundaries and seawater-volcanic rock interaction at spreading centers are under investigation as chemists consider the processes taking place at major ocean boundaries. Some critical questions in chemical oceanography revolve around the vertical transport and transformations in particles as they fall from the surface waters to the bottom of the water column. The photochemistry of the surface ocean and the marine atmosphere is critical to our understanding of the global sources and sinks for many gases. The genesis and composition of the oceanic crust and its interaction with seawater is important to a general understanding of the oceanic system. Studies concerning the interstitial water chemistry of deep sea sediments help us to better understand the diffusive flux of ions between sediments and the oceans. Work on the fluxes of organic carbon includes determination of the amount of organic carbon produced in surface waters, the distribution, nature, and biogeochemistry of specific organic compounds in the marine environment, and studies of processes responsible for formation and diagenesis of organic matter in sediments. While studying radioactive isotopes in the ocean, whether as a natural occurrence or as a form of pollution, chemists are also finding the known decay rates of the isotopes useful as indicators for studying rates of water circulation, the in situ rates of chemical processes in the sea, and rates of biological and chemical processes that change the composition of seawater. Stable isotopic studies in rocks can be used as geochemical and petrological indicators of large scale terrestrial mantle processes.

Geology and Geophysics

Marine geologists and geophysicists study the processes which form and affect the earth beneath the sea, as reflected in its underlying structure and composition. The sedimentary and volcanic material of the seabed is investigated by direct sampling and remote observation. Coring, dredging, or drilling techniques are commonly used to obtain samples, which are further classified in the laboratory by petrological descriptions, geochemical analyses, and measurement of physical properties. Geophysical methods include the fields of seismology, gravity, magnetism, and geothermics. The establishment of plate tectonics as the primary kinetic process creating and shaping ocean basins has focused attention at the boundaries where plates interact. At divergent plate boundaries, or mid-ocean ridges, the processes which bring up hot materials to create ocean crust and lithosphere are studied in detail. Investigations of rifted continental margins are important to understand how continental plates initially break apart. Finally, subduction of oceanic lithosphere beneath either continental or other oceanic lithosphere is a process which is ultimately associated with the creation of deep-sea trenches and back-arc basins, accompanied by the important geological phenomena of earthquake belts and volcanic island arcs. In such geological processes, earth materials sometimes behave like viscous fluids, which can be modelled in the laboratory. Research is actively pursued on processes of particulate flux in the ocean ('marine snow'), carbonate and silicate dissolution, and other phenomena relevant to the transport of biogenic material to the sea floor. The results are essential to a better understanding of the fossil record, which in combination with studies of its oxygen isotopic variation reveal 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 sea floor 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. Historically, the activities were largely in the development of sensors and systems in support of scientific research in the institution. Within the past several years, the department has grown into a major center for research in a wide spectrum of scientific areas normally resident in traditional engineering departments at universities, although with a necessarily oceanographic accent. At the same time, the department maintains its leading position worldwide in sensor development and technical support. The areas of research include fluid mechanics, acoustics, remote sensing, robotics, biological processes, image processing, signal processing and estimation, and the dynamics of oceanographic cables. Active fluid mechanics programs include sediment transport in the deep-sea and on the continental shelf, in estuaries and in the shoaling and surf zones, in the dynamics of wind forced and internal waves, their growth and decay, in boundary layers and the mixing of surface and bottom waters of the sea and in the importance of biological processes to benthic transport. The acoustics efforts include ocean scale tomography, sound propagation in the Arctic, scattering by particles and the floor and surface of the sea, Doppler sonar and others. Satellite data are processed to study the sea surface, the ocean geoid, the surface wave spectrum, wind speed and direction, eddies and tides. 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, laser and acoustic sensors, low power underwater computer systems, mooring dynamics, pressure housing, underwater imaging etc. The solution to challenging problems requires creative combinations of principles of physics and engineering. Modern ocean science demands innovative instruments and measurement systems.

Physical Oceanography

Physical oceanography is the study of the physics of the ocean. Its central goal is to describe and explain oceanic motions, which occur 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, so as to smooth out the climate of the planet and make large parts of the earth habitable. Variations of the temperature and salinity, the driving effects of the 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 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 the mesoscale eddying vortical patterns of flow 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" whose sizes are on the centimeter scale. Important scientific questions also arise in considering the interaction of the ocean with the atmosphere. The ocean and the atmosphere 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 the local climate and ecology. Physical oceanographers are involved in experimental, theoretical, laboratory, and numerical investigations. Small programs and large international projects are underway, and multidisciplinary efforts are increasing. Our ultimate goal is understanding the structure and movement of the world's oceans, the interaction of the sea with its boundaries, and the physical role of the ocean.

RESEARCH CENTERS

Coastal Research Center

The objective of the Coastal Research Center (CRC) is to conduct research contributing to an ever-expanding base of knowledge and improved understanding of the coastal ocean, its physics, chemistry, biology and geology, which in turn will provide a basis for wise management of coastal resources. Interaction of multidisciplinary groups of scientists at the Institution is encouraged, and the Center supports multi-organizational and multinational efforts as appropriate. CRC, founded in 1980, is directed by David Aubrey, who took over the directorship from John Farrington in mid-1987.

The CRC continues to provide facilities support for various coastal research activities. Besides the large Coastal Research Laboratory (CRL) that provides laboratory and office space, two flumes became operational in 1987, both under the supervision of Dr. Cheryl A. Butman. In addition, a small boat fleet is maintained for nearshore research, ranging in length from 14 feet to 50 feet.

With the presence of a new director, the research activities of the CRC have evolved in 1987. Four principal project areas have been identified, leaving room for other projects as the opportunity arises. The first programmatic emphasis is on coastal impacts of global climate change. Addition of trace gases to the atmosphere has raised the specter of significant changes in global climate, impacting global temperature, precipitation patterns, and water and sediment budgets, for instance. These global changes will have their own impacts on the coastal zone: sea-level rise, storm climate changes, salinity intrusion into estuaries and aquifers, disequilibrium of river deltas, and so on. The CRC program is directed towards predicting and assessing the potential coastal impacts of climate change; with the Marine Policy Center the CRC is evaluating the potential costs and responses to such impacts.

The second CRC program is Assimilative Capacity of coastal oceans, a continuation of past successful programs at Woods Hole. This multidisciplinary effort is funded through Institution Sea Grant funds as well as private foundation funds. The geographic focus for the past three years has been on Buzzards Bay.

Two additional CRC programs include Instrumentation and Rapid Response. The Instrumentation effort is designed to provide seed funding for new instrumentation to be used for multidisciplinary coastal research programs. Two large seawater flumes have been completed recently under funding by the Instrumentation program: a 20-meter long flume and a racetrack flume. These flumes are designed to strict tolerance specifically for experiments on turbulence, sediment resuspension and transport, and interactions with marine biota. The Rapid Response program is designed to provide a rapid source of funds for response to marine "events". Since conventional funding channels require long lead times before initiating projects, opportunities to acquire baseline data immediately after an "event" often are lost. The CRC's Rapid Response program is designed to provide support for initial responses; the investigator then pursues follow-up research through conventional funding sources.

Center for Marine Exploration

A Center for Marine Exploration (CME) was established in late 1986 to foster the continued development of unmanned deep ocean systems and to provide a focal point for marine scientists and others to explore the deep sea. CME has four primary goals: 1) to provide scientists with more advanced and cost-effective techniques for deep ocean exploration, furnishing the means to conduct seafloor experiments; 2) to enable engineers and technicians to create new technologies for the deep sea; 3) to provide marine archaeologists and other social scientists opportunities to utilize this technology for cultural and historic purposes; and 4) to increase public awareness of the marine environment by making scientific and technological advances and discoveries available to the public through visual means.

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.)*. *JASON, SR.* is now in final construction with initial testing scheduled in mid 1988. These systems will allow many more scientists as well as the public to be able to participate in marine exploration by being able to see and experience the challenges, excitement — and setbacks, of scientific discovery.

A major focus of the Center will be the continued exploration of the 46,000-mile Mid-Ocean Ridge, the largest geological feature on earth. Research on this vast underwater mountain range has led to the accepted theory of plate tectonics and seafloor spreading, but the ridge stem remains largely unexplored and little understood. In December 1985 the Institution's *ARGO* system imaged an area of ridge terrain in just one week equal to all that previously viewed from manned submersibles, proving the capabilities of unmanned vehicle systems.

CME will also continue to attract skilled technicians and experts in such areas as materials science, electronics engineering, image processing, acoustics, optics, mechanical engineering, computer sciences, robotics and telecommunications to aid marine scientists in developing unmanned submersibles. The Institution's intention through CME is to add vitality to deep ocean exploration and to greatly increase the scope of exploration, which will further basic knowledge and man's ability to use the marine environment, by providing a scientific and cultural window to the deep ocean.

Marine Policy Center

The Marine Policy Center is the social science and policy research unit of WHOI. Directed by Social Scientist James M. Broadus, the Center provides a multidisciplinary setting for research on problems associated with the use of the world's oceans. 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 place research emphasis on the economics of ocean space and on the role of science in governmental and industrial decision-making.

The Marine Policy Center plays a constructive role in making known to the public the significance and policy implications of important findings in marine science, and thus serves as a link between the scientific and public policy realms. The accelerating pace of scientific and technical change, together with increases in the scale of effect from human activities, is reducing the "reaction time" for public policy responses to new knowledge and new developments. It is important, therefore, to understand the uses of marine scientific and technical information in the policy-making process, and the ways in which scientific and technical progress are themselves affected by policy choices. A primary objective for the research at the Marine Policy Center is to facilitate reduction of the "policy lag" so that effective policy responses to a rapidly changing world (and sometimes even more rapidly changing understanding of that world) can be achieved on a timely basis.

The Center's threefold functions are: 1) *Research* through the efforts of an experienced professional staff and Research Fellows; 2) *Education* through the prestigious Marine Policy and Ocean Management Fellowship Program, Institution seminars, and interaction with students; and 3) *Forum* for information exchange through sponsorship of workshops and conferences. The Center offers Postdoctoral and senior Research Fellowships to professionals in the social sciences, law or natural sciences to apply their training to research in marine affairs.

Individually, and as small teams, the Marine Policy Center's staff and Fellows engage in both specialized disciplinary and broader interdisciplinary research projects. The research program concentrates on 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; and 4) Areawide Planning and Management.

Through the publication of research results, the staff and Fellows have established a solid reputation for the Center in many areas of marine policy and ocean management. The research at the Marine Policy Center this year has addressed such diverse topics as: The Legal Status of Federal Consistency in Coastal Zone Management (J. Archer and T. Eichenberg); The Economic and Legal Status of Historic Shipwrecks (P. Hoagland and S. Bramhall); Uses of Science in the Galapagos Islands Marine Reserve (A. Gaines and J. Broadus); Establishment and Management of Marine Reserves (R. Kenchington and T. Agardy); Law and Politics of International Marine Pollution Control (K. Ramakrishna, C. Carlson, P. Haas); Social and Economic Impacts of Sea-Level Change (A. Solow, S. Edwards, J. Broadus, F. Gable); The Pace of Exclusive Economic Zone Mineral Resources Development (J. Broadus and P. Hoagland); Antarctica and the Law of the Sea (C. Joyner); and Soviet Maritime Arctic Policy, (L. Brigham and J. Broadus).

REPORTS ON RESEARCH

Robert B. Gagosian

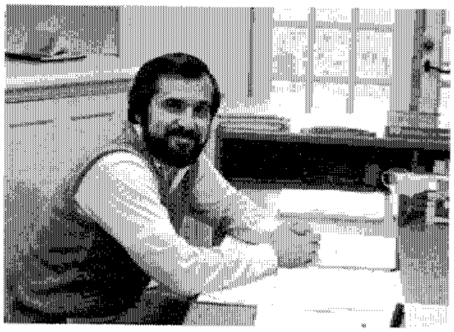


Photo by Shelley Lauzon

In this report we have usually highlighted a few specific projects within an area of research or given a broad overview of current research in our scientific departments. Due to the recent realization that human activity can contribute to processes of global change which can significantly alter our habitat within a few generations, it is most timely to focus on the Institution's contributions to our understanding of one of the most oceanographically important and environmentally sensitive regions of the world - **the polar regions of our earth system.**

The Arctic and Antarctic areas are of prime importance to a broad range of national interests that require scientific and engineering research. These include national defense, transportation and communication, management of natural resources and protection of these easily impacted environments. In addition these areas offer an excellent opportunity to undertake important scientific questions due to their uniqueness as natural laboratories.

One such problem is the understanding of global climate and weather. The polar regions are vital in controlling the global climate and are especially sensitive to climatic change. The recent field observations of the instability of the West Antarctic Ice Sheet and the seasonal decrease in stratospheric ozone levels over Antarctica are clear examples of this sensitivity. A better understanding of the coupling between the oceanic, atmospheric and continental systems of the earth's high latitude regions is crucial if we are to plan and predict the effects climate change, such as warming due to increased levels of carbon dioxide in the atmosphere, will have on our way of life.

Because of the cold temperatures of polar regions, they provide the heat sinks which drive the major atmospheric and oceanic circulation patterns. However, they are the least investigated of the world's oceanic areas. For long-term climate prediction, it is crucial that we understand certain processes unique to these regions such as the coupling between sea-ice cover and ocean circulation. Appreciating the importance of these processes, in the early 1980's, the Office of Naval Research launched a series of major experiments in the Arctic in which our scientists played a significant role - The Marginal Ice Zone Experiment (MIZEX) and the present Greenland Sea Project.

It has been further recognized by the scientific community that to predict the effects on climate change of man's increased burning of fossil fuel, we must determine, understand and model how the processes specific to polar regions remove heat transported to them by both the ocean and the atmosphere. For example, the extent and thickness of sea-ice has a major impact on this removal. Understanding this phenomena is important for the prediction of sea level rise in the future and its effect on coastal habitation. We are most fortunate that a unique record of past climates is preserved in the polar ice. Unraveling this historical record will not only yield information about previous climate patterns but will allow us to determine the processes important in controlling climate for future predictive capability.

The hostile environment of the polar regions is unique. It provides new and difficult technical challenges to our scientists and engineers while the perpetual ice cover restricts access to the ocean waters and sea floor. These harsh field conditions have spurred researchers on to develop autonomous measuring platforms and independent oceanic data collecting, analyzing and transmitting instruments at sites remote from both ice camps and ships. These systems have been developed to directly observe ocean currents under ice, map the outline of the polar ocean basins, determine the rates of sedimentation, and acquire acoustic propagation and meteorologican information on a comprehensive spatial and time scale. The application of satellite-based remote sensing techniques to assess the characteristics of the ice, such as ice sheet dynamics and melt rates beneath ice shelves and to detect and assess living and non-living resources in such harsh and desolate environments, has also proven to be quite an attractive approach.

Modern analytical chemical techniques have allowed our scientists to detect extemely low levels of human-produced chemicals such as freons and artificial radionuclides. These chemicals are extremely useful as tracers to examine ocean mixing, circulation, and geochemical processes. The success of this research has important implications on our understanding of the ability of the ocean to absorb substances from the atmosphere due to major perturbations such as the Chernobyl nuclear power station accident.

The overall importance of polar regions to the future success of our national goals has recently received increased recognition. For example, the Arctic Research and Policy Act of 1984 was an extremely important step in attempting to identify the scientific and engineering questions which need to be answered if we are to be successful in meeting our national objectives in the Arctic. A recent report by the National Science Foundation concerning its role in polar research emphasizes the important research areas which need to be addressed. The Interagency Arctic Research Policy Committee has created a document, United States Arctic Research Plan, which is a comprehensive five-year program plan for our overall national effort in Arctic research.

As will be seen from the following articles in this year's Annual Report, we highlight some of the science and engineering at Woods Hole Oceanographic Institution that is furthering the accomplishment of some of these national objectives in one of the least understood areas of the world oceans.

ARCTIC ACOUSTICS

Kenneth E. Prada and
Keith von der Heydt

Photo by Keith von der Heydt

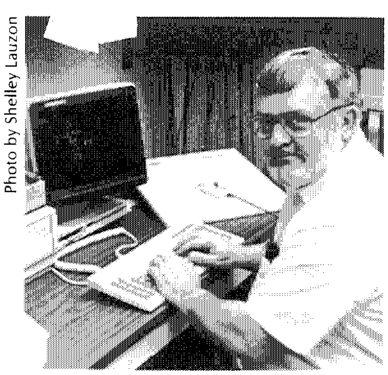
Photo by Keith von der Heydt

Top: The WHOI/MIT portion of the 1980 FRAM-II camp, located 86°N latitude, 22°W longitude. The boxy buildings were experimental prefab huts, complete with windows, used as sleeping quarters and a workshop. The more typical quonset style structure housed the acoustic and meteorological recording systems. Middle: Deploying radio link acoustic sensors through the ice during the 1983 Marginal Ice Zone Experiment (MIZEX). A helicopter transported a small team with equipment one to five kilometers (1/2-3 miles) from the ship (background). The small boat was sometimes used to cross between adjacent ice floes.

Bottom left: Keith von der Heydt. Bottom right: Ken Prada.

Photo by Shelley Lauzon

Photo by Shelley Lauzon



The Arctic is a critical region in which polar air, ice and water masses interact with the temperate ocean and climate systems. The processes which take place there profoundly influence hemispheric climate and have significant effect on commercial and naval operations. For more than a decade we have provided the principal tools and technological support personnel for Office of Naval Research (ONR)-sponsored acoustics research in the Arctic regions. In conjunction with a scientific team from the Massachusetts Institute of Technology (MIT) and an international group of scientists in many disciplines, we have participated in six major Arctic experimental programs, approximately one every two years.

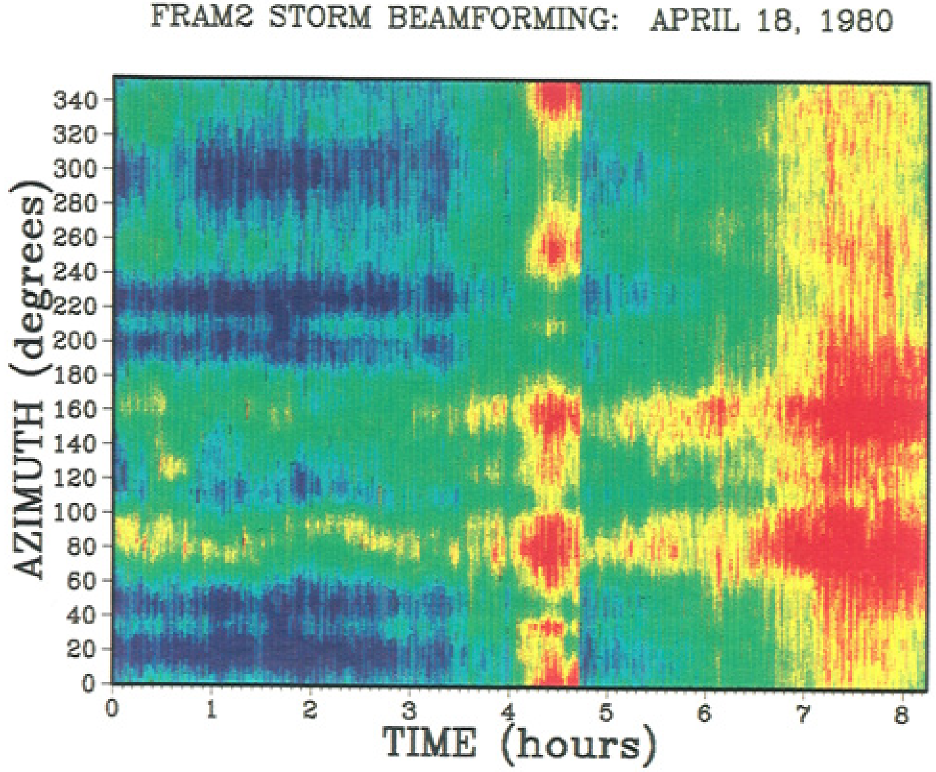
These programs have taken place in both the stable pack ice of the central Arctic and the dynamic floe areas of the Marginal Ice Zone (MIZ). The ice pack supports camps of 15-25 persons (see photograph), while work in the MIZ is from ice-strengthened ships that venture in and among the ice floes. In both cases, planes and helicopters provide extended range and mobility to carry out a wide variety of experiments. The programs typically involve from three to four weeks of concentrated measurements, with additional time needed for setup and breakdown of the camp. Depending upon the experimental area and objectives, satellite photographs may assist in determining the locations of suitable ice. Additionally, numerous low-altitude flights are made to determine local ice conditions and to locate ice regions of suitable characteristics. In general, a site is selected that has an older or "multi-year" floe, two to five meters (six to sixteen feet) thick, adjacent to a newly frozen area. The older floe, having survived collisions for several years, is likely to remain intact for the duration of the experiment program. The newer and smoother ice is used as a runway, often permitting aircraft to use wheels rather than skis.

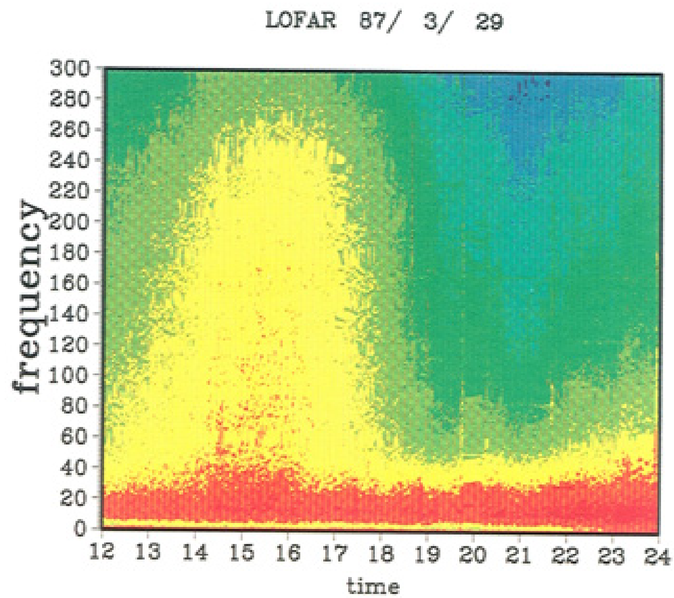
Our role in Arctic research is to provide the specialized tools needed to make measurements. Some of the tools developed here include:

- a multi-channel ice implanted hydrophone array;
- an acoustic hydrophone tracking system to monitor movement and configuration of the hydrophone array;
- a wide bandwidth multi-channel data collection system using microcomputer control and high volume laser disk data storage (up to one billion bytes);
- a real-time ambient noise spectra color display system.

The acoustic studies are numerous and varied. They include mass volume reverberation to map the outlines of the Arctic ocean basins, seismic refraction and reflection to map the ocean bottom and sub-bottom beneath the ice, coherent sound transmission to study the acoustic conduction properties of the waters beneath the ice, and ambient noise monitoring. Ambient, or background, noise is a measurement of considerable interest since it is highly affected by ice activity. Figure 1 shows a directional analysis of ambient noise encountered during a storm. The peaks of noise from specific directions indicate where the storm driven ice activity is the most intense. Localized variations in noise are shown in Figure 2. Sustained increases in wind velocity over a period of several hours caused the upward shifts in noise frequency and intensity. This type of color display is generated continuously throughout the duration of the field program and provides the researcher with valuable information concerning ice activity and their interaction with other experiments. The information aids in deciding when to conduct certain measurements that might be masked by an intense noise background.

Arctic research presents some unique and substantial problems. The perpetual ice cover restricts access to the ocean waters and bottom. Experiments are carried out from ice camps whose location is a compromise between desired scientific location and that allowed by ice conditions. These conditions influence the ability to safely establish and maintain a camp, and to provide a nearby





Top: Directional analysis of ambient noise encountered with an Arctic storm during the 1980 FRAM-II experiment. Data from 18 hydrophones suspended 90 meters (295 feet) below the ice were processed with a beam-forming technique. During the eight-hour period shown here, the ice camp drifted approximately three nautical miles and a major pressure ridge was forming to the south of the camp. Bottom: A reproduction of the real-time display from the PRUDEX 1987 recording LOFAR system, showing intensity and frequency shifts of ambient noise. The shifts are the result of increases and decreases in wind velocity and currents.

landing area for support aircraft. The ice chosen must be thick enough to support the camp and in a region presumed to provide long camp life. Camps are often disrupted by ice break-ups, ridging or rafting.

An acute problem is the limitation imposed by ice camps and ships. Ice camps are rarely stationery but move at the whim of winds and currents. Measurements are made where the ice carries the camp. Ships operating in the MIZ are restricted by highly variable ice conditions and the individual ship's ability to penetrate the ice. Many phenomena, such as the growth and propagation of ice-ocean eddies or the generation of ice edge low air pressure zones, cannot be studied because the camp or ship cannot be placed at the proper location at the proper time.

Our most recently developed tool is meant to overcome some of these limitations. It is an autonomous measurement platform designed to concurrently collect and analyze acoustic, meteorological and oceanographic data at sites remote from both ice camps and ships. It is a highly intelligent instrument capable of adaptive sampling based upon varying conditions and data values. This platform can transmit some of its collected data by satellite or to overflying aircraft. Larger amounts of data can be stored internally using new technology laser disks. The instrument's goal is to broadly expand data coverage in both space and time while reducing the burden on ships and aircraft in obtaining measurements. It can enhance the usefulness of data in expanding our understanding of the Arctic ice-ocean-air processes, and provide future autonomous measurements over extended periods of time that ships or ice camps cannot sustain without great cost or difficulty.

All aspects of Arctic research present unique and difficult challenges to the involved scientists and engineers. The environment demands critical attention in the design of instrumentation. That same environment is no less harsh for the researcher who must establish the ice camp, deploy the instruments, and collect the data. The weeks of life and work in the Arctic regions are challenging, difficult and uniquely rewarding.

GREENLAND SEA TOMOGRAPHY

James F. Lynch

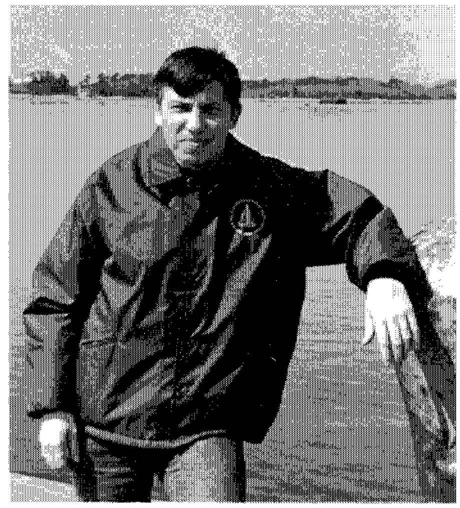


Photo by Shelley Lauzon

Ten years ago, Walter Munk of the Scripps Institution of Oceanography and Carl Wunsch of the Massachusetts Institute of Technology (MIT) published a classic paper which outlined the basic formulation of ocean acoustic tomography (OAT). During the ensuing decade this technique, which in simplest terms acoustically makes a series of 3-D snapshots of the sound speed and current structure of a volume of ocean, underwent an intense period of both theoretical development and experimental testing. The results of this ten-year development period were a reliable experimental technique, a suite of well-engineered acoustic instruments, and a wealth of new knowledge concerning acoustic propagation in the ocean.

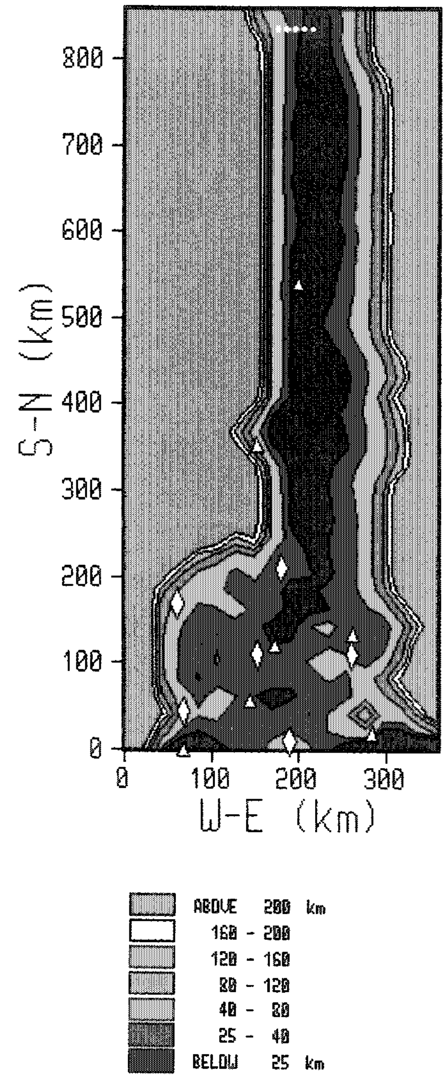
Novel oceanographic results were rather scarce during this period, as these depend to a larger extent on the maturity of the experimental and analytic techniques. However, during the last year, two related basin-scale tomography experiments in the Pacific Ocean were successfully conducted which promise to produce exciting new oceanographic results, as well as enhance our understanding of acoustic propagation. Two more large-scale tomography experiments with a strong oceanographic component are due to be deployed in September 1988, one to monitor the Gulf Stream as part of the SYNOP experiment and the other to monitor the Greenland Sea gyre as a central component of the Greenland Sea Project. Should all these experiments deliver the expected results, many insights into large-scale ocean circulation will be gained, and tomography will take its place in the experimental oceanographer's too box.

The Greenland Sea tomography experiment is a major component of the Greenland Sea Project (GSP), a multinational, multidisciplinary effort to study the Greenland Sea on a long-term basis. The tomography array, which is a Scripps/Woods Hole Oceanographic Institution (WHOI) collaboration, is composed of six moored transceivers (transmitters and receivers) surrounding the gyre which will send out six acoustic transmissions per day over the course of an entire year, thus allowing six daily snapshots of the gyre.

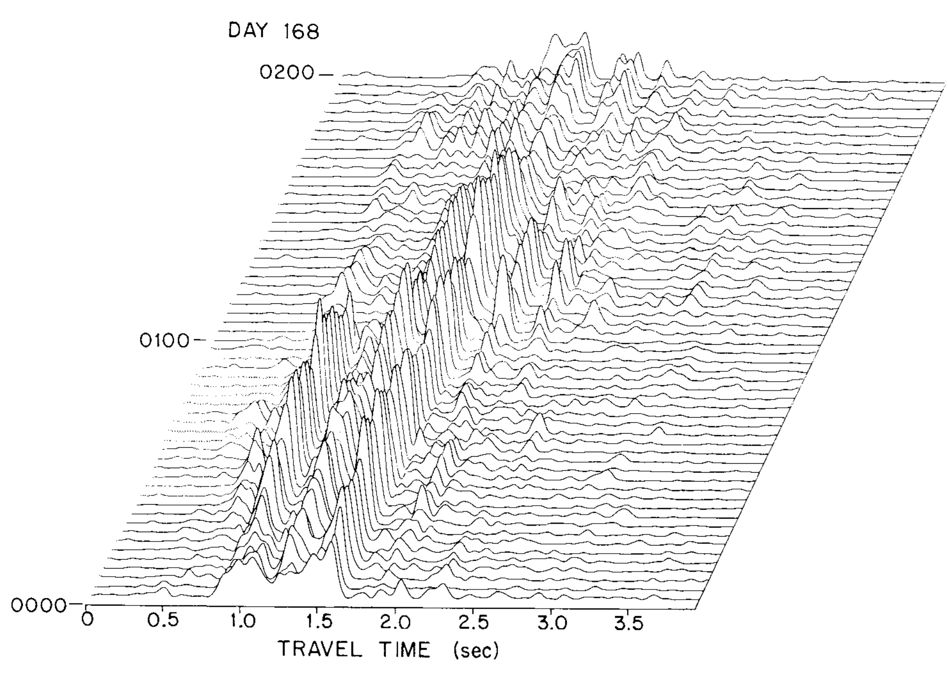
These transmissions will be supplemented by year-long CTD (conductivity/temperature/depth) surveys, meteorological observations to determine wind stress, aircraft and satellite remote sensing, and numerous nearby oceanographic instrumentation moorings. The tomographic transmissions will also be monitored in the spring of 1989 by a drifting acoustic array moored to ice floes some 600 kilometers (375 miles) to the north. This northern array, an MIT/WHOI joint experiment, is part of the Coordinated Eastern Arctic Experiment (CEAREX).

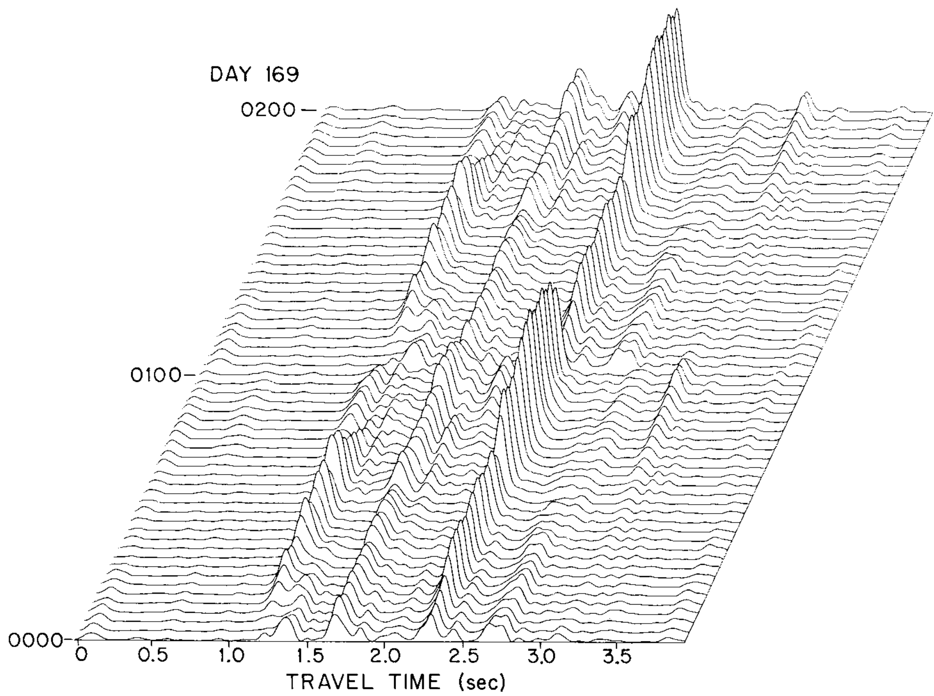
The size resolution of ocean features we will achieve is shown in Figure 1, with the acoustic tomography array being denoted by white diamonds, the moored current meters/temperature sensors being denoted by white triangles, and the drifting northern array being denoted by a row of white circles. This diagram indicates that we can generally resolve ocean features on the order of 25 kilometers (15 miles) across. As the mesoscale (eddy size) distance is on the order of 10 kilometers (6.2 miles) at this latitude (80°N), this is a bit less resolution than what we would optimally desire, but still good considering the total amount of area the array covers. By adding satellite and aircraft remote sensing to this array experiment, it becomes possible to resolve ocean features and ice cover to submesoscale distances, our ideal for oceanographic studies. A direct benefit of having reasonably fine-scale feature resolution, as well as a diverse suite of oceanographic measurements, is the possibility of assimilating our data into numerical models of the ocean, which can then be used in forecast and hindcast modes to check their consistency with the real world. A Marginal Ice Zone (MIZ) region such as the Greenland Sea is a challenge to model numerically, particularly because of the complicated heat exchange and wind forcing dynamics induced by the fluctuating ice cover. This makes the interaction of the models with our data set all the more interesting and important. We are currently talking to groups at Harvard University (A. Robinson) and Princeton University (G. Mellor) regarding the use of their models and have high hopes for fruitful collaborations.

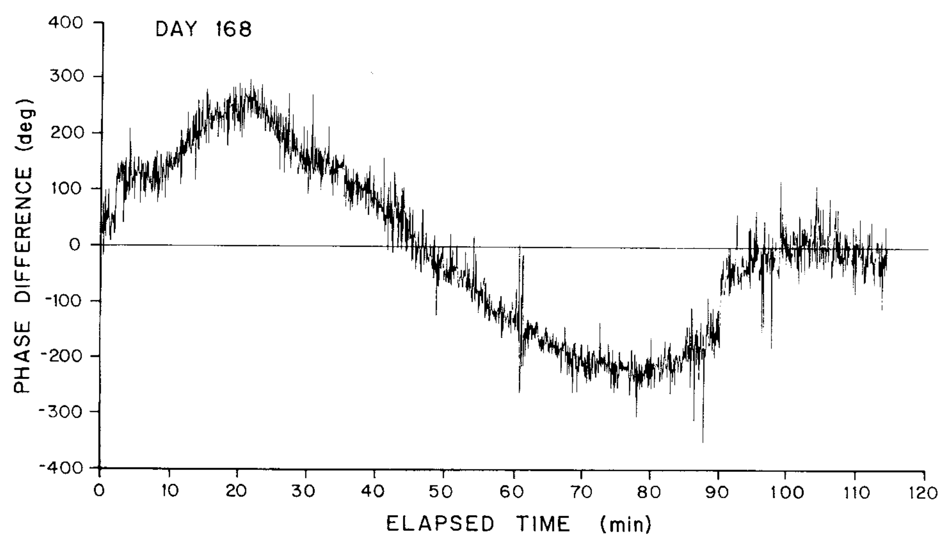
There are many scientific questions the Greenland Sea tomography experiment will attempt to answer. We will consider only three of the major ones here, two concerning physical oceanography and one concerning acoustics. The first question we hope to answer is: How is the anomolously oxygen-rich Greenland Sea Deep Water (which later becomes North Atlantic Deep Water) formed? There are various theories to explain this phenomenon, perhaps the most popular being the drastic overturning of the gyre by means of convective "chimneys" which funnel the surface water down ward. Currently, there are no observations to support or disprove any specific theory. Our year-long observation schedule gives us an excellent chance to detect short-lived, infrequent events such as chimney formation, though our spatial resolution may or may not be adequate to detect individual chimneys.



Top right: The size resolution of ocean features is shown in Figure 1, with the acoustic tomography array denoted by white diamonds, the moored current meters/temperature sensors denoted by white triangles, and the drifting northern array denoted by a row of white circles. Bottom: Waterfall plot of the acoustic multipath arrival time structure on day 168. (Figure 2)







Top: Waterfall plot of the same transmission path on day 169 (Figure 3). Bottom: The scattering of a single multipath in MIZEX '84 (Figure 4).

The second oceanographic question of interest is: How does the wind stress on the surface drive the circulation pattern (vorticity) of the gyre? The simultaneous measurements of the meteorology, ocean currents and ice cover (which to some extent cuts off the wind stress) should allow an understanding of the gyre forcing throughout its annual cycle. The last question concerns acoustics: What is the nature and variability of acoustic propagation in a strongly surface-interacting region like the Greenland Sea, where the ice cover varies drastically both in extent and character during the course of a year? Although some measurements of surface scattering in the Marginal Ice Zones (MIZ) have been made to date (some which we will discuss below), no long-term monitoring of a precise acoustic signal has yet been done, making this a unique opportunity.

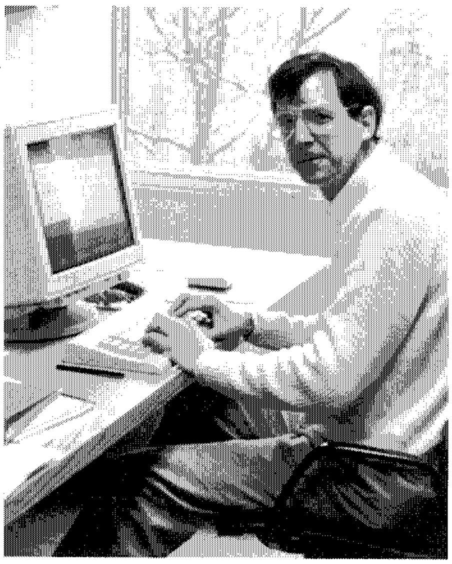
It should be noted that the Greenland Sea tomography experiment will not be the first tomographic transmission in the MIZ. Four years ago, a group led by Robert Spindel of WHOI set out a tomographic source just north of the Greenland Sea gyre off Spitzbergen to "test the waters" on a small scale for the GSP tomography experiment. These transmissions, which were at close to the same center frequency as the GSP will be (but using much lower power and bandwidth) lasted for ten days as part of the summer 1984 Marginal Ice Zone Experiment (MIZEX '84). In even that short time, we were able to see very detailed effects of surface scattering, which will be crucial to acoustic transmissions in the upward refracting Greenland Sea. Figures 2 and 3 show waterfall plots of the acoustic multipath arrival time structure for the same transmission path on two different days. While the day 168 paths (Figure 2) are very noisy and irregular, the day 169 paths (Figure 3) are stable, clean and more intense. These differences were caused by rough surface scattering by surface waves, day 168 showing four-foot waves while day 169 was flat calm. This scattering generally makes a big difference in how many ray arrivals can be seen, their intensity (signal to noise), how they are identified, and their stability (duration), all of which are crucial to the tomographic solution for ocean structure.

Figure 4 shows in more detail the scattering of a single multipath in MIZEX '84 (using phase difference, which is proportional to travel time). The large sine wave reflects internal wave scattering, whereas the fine fluctuations are due to surface waves. These scattering signals will be noise to us for the Greenland Sea tomography effort, but may also be taken as signals in other contexts. This particular observation in MIZEX '84 by WHOI researchers led to the development of surface wave tomography, a new branch of acoustic tomography. It is hoped that the rich Greenland Sea data set will yield equivalent insights into surface scattering as well as answers to the important oceanographic questions posed in this report.

SEA-ICE EXTENT

W. Brechner Owens

Photo by Shelley Lauzon



The Earth's polar regions have a principal role in global climate since they provide the heat sinks that drive the major circulation patterns in both the atmosphere and oceans. Before we can correctly predict climate changes due to such effects as the burning of fossil fuels and the diversion of major rivers flowing into the Arctic Ocean, we must be able to observe and model several important processes unique to polar regions. These processes determine the way in which heat transported towards the poles by both oceanic and atmospheric circulations is removed. For example, the surface heat budget in ice covered regions is sensitive to the surface albedo which, in turn, changes dramatically depending on the presence of ice or open water. This implies that we must monitor and model sea-ice extent and thickness distributions. Cold saline water, produced at the surface due to brine rejection during ice formation and by atmospheric cooling of open water, is believed to be the source for the mid-latitude abyssal circulation of the world's oceans.

New oceanographic evidence suggests that deep water formation involves many processes that occur throughout the polar regions (Aagaard, et al., 1985), rather than only those local to the regions of deep convection, such as the Greenland Sea or Iceland Sea (Figure 1). For example, an active Arctic thermohaline circulation is believed to have a dramatic effect on the heat transfer from the ocean into the atmosphere. During ice melt a shallow, fresh surface layer is formed that impedes the vertical release of heat from the warm Atlantic water that flows into the Arctic Ocean. During ice formation, cold saline water produced on the continental shelves mixes with the Atlantic water and changes its properties. This modified water flows out into the Greenland Sea and is crucial to deep convection.

Two activities in the Institution's Physical Oceanography department address these important issues: modeling of the interactions between the atmosphere, sea-ice and the upper layers of the ocean; and the development of a neutrally buoyant, acoustically tracked float system for directly observing ocean currents beneath ice cover regions.

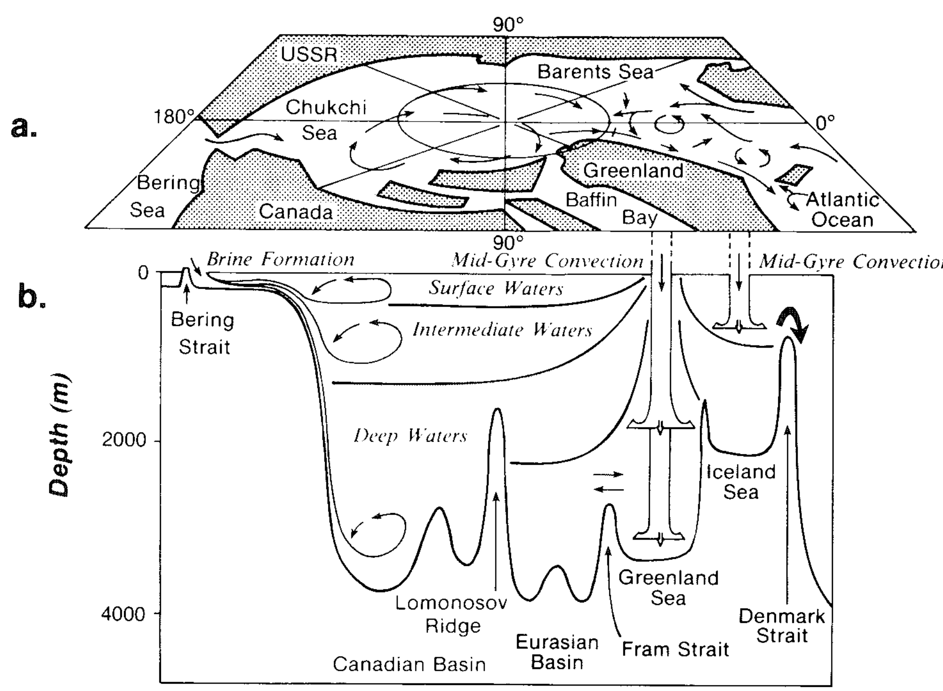


Figure 1: Schematic circulation (a) and water-mass structure (b) of the Arctic Ocean and surrounding seas (from Aagaard, et al., 1985). The cross-section corresponds approximately to the 0°-180° longitudes.

The modeling effort, begun in September 1986, is a collaborative effort with P. Lemke at the Max Planck Institut fuer Meteorologie, Hamburg, Federal Republic of Germany, and W. Hibler at Dartmouth College. We have developed a coupled sea-ice-upper ocean mixed layer model and have used it to simulate the seasonal cycle of ice extent and thickness in the Weddell Sea. Sea-ice at a grid cell of the model will grow or disappear due to exchanges of heat through the upper surface of the ice by radiation, sensible and latent heat fluxes as well as by horizontal advection due to ice movement. The ice velocities are calculated from a momentum balance that includes atmospheric, oceanic, and internal ice stresses, Coriolis force and inertial effects. The heat flux from the ocean into the sea ice is determined through the entrainment heat flux into the mixed layer, which is in turn determined by the dynamic mixed layer model. Deepening of the mixed layer by convective overturning due to brine rejection during ice formation is also included.

A series of simulations of the annual cycle of ice cover in the Weddell Sea have been carried out to investigate the sensitivity of the model to changes in its various parameters. For example, when changes occur in the area of the Weddell Sea covered by ice, that change represents ice extent and is particularly sensitive to the details of the mixed layer model. In ice-free areas, the heat content of the ocean depends on ocean physics: ice cannot form until the ocean is cooled to the freezing point. On the other hand, parameters which change the thermodynamics and internal ice stress do not have a dramatic effect on extent, but can significantly change the ice volume (or equivalently, the thickness of the ice cover). For example, the addition of a snow layer on top of the ice has two competing effects: an increase in surface albedo which decrease the absorption of radiation, and greater insulation which reduces the heat flux through the ice during winter. The latter effect is stronger, resulting in a decreased ice volume (Figure 2). Work is now underway to integrate this sea ice-mixed layer model to a oceanic general circulation model.

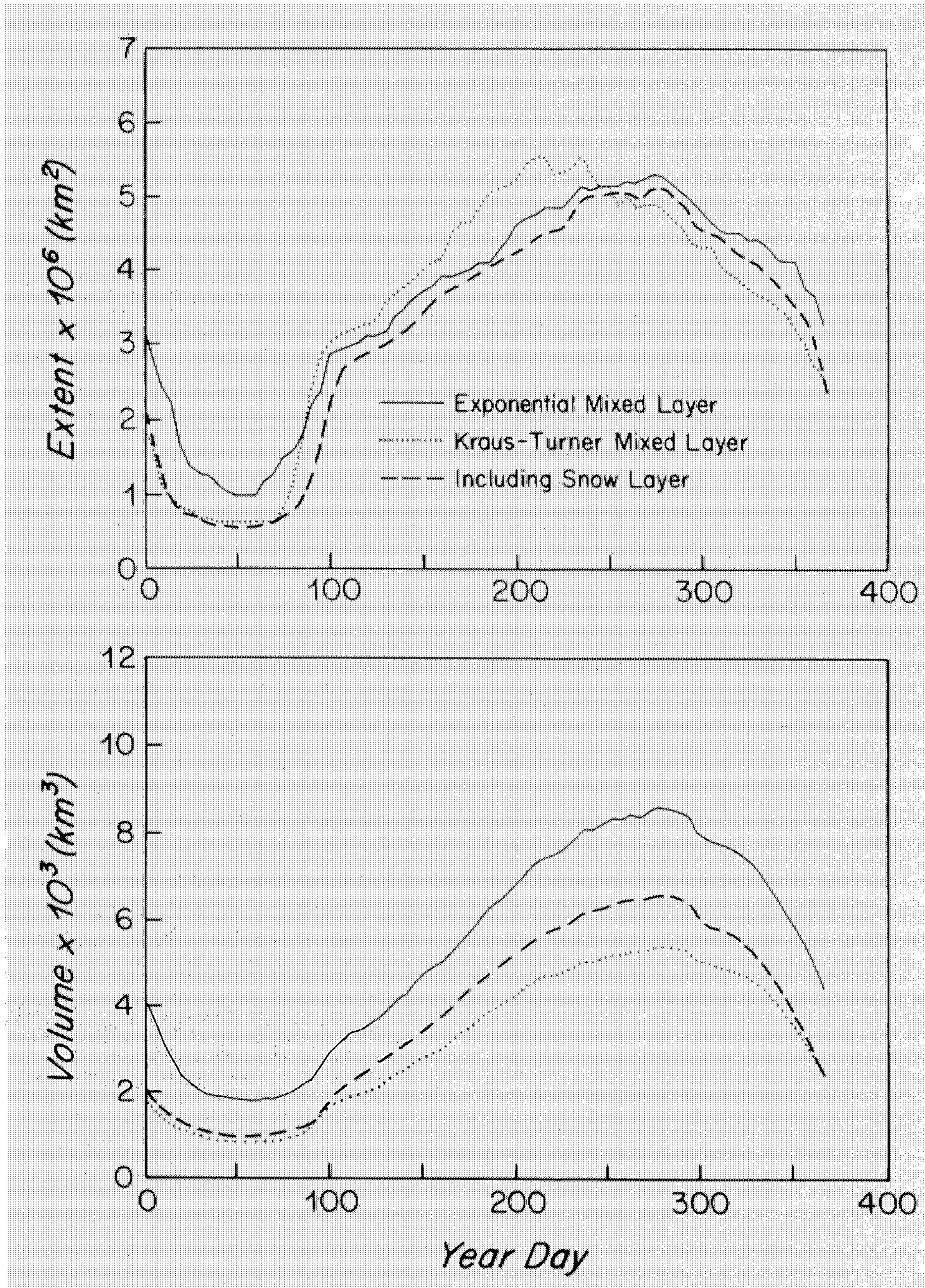


Figure 2: Simulations of the seasonal cycles of ice extent (areal coverage) and total ice volume for the Weddell Sea. Curves are: a) mixed layer model with exponential profile, b) inclusion of snow cover, and c) mixed layer model with three slab layers.

This will allow us to determine how the ocean responds to the strong input of salt and the removal of heat associated with ice formation.

The second activity, also begun in 1985, is the modification of the Sound Fixing And Ranging (SOFAR) float technology for use in ice-covered regions. These instruments are neutrally buoyant floats that send out acoustic signals at regular intervals. These signals are detected by other moored instruments (Figure 3). Knowing the average speed of sound between the float and listening stations and using simple geometry, we can then obtain the position of the floats. By following the float we can obtain direct velocity measurements. Two modifications of the existing, mid-latitude system are necessary, however, before the floats can be used in polar regions. The frequency of the acoustic signal must be lowered from 250 Hz to 80 Hz, and a version of the listening station that can be moored through the ice must be developed.

The first modification is necessary because the vertical profile of sound speed in polar regions is very different from that in mid-latitudes. Sound waves are trapped in a surface duct, and as they travel away from the floats they repeatedly reflect off the bottom of the ice. In mid-latitudes a mid-depth sound duct trap allows the floats to be tracked at ranges in excess of 2000 kilometers (1250 miles). By going to lower frequencies, we increase the wavelength of the sound waves. There is less bottom roughness at these longer scales so that the waves are more efficiently reflected and can be detected at longer ranges of up to 1000 kilometers (624 miles).

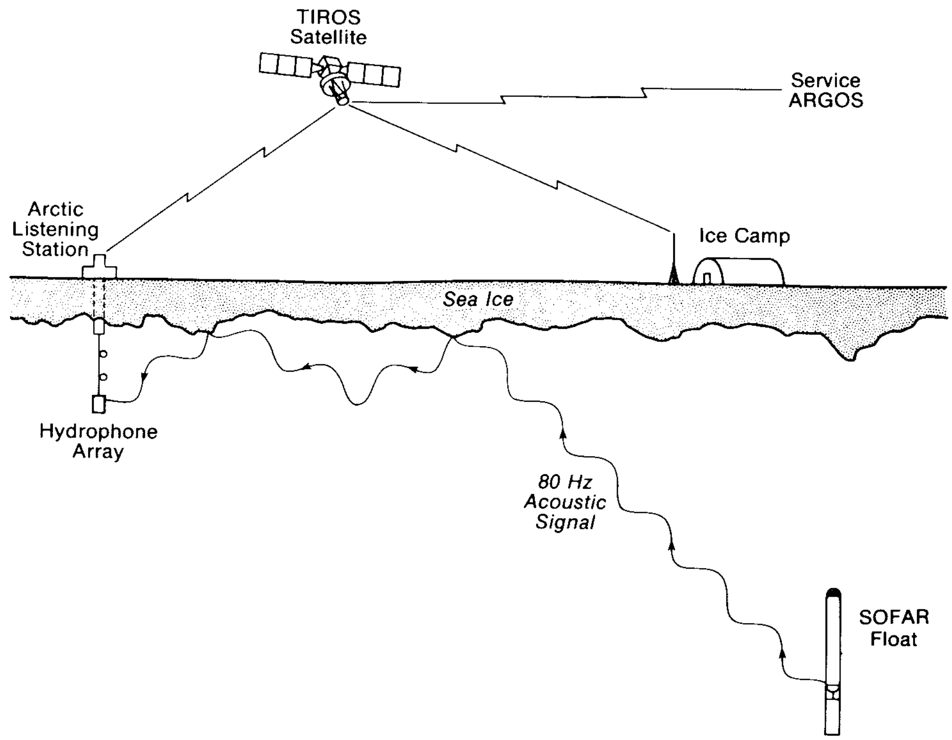


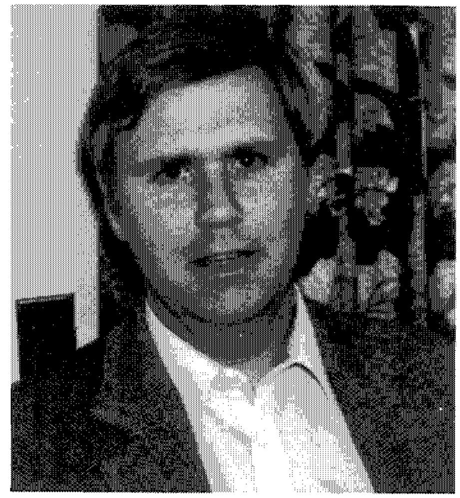
Figure 3: Schematic of the acoustically tracked float system for use in polar regions.

This new float system will be used as part of the Coordinated Eastern Arctic Experiment (CEAREX) starting in September 1988. The floats will be deployed in the Atlantic water flowing into the Arctic Ocean north of Svalbard to provide the first long-term direct current measurements of this flow in the central Arctic. Additional floats will be deployed in collaboration with T. Manley of Lamont-Doherty Geological Observatory in mesoscale eddies in the Marginal Ice Zone so that these eddies can be tracked in real-time and changes in its ecological system monitored. Plans are now being made to use this new measurement system to carry out an investigation of the poorly understood Weddell Sea Gyre which is thought to be a major source for Antarctic Deep Water.

Once we have proven the viability of this new technology for measuring currents under ice cover, we expect to use it to map out the circulation and eddy variability in the polar oceans. Similarly, the development of a well-understood coupled sea-ice-ocean model is important to long-term climate prediction.

THE ANTARCTIC AND REMOTE SENSING

Christopher C. Joyner



The Antarctic is a unique wilderness habitat encompassing nearly one-tenth of the earth's surface. The continent is a vast white desert, an archipelagic-like land mass cemented together by an immense ice sheet. Antarctica is also the highest, coldest, windiest, driest, most desolate and lifeless region on earth. Yet, the surrounding Southern Oceans teem with biological bounty and serve as the feeding ground for millions of whales, seals, penguins, birds of flight, and zooplankton, particularly krill. Given the largely unexplored, environmentally harsh and desolately estranged nature of the Antarctic, satellite-based remote sensing activities would appear an attractive opportunity to facilitate detection, location and assessment of living and non-living resources on and around the continent. The Antarctic Resource and Remote Sensing Project undertaken at the Marine Policy Center during the summer of 1987 examined the feasibility of remote sensing technology presently available for resource detection operations both on and offshore Antarctica, as well as the international legal and policy implications of conducting remote sensing activities by satellites overflying the Antarctic region.

The far side of the moon today is better mapped than much of the Antarctic continent. Remote sensing systems operate to detect the intensity of electromagnetic radiation that the earth's surface reflects, emits, or scatters along different spectral bands in visible and infrared wavelengths. Valuable but limited data is presently being gathered about the Antarctic by three principal kinds of satellite remote sensors: visible and infrared scanners, which portray spatial resolution but are severely inhibited in the Antarctic by cloud cover and darkness; microwave radiometers, which measure thermal radiation from the polar surface expressed as brightness temperatures; and synthetic aperture (imaging) radar, which uses the satellite's motions to synthesize a larger radar beam for higher resolution of the sensed surface. Within the next decade, the United States, Canada, France, Japan, and the European Space Agency will have launched at least ten series of polar-orbiting satellite missions carrying remote sensors for Antarctic-related studies.

Satellite application of remote sensing to the Antarctic thus far has primarily analyzed and assessed the character of ice, the most pervasive known resource on and around the continent (Figure 1). The continental ice sheet contains more than 90 percent of the world's ice (amounting to 70 percent of the earth's fresh water) and covers some 13.9 million square kilometers (87 million square miles), an area larger than the United States. The surrounding belt of Antarctic sea ice expands out to a maximum of 20 million square kilometers (13 million square miles) during the austral winter, nearly doubling the size of the continent. Data received from remote sensing satellites has revealed much about ice sheet dynamics, drainage basin activity on the continent, glaciological stress and calving rates, melt rates beneath the ice shelves, and the interrelationship between ocean circulation and sea ice cover. However, when applied to minerals prospecting, remote sensing over Antarctica has been severely constrained. Satellite sensing techniques are unable to penetrate the massive, 2000-meters (6560 feet)-thick ice sheet overlaying virtually all of the continent. Consequently, location of subglacial bedrock provinces and precise determination of their mineral composition lie beyond the technological capability of contemporary remote sensing systems.

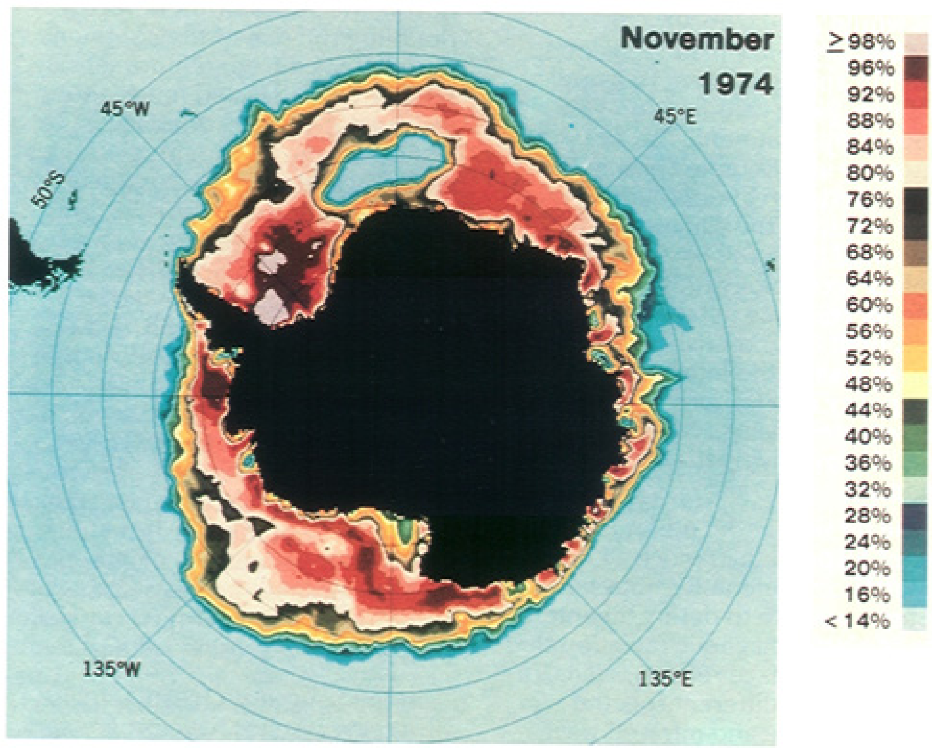
In the Southern Ocean, satellite observing systems have progressed sufficiently to facilitate sophisticated studies of polar oceanography. Images produced by satellite remote sensing can determine ice concentration (Figure 2), sea-surface temperature and chlorophyll pigment concentration in phytoplankton. In the circumpolar Antarctic marine ecosystem, use of these processes has taken on particular significance for ascertaining krill locations more accurately. Krill tend to swarm in regions of upwelling where nutrient levels are high and phytoplankton bloom. Phytoplankton serve as the principal source of food for krill, which represent the key ingredient in the Antarctic marine food chain. Correspondingly, where dense concentrations of phytoplankton are located, there are likely to be found high populations of zooplankton, undoubtedly including many krill swarms. Remote sensing data not only supply clearer indications of krill swarm locations; they also reveal more precisely composite biomass and productivity trends.

Remote sensing of the Antarctic sea floor is largely precluded by the physical fact that water absorbs or reflects most wavelengths of electromagnetic energy. At great depths, such as in the Southern Ocean, scant energy can be reflected from the ocean floor; hence, useful image detection of seabed terrain, never mind that of possible dispersed deposits of ferromanganese nodules, is substantially prevented. In sum, use of remote sensing for gauging Antarctica's natural resource potential is limited, simply because several desirable applications are presently beyond the scope of technological capability. Neither resource discovery nor recovery on, in or around Antarctica has yet been revolutionized by satellite remote sensing.

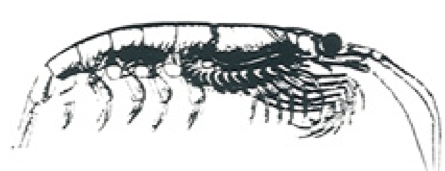
The international regime administering national activities in the Antarctic operates under the legal auspices of the Antarctic Treaty of 1959. There are today thirty-seven parties to this treaty, twenty of which are Consultative Parties which make policy for the region. Seven states — Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom - have made national claims to the continent. No other state, however, recognizes the validity of those claims, thus creating political complications and sovereignty problems for the legal jurisdictional situation in the Antarctic.

As determined by investigations during the project, the lawful ability to conduct remote sensing activities has scarcely been affected by the claims conundrum, principally for three reasons. First, the Antarctic Treaty itself mollifies the situation by "freezing" the legal status of the claims in order to accommodate all the parties' legal views. Second, the absence of acknowledged borders for demarcating national claims alleviates the possibility that some claimant might object to a remote sensing satellite violating its purported sovereign air space without its consent. Third, those states conducting

Photos courtesy National Science Foundation



Top: Ice coverage on and around Antarctica (Figure 1). Bottom: Satellite remote sensing image of ice concentration (Figure 2).



krill, *Euphausia superba*
(actual size)

remote sensing operations over the Antarctic are all parties to the Antarctic Treaty system, and would carry out their missions within the framework for scientific research afforded by the Treaty.

The specific international law governing remote sensing activities over the Antarctic is still evolving. Most recently, in late 1986, the United Nations Committee on the Peaceful Uses of Outer Space reached consensus agreement on a set of fifteen Draft Principles on Remote Sensing. These principles, while not codifying international law, clearly indicate the direction in which norms are evolving. The principles declare that remote sensing should be carried out for the benefit and in the interest of all states, according to international law. Moreover, remote sensing activities should be conducted with respect for full and permanent sovereignty of all states over their natural resources, in accordance with principles of freedom of exploration and use of outer space on the basis of equity. Other provisions call for international cooperation in remote sensing activities, the exchange of technical assistance, the protection of the earth's environment, and access by the sensed state to primary and processed data collected from its territory on a nondiscriminatory, reasonable cost basis. In short, the 1986 set of agreed principles on remote sensing plainly authorizes states, international organizations, and non-governmental entities to undertake such space-based research activities over the Antarctic region.

The conduct of remote sensing operations today contributes much information about geophysical processes and the surface structure of Antarctica, as well as biological conditions in the Southern Ocean. As the Marine Policy Center project clearly revealed, expectations of technological application must comport with technological capability, particularly in so far as subglacial mineral and hydrocarbon resource detection on and offshore the continent is concerned. These satellite-based research activities are permissible and lawful under the Antarctic Treaty system, and have gained extra international legal support with recent policy trends in the evolution of outer space law governing remote sensing. Perhaps most important, the project results suggest that remote sensing contributes notably to enhancing scientific investigation and knowledge about the Antarctic, a fundamental purpose underlying the Antarctic Treaty's function. To that end, remote sensing activities promise to yield much for the Treaty's continued success. Moreover, they will offer significant new opportunities for further international cooperation and scientific exchange of information about resource and geophysical conditions in the Antarctic.

Seals and penguins share the terrain on Antarctica.

Photo by Paul Dudley Hart

Chlofluorocarbons are not very toxic to organisms, and are probably almost completely unreactive in seawater. From the surface, these chemically inert compounds can be mixed downward and carried by currents into the interior of the ocean. Sensitive analytical techniques have been developed which can detect these compounds at extremely low levels in seawater, and vertical profiles of the concentrations of dissolved chlorofluorocarbons have been obtained recently at a number of locations. Such measurments of the penetration of these man-made compounds in the ocean can be used to trace the pathways by which physical mixing and circulation processes operate in the ocean.

Recently, measurements of dissolved chlorofluorocarbons have been made during oceanographic expeditions to the Arctic and Antarctic. These regions play an important role in the deep circulation of the ocean. The density of surface seawater in these regions can increase as a result of the combined effects of cooling and the addition of high salinity brines released during sea-ice formation. Such increases in density can cause near-surface seawater to rapidly sink into the deep ocean. After sinking, these dense polar waters begin moving equatorward as deep or bottom currents. As a consequence of the rapid sinking and the outflow of very cold waters from the polar regions, typical temperatures of deep waters throughout the ocean, even in the tropics, are usually within a few degrees of the freezing point.

Figure 2 shows a map of the Weddell Sea, which is bounded on the west by the Antarctic Peninsula and on the south by thick shelves of floating ice derived from glaciers on the Antarctic continent. On the continental shelf along the southern margin of the Weddell Sea, rapid cooling of surface seawater and sea ice formation leads to the production of some of the densest water found anywhere in the ocean. As this water flows down the continental slope, mixing with surrounding waters leads to the production of Weddell Sea Bottom Water (WSBW). This dense newly formed WSBW

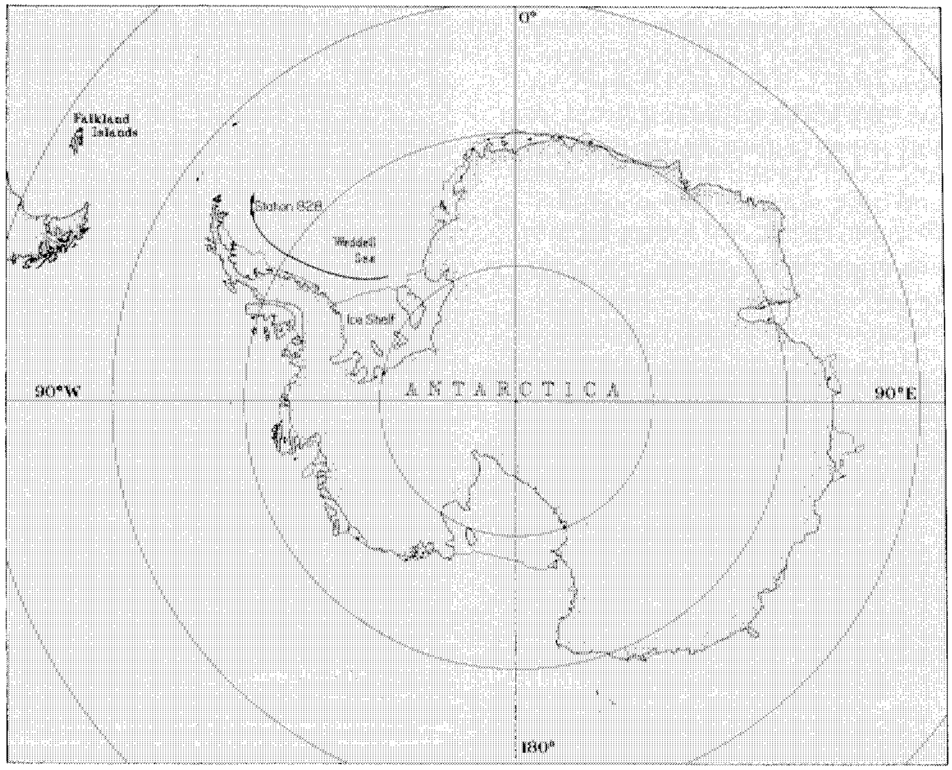


Figure 2 (top): Measurements of dissolved chlorofluorocarbons (along with other tracers) were made in 1987 during an oceanographic expedition to Antarctica on the West German Research Vessel *Polarstern*. High concentrations of dissolved F-11 and F-12 were found in new Weddell Sea Bottom Water (WSBW), which forms along the southern margin of the Weddell Sea. The arrow indicates the northward flow of this dense water away from the source region.

Photo by John Bullister

Left: Deployment of a CTD (conductivity/temperature/depth).

ARCTIC OCEANOGRAPHY AS TRACED BY THE ARTIFICIAL RADIONUCLIDES

Hugh D. Livingston and
Ken O. Buesseler

With the advent of the atomic era in the 1940's, man-made radionuclides have been accidentally or intentially released from many sources into the environment. In our laboratories we have been using these so-called "artificial" radionuclides as tracers of geochemical processes in a variety of settings, including the Arctic Ocean. The Arctic Ocean is a rather unique and interesting basin which has received relatively little attention, primarily due to its inaccessability. The artificial radionuclides prove quite valuable in our Arctic work since their presence or absence in a particular water sample can be used as a time-marker to estimate the age of a given parcel of water.

There have been three major sources of artificial radioactivity in the Arctic Ocean. The earliest source of man-made radioactivity was atmospheric deposition of fallout from above ground nuclear weapons testing which occurred primarily in the 1950's and early 1960's (Figure 1.). This was followed in time by releases to the Irish Sea of liquid radioactive waste from the Windscale nuclear fuel reprocessing plant in the United Kingdom. In the 1970's the Windscale plant was the largest source of artificial radioactivity to the oceans, and scientists have shown that much of the radioactivity released from Windscale was carried by surface currents along the coast of Scandinavia into the Norwegian, Greenland and Arctic Seas. Most recently, in April of 1986, fallout from the Chernobyl nuclear power station accident spread across Europe and as far north as the Arctic, representing a new source of artificial radionuclides to the Arctic region. Each of the above-mentioned sources of radioactivity can be identified in samples by the relative composition of the radionuclides that are measured. In the simplest case, the isotopic signature and hence the age of origin of a given parcel of water which mixes into the Arctic basin can be determined in this manner.

The Arctic Ocean is bounded by the northern extensions of the American and Eurasian continents and has as its principal features two deep basins surrounded by extensive shallow continental shelf seas (Figure 2). Connections to the world oceans to the south are through the shallow Bering Strait and the deeper Fram Strait. The major water exchanges into and out from the Arctic Ocean occur at Fram Strait. In consequence, the Eurasian Basin is mixed significantly more vigorously than the Canadian Basin. A major influx of warm, salty Atlantic water flows into the Arctic through the eastern side of Fram Strait. A return flow of cooled Atlantic water leaves the Arctic on the western side under the East Greenland Current. Deep water exchanges parallel the surface patterns. It has been recognized that the shallow shelf seas in the Arctic play an important role in the basin circulation - by advective transport of cooled shelf waters into the interior.

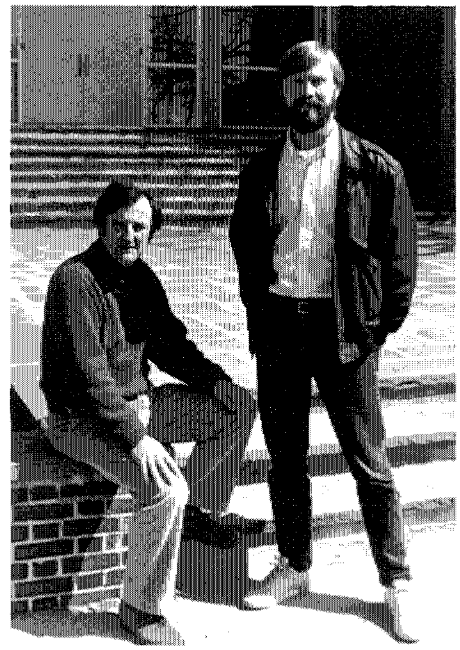
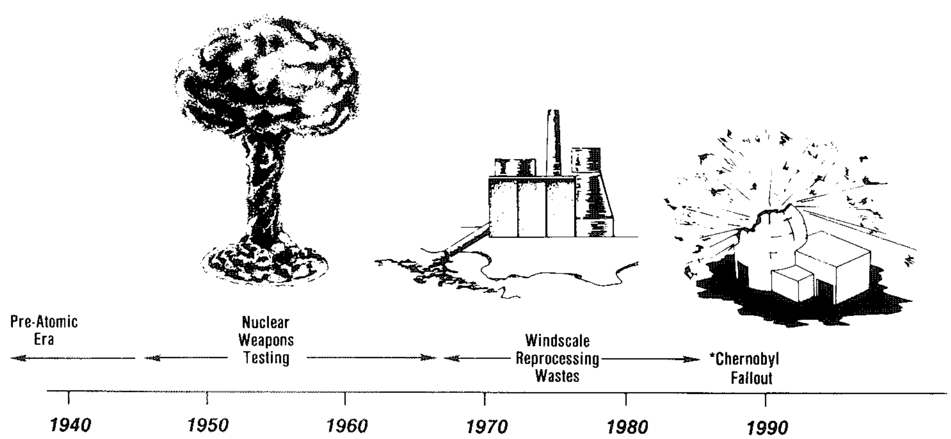
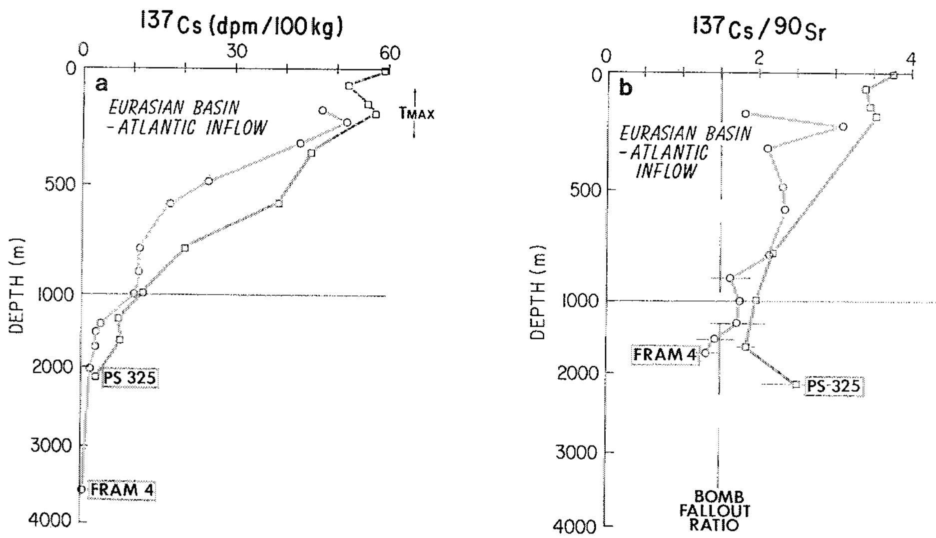


Photo by Shelley Lauzon

Right: Hugh Livingston (seated) and Ken Buesseler. Bottom: Sources of man-made radioactivity (Figure 1).



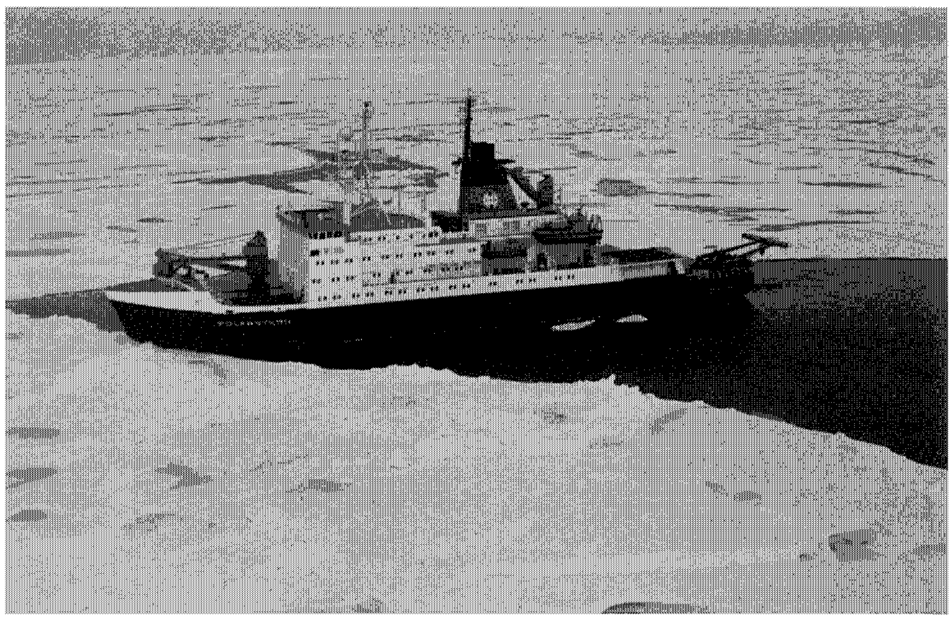
An illustration of the use of artificial radionuclides as tracers in the Arctic is given in Figure 3. Shown are the depth distributions of radiocesium and radiostrontium at stations in the region of inflowing Atlantic water in the Nansen Basin in 1982-83. They include a manned ice station (FRAM 4) and one occupied by the German icebreaker *POLARSTERN* (PS 325). The strong radiocesium signals found in the upper thousand meters derive from the recent inflow of Atlantic water labelled with radiocesium primarily from coastal nuclear water discharges to the Irish Sea and subsequently advected northwards. The relative proportions of radiocesium and radiostrontium can be used to distinguish between these Windscale signals and the older signals derived from atmospheric nuclear weapons testing fallout. The nuclear waste signal is characterized by a strong enrichment in radiocesium - shown in Figure 3 by the higher values of the 137Cs/90Sr ratio relative to that which is normally found in bomb-fallout (dashed line). Even the small quantities of radiocesium detected in the deep water at one of these stations show the presence of tracer from the nuclear waste source (i.e., note the elevated 137/Cs / 90/Sr ratio on the deep water in Figure 3). This has been taken as evidence of the transfer of Arctic shelf water to depth in the basins, as there is a little evidence of such markers in the deep waters of the Norwegian Sea in the south which were traditionally viewed as a major contributor to Arctic Ocean deep waters. These signals, and others of Chernobyl origin yet to be studied, provide useful time-markers of the various bodies of water which are found to circulate within the Arctic basins. The evolution of the patterns of these markers in space and time yield information on the routes and rates of the circulation. On the other side of the coin, these studies address questions of the ultimate fate and extent of dilution of pollutants introduced to the European continental shelf seas to the south.



Top: The Arctic Ocean is bounded by the northern extensions of the American and Eurasian continents and has as its principal features two deep basins surrounded by extensive shallow continental shelf seas (Figure 2). Bottom: Depth distributions of radiocesium and radiostrontium at stations in the region of inflowing Atlantic water in the Nansen Basin in 1982-83 (Figure 3).

Photo by Ken Buesseler

Photo by Ken Buesseler



Top: Setting up instruments in the ice. Bottom: The West German research icebreaker *Polarstern*.

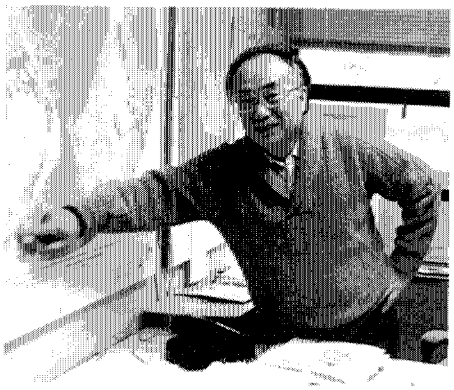
As mentioned previously, one of the main obstacles in furthering our understanding of Arctic oceanography is our ability to collect samples from the large central basins of the Arctic which are permanently ice covered. During the summer of 1987 we were fortunate to have been able to participate on a two-month cruise aboard the German research icebreaker *POLARSTERN* (photo), along with fifty-five other scientists representing over twenty different research institutions. Departing from Tromsö, Norway, we were able to penetrate through up to 20 feet of ice as far north as 86 degrees 11 minutes north. This expedition came within 240 miles of the North Pole and represents the northernmost penetration in the history of Arctic oceanography by any oceanographic research vessel.

The samples obtained on this cruise will provide valuable insights into the chemistry, geology, biology, and physical oceanography of the interior Arctic. Our group collected both dissolved and suspended particulate samples for radionuclide analyses. Once analyzed, these samples will provide information on the rates of circulation of the Arctic water masses, and the extent to which the more particle reactive tracers are removed to the deep Arctic sediments. Due to the permanent ice cover and low biological productivity in this ocean, we expect to find a somewhat unique geochemical environment with respect to the radionuclide tracer distributions relative to other open ocean basins. A continued interest in Arctic oceanography and future sampling all the way to the "top of the world" will be needed to complete even the most basic understanding of the oceanography of this northernmost of oceans.

SEDIMENTARY ENVIRONMENT IN THE ARCTIC OCEAN AND ITS MARGINAL SEAS

Susumu Honjo

Photo by Shelley Lauzon



One of the most decisive environmental factors governing the present and geological past of the northern hemisphere of the Earth is the evolution of the hugh ice-cap which covers the Arctic Ocean. Unlike Antarctica, which is a subcontinent, the Arctic is covered by a large ocean, and the retention of heat by water should effectively buffer the cold atmosphere where the ocean is exposed to the air cover above. However, a major portion of the Arctic Ocean is insulated by thick ice which inhibits heat exchange between the air and seawater. Thus, the air mass over the Arctic can be cooled as in the interior of a large continent, and this defines the modern weather patterns of the northern hemisphere. Geologists believe the ice cover disappeared a number of times from the Arctic and brought mild weather to the Earth's northern hemisphere, including relatively recent episodes several thousand years ago. The best records of changing climate are recorded in deep-ocean sediments under the Arctic Ocean. However, we know almost nothing about how sediments under the Arctic Ocean are formed. Experiments to assess the quality and quantity of modern particle fluxes in the Arctic Basin are thus indispensable for understanding the oceanic environment of the Arctic, and these require efforts to recover sediment records by coring and deep sea drilling in the Arctic. Exploration of the origin and sources of sediment now accumulating in the Arctic Ocean bottom and how these change in time and space are imperative for meeting this objective. Obviously, such experiments are very difficult because of the harsh Arctic conditions.

Technologies to address such major questions are now available in modern oceanography. Automated, large sediment traps moored along a strong array can monitor the rate of sedimentation and collect samples throughout the year regardless of ice coverage. Data of many oceanographic parameters such as turbidity, temperature, and conductivity which are measured along an array, can now be safely stored *in situ* for long periods of time and recovered when weather permits. In recent years international cooperation in Arctic research has contributed greatly to progress in Arctic oceanography; in particular, the West German ice-breaking research vessel *POLARSTERN* of the Alfred Wegener Institute for Polar and Marine Research has played a central role in making such large-scale research possible.

We have concentrated our efforts in the past four years in the Nordic Sea region, which is a boreal basin surrounded by Greenland, Spitsbergen, Scandinavia and Iceland. The area is roughly equivalent in size to the Mediterranean Sea. We deployed sixteen sediment traps and other instruments along fourteen moorings all over the Nordic Sea from Fram Strait to the Iceland Plateau, and from Lofoten Basin to Scorseby Fjord in Greenland. To measure the sediment fluxes under the ice-covered ocean, we deployed instrument packages with mooring arrays during the summer when the sea ice was temporarily opened and recovered the arrays during the following summer, with samples and data recorded for one year.

We have made a number of new and important discoveries as a result of the Nordic Sea experiments. For example, we found that the Nordic Sea is a vigorous ocean in supplying essential biogenic matter, such as organic carbon and nitrogen in the form of particle fluxes, to the deeper layers. The annual organic carbon flux in the Nordic Sea was as large as 0.15 to 1 g/m^2, two to three times larger than in the Sargasso Sea and other subtropical ocean gyres. Being at such a high latitude, scientists had long believed that the Nordic Sea and southern Arctic Ocean was supplying biogenic silica particles produced by diatoms. We found that this was not true, but that the majority of particles were coccoliths, minute carbonate shields which cover plant plankton known as coccolithophorids. In fact, we found a relatively large coccolithophorid population (along with planktonic foraminifera) in permanently ice-covered water as far north as 86°N in the Arctic Ocean.

While pursuing this research, we discovered an interesting ocean phenomema which we named a "winter burst" of shelf sediment into deep basins. In the Barents Sea the summer is too short to utilize all of the plant plankton which is produced there. A large volume of

Photo by Richard Krishfield

Photo courtesy Ken Buesseler

Photo by Richard Krishfield

Top: The Arctic Environmental Drifting Buoy (AEDB) is off-loaded from the *Polarstern*. Middle: Ken Buesseler (right) and Rich Krishfield carried the Woods Hole Oceanographic Institution flag to 86°N during the summer of 1987. The AEDB is visible behind the flag. Bottom: A sediment trap is prepared for deployment.

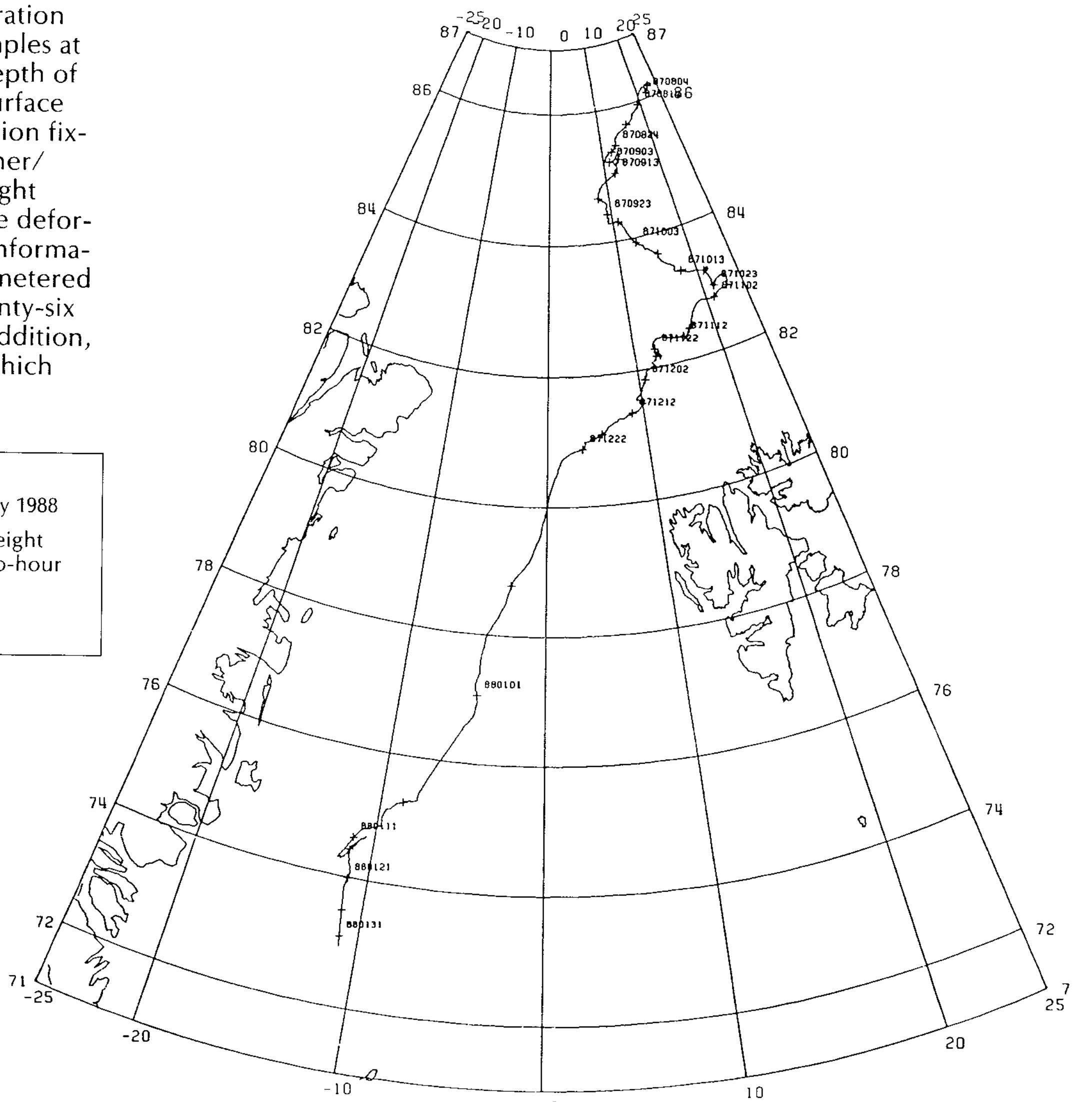
fresh plant remains is deposited along sea floor depressions and underwater fjords. In late December, seawater in the northern Barents Sea is cooled and the sinking water produces a strengthened southward-flowing bottom current. This winter current flushes unconsolidated sediment, deposited during the spring/summer of the same year, into the deep basins. We have observed such offshore transport from the northern Barents Sea into the northern Norwegian Basin from December to mid-April, reaching a maximum in February. The sediment transported by such winter bursts contains unusually large amounts of organic carbon because it is so fresh. The sediment forms a terminal fan, like a river delta, fronting a deep basin. The organic-rich sediment may turn to fossil hydrocarbons if the requisite burial conditions are met. This explains the succession of hugh topographic bulges observed along the western edge of the Barents Sea which were not present when the last glaciation leveled this area 18,000 years ago.

The amount of ice which must move out of the Arctic Ocean is equivalent to the total amount of water entering from Siberian rivers. Thus, a huge amount of sea-ice flows south from the North Pole through the Fram Strait, passes through the Greenland Sea and finally melts in the southern Nordic Seas. This river of ice in the ocean is called the Arctic Transport and is the main constituent of the negative heat pump in the northern hemisphere. Just like a river transports particle loads downstream with water, the Arctic Transport brings sediment along the east coast of Greenland with melting ice. Understanding this Arctic Transport is indeed one of the most important tasks for global oceanography.

On August 4, 1987, supported by the Office of Naval Research, we launched a new high technology oceanographic buoy, the Arctic Environmental Drifting Buoy (AEDB), on a large ice-island located at 86°N, 22°E. Once again the *POLARSTERN* played a major role in this very demanding experiment. A 140-meter-long (460-foot) instrumentation mooring array was tethered to the five-foot steel/composite sphere. The array was deployed through a one-meter diameter hole bored through six meters (twenty feet) of ice. The AEDB has a unique amphibian capability: it was deployed through the sea-ice with the sphere on the ice surface. The buoyancy of the sphere is designed to support the underwater array when the buoy falls into the ocean. Along this array were attached a fluorometer, thermister chains, conductivity sensors, transmissometers, and very sophisticated acoustic current profilers to collect and store data every hour. These instruments are synchronized to monitor the standing crop of plant-plankton, the effect of ice melting into the ocean water below the sea-ice, and water turbidity caused by falling particles from the ice along with the movement of sea-water at various depths. A sediment trap one meter (three feet) in diameter and an automated sea-water filtration device collect sediment samples at 10 to 15-day intervals at a depth of 140 meters (460 feet). The surface sphere houses satellite position fixing transmitters, eight weather/temperature sensors, and eight strain gauges which measure deformation of the sphere. This information from the sphere is telemetered to Woods Hole roughly twenty-six times a day via satellite. In addition, there are sixty thermisters which measure, with great precision for a long period of time, the temperature profile of the sea-ice which supports the buoy.

This automated polar oceanography research center is undoubtedly one of the most advanced buoy systems ever designed. The AEDB experiment is particularly significant in reference to the history of Arctic research. Fifty years ago three courageous Soviet scientists completed an experiment in which they stranded themselves on an ice island which drifted from the North Pole to the north of Iceland. Our AEDB took a similar route and arrived at 71°N on the same date: February 19th (1987).

The AEDB is still in the ice field north of Iceland, having traveled about 1,000 miles, and still has about 300 miles to go. Recovery is expected in mid-April1988 near Iceland. The AEDB has already provided us with an extraordinary quantity of high quality information via ARGOS satellite telemetry. This includes its precise movement, rotation of the ice island, and air temperature which are updated about once every hour. Also, engineering data, such as the stress on the buoy sphere when it was attacked by ice and the voltage level maintaining the system's electronics, are monitored constantly for future improvements of high technology polar ocean buoys. The AEDB, on its first deployment, has proven itself an effective research tool for work in the hostile polar regions.

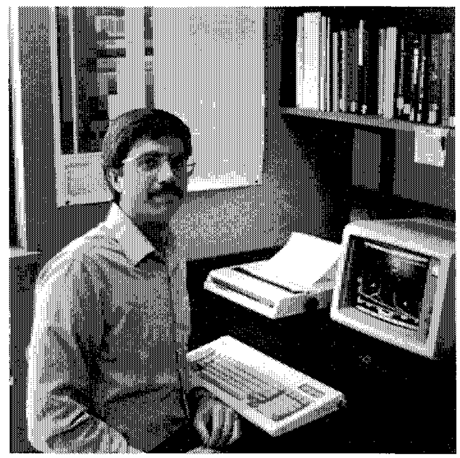


AEDB 180 DAY SUMMARY
4 August 1987 through 31 January 1988

*positions passed through half-weight Gaussian filter and plotted at two-hour intervals.
*each mark represents five days traveled.

ARCTIC OCEAN SEDIMENT CHRONOLOGY AND PALEO-ENVIRONMENTAL RECONSTRUCTION

Glenn A. Jones and Scott J. Lehman



Top: Glenn Jones. Bottom: Scott Lehman.

The last approximately two million years of earth history has witnessed large changes in climate, the most dramatic manifestations of which were the growth and decay of the great Pleistocene ice sheets that periodically overwhelmed the high and mid-latitude areas of the northern hemisphere. Paleo-climate research in the last decade has demonstrated that the pace of these events is governed primarily by variations in different elements of the earth's orbit about the sun, which modulates both seasonal and annual solar insolation receipts in the northern and southern hemispheres (Figure 1). Now, paleo-climate research is aimed at an understanding of three related questions: 1) what are the features of the climate system that are most important in amplifying variations in solar insolation; 2) what are the mechanisms that drive the transition from one climate state to another (glacial to non-glacial); and 3) what are the rates of these transitions?

Global numerical climate simulations played out on super computers suggest that the high latitudes are unusually sensitive to changes in certain climate variables. For instance, the extent of snow cover, sea ice and glacier ice is extremely sensitive to changes in summer insolation. Because the areal extent of these surfaces alter the ratio of absorbed and reflected incoming radiation (albedo), a robust positive feedback system can be set in motion. In this and similar ways, the Arctic may be critical in amplifying climate change on the global scale.

Despite the implied importance of the high latitudes as a sensitive link in the hydrosphere-atmosphere-cryosphere climate system, the central Arctic basin remains the least understood of all the world's oceans. Basic research in this region has been restricted by the difficulty of probing a remote, and often ice covered, landscape. For instance, much of the high Canadian Arctic was not even reconnaissance-surveyed until the 1960's, at which time the first systematic recovery of Arctic Ocean sediment cores from Fletcher's ice island (T-3) began. The first regional lithostratigraphy for Arctic Ocean sediments was not developed until 1980. By contrast, the systematic recovery and study of cores in the Atlantic and Pacific Oceans had begun as early as the late 1800's. Not until 1987 were the first sediment cores obtained from a self-propelled platform in the Arctic Ocean, when the West German icebreaker *POLARSTERN* allowed scientists to navigate toward areas of particular interest, rather than being reliant on the drift of ice islands. The U.S. Coast Guard icebreaker *POLAR STAR* is scheduled to cruise north of Point Barrow this summer to, in part, recover cores from the Canadian Basin of the central Arctic. This new era of sampling from self-propelled platforms will allow scientists to dramatically improve their understanding of what role the Arctic plays in influencing global climate change.

Arctic Ocean sediments potentially provide a wide variety of information concerning the climate history of the central Arctic and the surrounding land masses, where the inception of the large Pleistocene ice sheets took place. However, before study of these sediments can provide a meaningful record of paleo-climate history, at least two fundamental requirements must be met. Firstly, faithful climate recorders, such as the fossil remains of organisms for which the modern temperature and/or salinity tolerances are known, must be recovered. Secondly, the record of their variation must then be fit into an independently derived and accurate chronologic (age) framework.

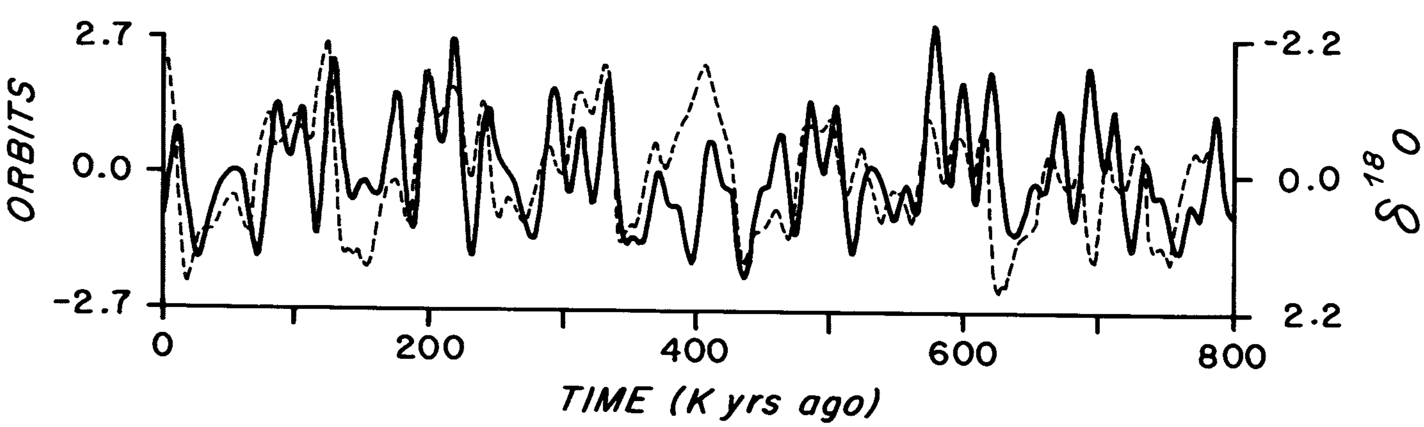
In view of these basic requirements the Arctic presents some unique challenges to the paleoceanographer. For instance, the Arctic seems to be characterized by a depauperate and undiversified fauna, but it is not known how these relate to modern environmental parameters (temperature and salinity, etc.). This results from the difficulty in obtaining intact, modern core-top sediments because of coring disturbances associated with the methods in use on the ice islands. Without a core-top database which relates the existing fauna to oceanographic variables, it is difficult to interpret the fossils preserved in order to use Arctic sediments to determine past oceanographic conditions. Studies of Arctic sediments have been further complicated by the difficulty of accurately age - dating the materials under study. The carbon-14 method has proven to be one of the most important and widely used tools available to the geologist interested in dating and understanding the climate history of the past approximately 40,000 years. However, because Arctic Ocean sediments are typically a complex mixture of non-contemporaneous land-derived components and contemporaneous marine biogenic components, these sediments often provide spurious, artificially old and often uninterpretable radiocarbon dates. Such results confuse the relationship between the record of climate change in the Arctic and the better known, more reliably dated records in other regions. It was generally not possible to circumvent this problem until the recent advent of radiocarbon dating by accelerator mass spectrometry (AMS). Using this method atoms of C-14 are counted directly, permitting the analysis of samples several thousand times smaller than those subjected to the traditional beta-decay method. With the smaller sample size requirement it is now possible to isolate and date specific contemporaneously deposited marine biogenic components, even in the complex sediments of the Arctic Ocean.

Because of the logistical difficulties of collecting sediments from the Central Arctic and the technical difficulties in analyzing these sediments, interpretations of the sediment record have varied widely in the past. For instance, early studies suggested that sedimentation rates in the central Arctic Ocean were very low, approximately one-twentieth of that known from the rest of the global oceans. But these findings were based on poorly resolved paleomagnetic analyses (another widely used method of age determination). More recently researchers studying the rates of diagenesis in fossil protein remains (amino acid racemization) suggested that sedimentation rates in the central Arctic Ocean were at least an order of magnitude greater than previously believed. Extrapolations based on these different interpretations resulted in widely different chronologies for central Arctic sediments, which in turn lead to widely differing interpretations of the climate history of the region. This debate has been largely resolved by recently completed paleomagnetic and AMS C-14 studies of central Arctic sediments, performed at WHOI, which support to a large degree the slower sedimentation rate model for the Arctic Ocean (Figure 2).

Now that the first secure chronology of the Arctic Ocean is at hand, researchers can begin to direct their efforts toward a fuller understanding of the temporal dynamics and spatial configuration of the northern hemisphere ice sheets, the northern limits of which have been the subject of vigorous debate amongst land-based glacial geologists for more than fifty years (Figure 3).

Although the most obvious effects of ice sheet growth and decay occurred on land and on shallow continental shelves, the land record of these glaciations is discontinuous due to repeated erosion by successive glacier expansions which partially or fully destroy records of previous events. The global deep-sea record, which is by comparison virtually uninterrupted by erosional processes, has allowed researchers to roughly determine the total volume of the ice sheets by studying the temporal variations in the different isotopes of oxygen found in the remains of marine zooplankton (foraminifera). However, this record

Figure 1: A stacked and smoothed oxygen isotope record for the last 800,000 years is compared to the relative magnitude of insolation change resulting from variations in the three changing elements of the earth's orbit about the sun: precession, obliquity and eccentricity. Periods of heavy oxygen isotope enrichment refer to episodes of continental scale glaciation. Both the oxygen isotope and orbital data have been normalized before summation and are presented in standard deviation units. The data are from Imbrie et al. (1984).



provides no information on the spatial configuration of the ice sheets. The Arctic Ocean, however, provides us with the first means of independently analyzing the temporal and spatial history of the northern hemisphere ice sheets since the sediments are mixtures of land-derived and marine biogenic components. Although the land-derived components are troublesome from the point of view of age dating, they provide valuable information regarding the waxing and waning of the ice sheets. Ice sheet expansion and erosion over different geologic terrains containing unique clay mineral and chemical signatures provide a tracer of sediment source area (provenance) which is subsequently deposited in the central Arctic Ocean basin. Studies of land-derived clay minerals, in progress at WHOI, allow us to determine which land areas have been glaciated at different times, and to reconstruct average glacier flow line directions for the northern sectors of the ice sheet. By deducing the approximate volume of the ice sheets from oxygen isotope analyses and knowing the spatial extent of the ice sheets by analysis of sediment tracers, we can more realistically reconstruct the dynamics of the northern margins of the northern hemisphere ice sheets.

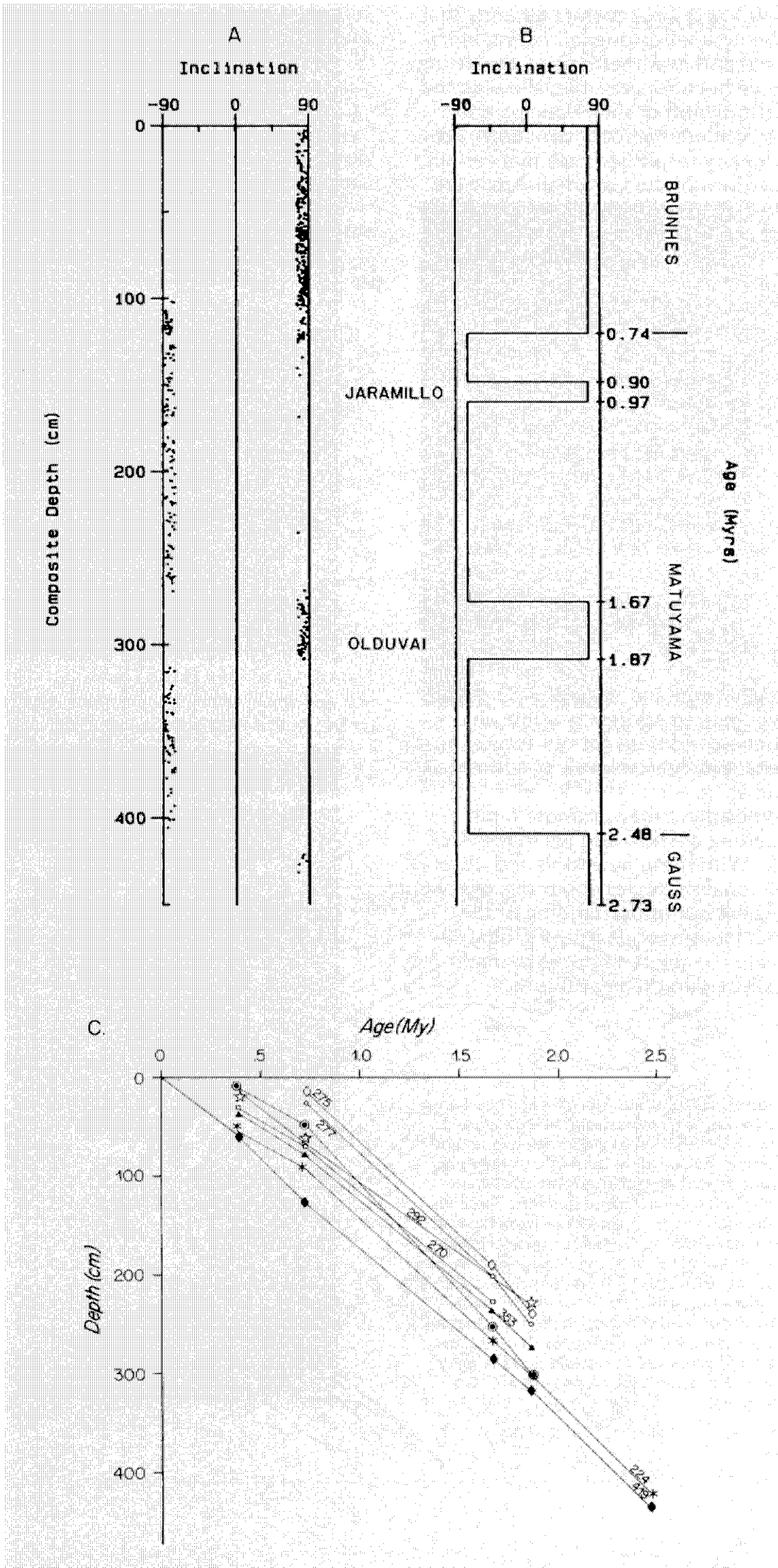


Figure 2: A composite plot of all paleomagnetic data from Fletcher's ice island (T-3) cores showing only the magnetic inclinations steeper than 75 degrees (a). This record is compared to the generally accepted, independently dated paleomagnetic age scale (b) of Mankinen and Dalrymple (1979). The most parsimonious fit between the Arctic Ocean record and the accepted timescale is obtained assuming a linear sedimentation rate history of 0.165 cm/ka. The age-depth relationships so obtained for a selection of cores (c) indicates that most of T-3 cores lack intact, modern coretops, probably due to coring disturbances and the low sedimentation rate environment. AMS C-14 dates constrain the age of the youngest sediments in core FL-419, which has the best core-top recovery.

It has only been very recently that the new self-propelled coring initiatives and new methods of age dating have become available, allowing the formulation of such basic paleoenvironmental reconstructions. Preliminary results indicate that certain portions of the Canadian Arctic are glaciated with an approximate frequency of every 100,000 years, while other sectors appear to be glaciated only every 40,000 years. Our next step is to determine whether there is a recurrent and systematic dependence of the ice sheet dynamics in each of these sectors on the paleooceanography of the Arctic Ocean and adjacent northern seas. These oceanographic conditions largely govern the trajectory of storm tracks responsible for nourishment and starvation of potential ice sheet source areas. In a related effort we are employing the detailed AMS-14C chronology to help define the extent of Arctic Ocean ice cover during the global climatic optimum that occurred approximately five to seven thousand years ago. This study will help us address possible analogue conditions for our future, in which increased levels of anthropogenic "green house" gases in the atmosphere may promote rapid melting of snow and ice in the Arctic. With these new tools and observational strategies at our disposal we expect our understanding of the mechanisms and rates of global climate change to improve dramatically within the near future.

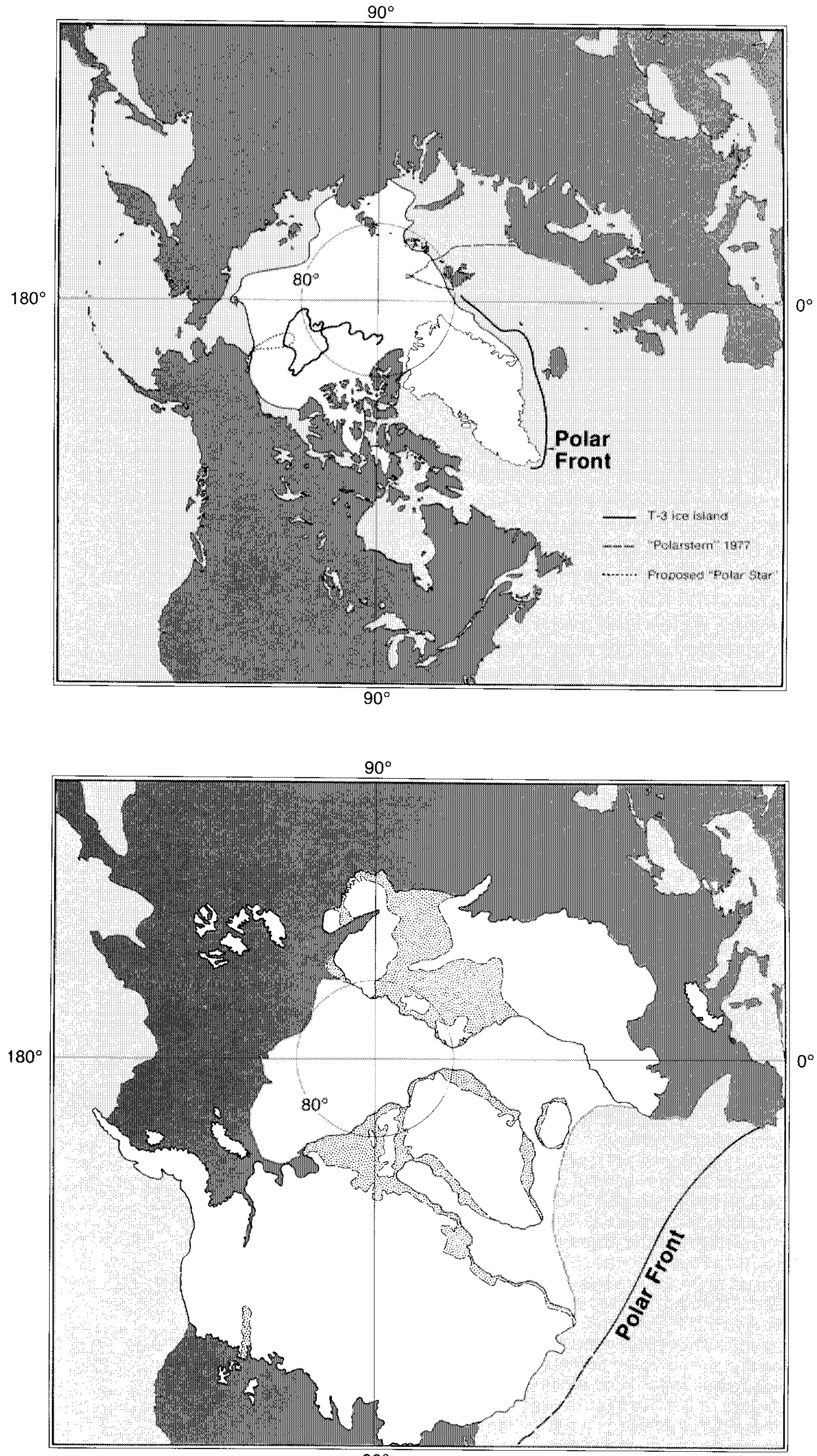


Figure 3: Map of the Arctic Ocean basin and surrounding land masses showing the modern (a) distribution of glacier ice (white) and summer sea ice (light brown), and the Polar Front demarcating the transition between polar and subpolar surface waters. These distributions and boundaries can be compared with those during Quaternary glacial periods (b). Stippling refers to the difference between possible extremes in the reconstructed extent of glaciation within or between individual glacial episodes. The largest discrepancies are evident in areas bordering the Arctic Ocean. Past and proposed ship tracks and the drift track of Fletcher's ice island (T-3) are also shown (a).

SOVIET MARITIME ARCTIC POLICY

James M. Broadus and Lawson W. Brigham

The Arctic Ocean is a region of growing importance for political, scientific, environmental and strategic reasons. Largely because of its geographic location, the Soviet Union is the dominant nation in the Arctic. It is important, therefore, for Western scholars to examine Soviet domestic and international policies in the Arctic Ocean.

In order to provide an opportunity to report on the status of such studies and to consolidate our knowledge about the Soviet Union's use of its maritime Arctic region, the WHOI Marine Policy Center organized an international workshop in Woods Hole on May 10-13, 1987. A grant from the John D. and Catherine T. MacArthur Foundation of Chicago allowed the Participation of recognized scholars from Canada, Great Britain, Norway and the United States. The interdisciplinary workshop sessions addressed a wide spectrum of concerns - strategic, geographic, historical, legal, scientific, technological, transportation, geopolitical and resource development. A WHOI Technical Report and a book in preparation will present a unique and comprehensive review of Soviet use of and policies toward the Arctic Ocean.

Workshop discussions and formal presentations revealed significant new findings about the Soviet Maritime Arctic. The history of Russian interaction in the Arctic Ocean spans more than 500 years. The Northern Sea Route across the top of Eurasia was in commercial use by 1600 and much of that coast had been explored and charted with surprising accuracy by 1743. A case was also made that Russian nationalism may be the primary driving force in achieving the record of success the Soviet Union has enjoyed in the Arctic.

Recent Soviet legislative enactments indicate that the balance of political, economic, legal, strategic and other interests embodied in the Law of the Sea Convention are largely acceptable to the Soviet Union. Evidence shows that some of the more extreme doctrinal characteristics of the legal status of the seas north of the Soviet coast do not enjoy support in law or in State practice. In particular, those characterizations of sector lines as State boundaries (lines running from the Soviet northern coast directly to the North Pole) are today without any support whatever, and so too are many of the historic seas (or bays) doctrines that date from periods of Soviet maritime weakness. Recent Soviet legislation on the creation of joint enterprises with capitalist and Third World countries opens up new opportunities for joint resource exploitation in the Arctic which a number of Western nations may wish to pursue.

The Soviet Union operates the world's largest fleet of polar ships, the majority of which are used along the Northern Sea Route. Technological advance (including nuclear power for icebreaking ships), adaptation and technology transfer from the West have played leading roles in the development of this diverse fleet. Estimates from the Soviet press place the current level of operations at approximately 600 freighting voyages carrying six million tons of cargo across the Soviet Maritime Arctic. Year-round navigation has been maintained in the Kara Sea for the carriage of Noril'sk nickel ore to

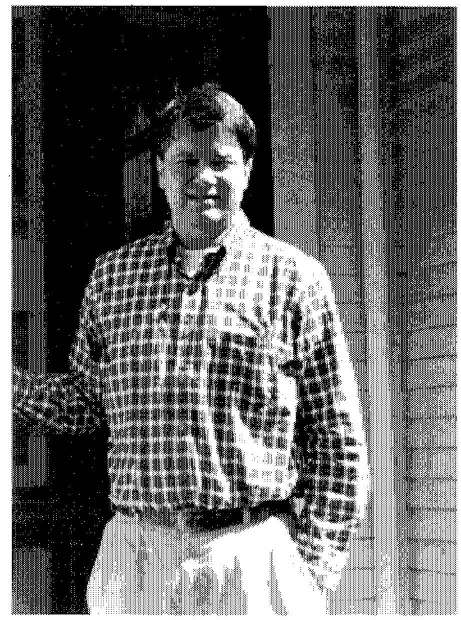
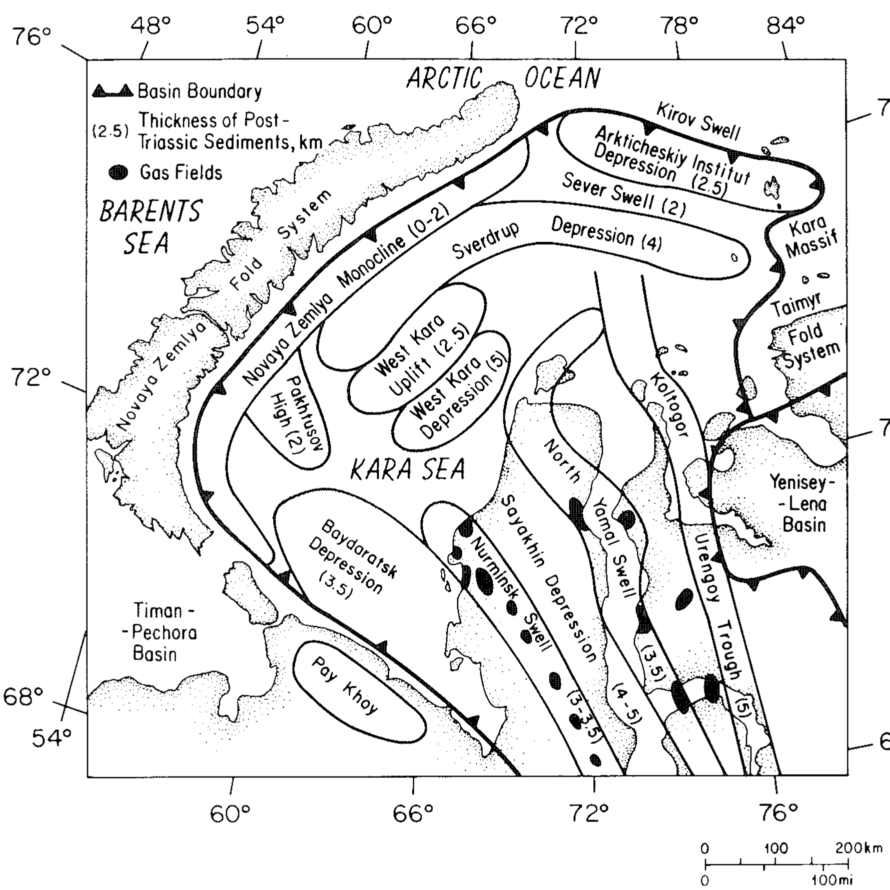


Photo by Shelley Lauzon

Top: Jim Broadus. Bottom: The extensions of the geological structures for the Western Siberian onshore where major gas fields have already been developed.



Murmansk. The transport of gas industry freight, largely pipes, to Western Siberia and the Yamal Peninsula has also been an important use of the Northern Sea Route.

The Soviet Arctic offshore area (Figure 2), including the Barents, Kara, Laptev and East Siberian Seas, is the largest unexplored potential oil-gas region in the world. The first exploratory well on the Soviet Arctic continental shelf was drilled in 1982 in the Barents Sea; Soviet plans call for extending exploration east and into the Kara Sea. Figure 1 shows the extensions of the geological structures for the Western Siberian onshore where major gas fields have already been developed. Western offshore oil drilling technology may well play a key role in Soviet plans for potential oil-gas resources in the offshore Arctic.

Soviet Arctic scientific and engineering efforts have been extensive. Technical innovation in Arctic shipping and icebreaking, overcoming permafrost problems and forecasting ice conditions has been legendary. Contrary to generally held views, there is substantial openly published Russian material available about the Soviet Arctic. The basic scientific efforts have been extensively published for scrutiny by the world's scientific and academic community.

It is widely believed that the Soviet Union considers the Arctic too sensitive for national security reasons to be an appropriate focus for international cooperation. In fact, the USSR belongs to conservation regimes involving fur seals and polar bears, the management regime for the Svalbard archipelago (the 1920 Treaty of Spitzbergen), and an array of broader multilateral regimes (such as the International Whaling Convention of 1946) applicable to the Arctic. Recent events point to future Soviet cooperation in the region. In October 1987 General Secretary Gorbachev called for increased Arctic cooperation, including joint scientific research and a comprehensive plan for protection of the northern environment.

One of the key conclusions of the May 1987 workshop and follow-up research has been the observation that Soviet concerns in the Arctic represent an amalgam of economic, environmental, resource, political, cultural and strategic interests. It would be wrong to single out any one of these interests as predominant to the exclusion of the others. In particular, excluding the Barents Sea where the Soviet Union operates the world's largest naval force, it is no longer evident that security interests are as sensitive as in previous years.

Future Marine Policy Center studies on the Soviet Arctic will aim to continue the participation of foreign investigators, including Soviet scientists and policy-makers. We are excited about the prospects for continuing the dialogue and research regarding Soviet Arctic marine policy, oceanography and technology.

Photo by Shelley Lauzon

Top: The Soviet Arctic offshore area (Figure 2) is the largest unexplored potential oil-gas region in the world. Bottom: Lawson Brigham.

1987 DEGREE RECIPIENTS

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

Doctor of Philosophy

M. BENNO BLUMENTHAL
A.B. Princeton University
Special Field: Physical Oceanography
Dissertation: *Interpretation of Equatorial Current Meter Data as Internal Waves*

PAOLA CESSI
Laurea Universita di Bologna
Special Field: Physical Oceanography
Dissertation: *On the Role of Topography and of Boundary Forcing in the Ocean Circulation*

MAVIS L. DRISCOLL
B.A. University of California, Berkeley
Special Field: Marine Geology
Dissertation: *Applications of Seasat Altimetry to Tectonic Studies of Fracture Zones in the Southern Oceans*

MARGARET R. GOUD
B.S. Stanford University
Special Field: Marine Geology
Dissertation: *Prediction of Continental Shelf Sediment Transport Using a Theoretical Model of a Wave-Current Boundary Layer*

DAVID W. GRAHAM
B.S. Florida Institute of Technology
M.S. University of Rhode Island
Special Field: Chemical Oceanography
Dissertation: *Helium and Lead Isotope Geochemistry of Oceanic Volcanic Rocks from the East Pacific and South Atlantic*

BERNWARD J. HAY
Vordiplom, George August University
M.S. Cornell University
Special Field: Marine Geology
Dissertation: *Particle Flux in the Western Black Sea in the Present and over the Last 5,000 Years: Temporal Variability, Sources, Transport Mechanisms*

DEAN M. JACOBSON
A.B. Occidental College
Special Field: Biological Oceanography
Dissertation: *The Ecology and Feeding Biology of Thecate Heterotrophic Dinoflagellates*

ROBERT S. PICKART
B.A. Susquehanna University
Special Field: Physical Oceanography
Dissertation: *The Entrainment and Homogenization of Tracers within the Cyclonic Gulf Stream Recirculation Gyre*

JAMES B. RILEY
B.S. Yale University
Special Field: Oceanographic Engineering
Dissertation: *Laser Diffraction Particle Sizing: Sampling and Inversion*

ELIZABETH M. ROBINSON
B.S. Reed College
Special Field: Marine Geophysics
Dissertation: *The Effect of a Shallow Low Viscosity Zone on Mantle Convection and its Expression at the Surface of the Earth*

LESLIE K. ROSENFELD
B.S. University of Washington
Special Field: Physical Oceanography
Dissertation: *Tidal Band Current Variability over the Northern California Continental Shelf*

DOUGLAS R. TOOMEY
B.S. Pennsylvania State University
Special Field: Marine Geophysics
Dissertation: *The Tectonics and Three-Dimensional Structure of Spreading Centers: Microearthquake Studies and Tomographic Inversions*

ELI TZIPERMAN
B.Sc. Hebrew University
Special Field: Physical Oceanography
Dissertation: *Mixing and General Circulation Dynamics: Theory and Observations*

Doctor of Science

JOSKO A. CATIPOVIC
B.S. Massachusetts Institute of Technology
SSpecial Field: Oceanographic Engineering
Dissertation: *Design and Performance Analysis of a Digital Acoustic Telemetry System*

MEIR FEDER
B.Sc., M.S.E.E. Tel-Aviv University
Special Field: Oceanographic Engineering
Dissertation: *Statistical Signal Processing Using a Class of Iterative Estimation Algorithms*

ANDRE A. MERAB
B.S., M.S., Massachusetts Institute of Technology
Special Field: Oceanographic Engineering
Dissertation: *Exact Reconstruction of Ocean Bottom Velocity Profile from Monochromatic Scattering Data*

JAMES H. MILLER
B.S.E.E. Worcester Polytechnic Institute
M.S.E.E. Stanford University
Special Field: Oceanographic Engineering
Dissertation: *Estimation of Sea Surface Wave Spectra Using Acoustic Tomography*

HAIM NELKEN
B.Sc. Hebrew University
Special Field: Physical Oceanography
Dissertation: *Thermally Driven Circulation*

Ocean Engineer

PAUL J. BUSHONG
B.S.M.E. United States Naval Academy
M.S. Massachusetts Institute of Technology
Special Field: Oceanographic Engineering
Dissertation: *Tomographic Measurements of Barotropic Motions*

FERDINAND J. DIEMER
B.S.E.E. United States Naval Academy
Special Field: Oceanographic Engineering
Dissertation: A Prony Algorithm for Shallow Water Waveguide Analysis

DEAN'S COMMENTS

Charles D. Hollister

Photo by Shelley Lauzon

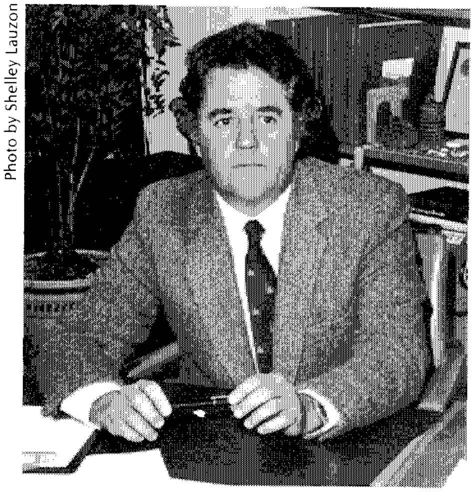


Photo by Shelley Lauzon

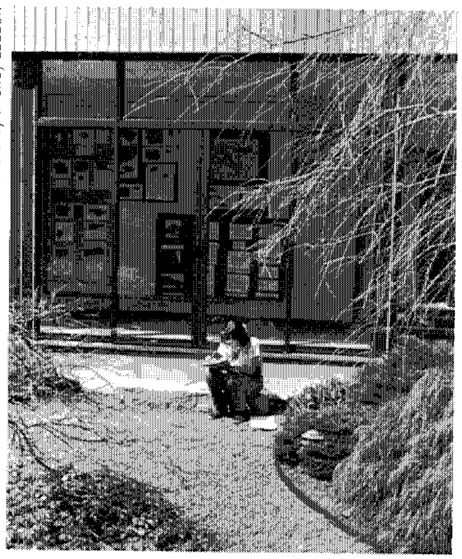


Photo by Shelley Lauzon

Top: Dean Charles Hollister. Middle: A quiet time to study in the McLean Laboratory atrium. Bottom: Catching up on the news outside the Education Office in the Clark Laboratory.

The year 1987 was a busy one and filled with new beginnings for the Education Program. In June, some two dozen undergraduate college science teachers spent a week at Woods Hole and another 15 were at the University of Washington in Seattle to learn about ocean science. The concurrently held workshops, supported with a grant from the Office of Naval Research and the Pew Charitable Trusts, were organized as a result of our concern over the declining numbers of applicants to graduate schools in oceanography nationwide.

Our hope in this new approach to recruiting is that the professors will spread the word about the excitement of our work to their students who go on to graduate school. The responses from the 1987 WHOI workshop indicate that we are on the right track. Alfanso Albano, a physics teacher from Bryn Mawr College in Pennsylvania, wrote: "I must confess that before this week, my idea of what oceanographers do for a living did not go much beyond speaking with a French accent and drinking canned Beaujolais while sailing into tropical sunsets. This week was a very intensive educational experience. I found myself fascinated by the variety of the problems that you in the oceanographic community study, impressed by the quality and diversity of the intellectual and technological arsenals that you bring to bear on them, dazzled by many of your results and convinced of the seriousness of your manpower needs..." We hope to host more workshops in 1989.

While there are fewer people going to college and still fewer studying science, the shrinking national applicant pool has not seriously affected our own WHOI/MIT Joint Graduate Degree program in terms of the quality or quantity of applicants.

According to a new survey of the major oceanographic schools and institutions in the U.S., the Joint Program attracts some of the brightest students in the applicant pool. The mean graduate record exam scores for students entering the WHOI-MIT graduate degree program fall above the 85th percentile. About 80 percent of our graduate students successfully complete their programs and 80 percent earn jobs in teaching and research, almost always the preferred option. The survey, the most extensive of its kind, was designed by the Dean's Retreat group which represents the leading U.S. schools and institutions offering graduate programs in all fields of oceanography.

This was the first operating year of the Ocean Ventures Fund, established in 1986 to give our graduate students access to unrestricted private money which had been available only to established scientists. While we received 24 research proposals, our start-up funds allowed us to award grants for only five. The top-ranked research project focuses on trying to determine whether it is possible to "read" a year long temperature record in the shells of crabs that live near hydrothermal vents in the deep ocean. We hope to continue securing funds for student research projects which show promise and which might develop into major research initiatives. At year's end, we published the premier edition of our newsletter Ocean Ventures, which reports on the research sponsored by the Ocean Ventures Fund.

Another highlight of 1987 was the summer graduation of the first U.S. Navy officers enrolled in the Joint Program as a result of an education initiative established in 1985 by then Secretary of the Navy John Lehman. Lts. Ferdinand Diemer and Paul Bushong received Ocean Engineer degrees. Seventeen male and female naval officers remain in the program working toward master's and doctoral degrees.

Eighteen doctoral degrees were awarded in 1987 to graduates of the MIT/WHOI Joint Graduate program, bringing the total number of degrees awarded since the program's founding in 1968 to 212 (Ph.D. - 167, Sc.D. - 19, Engineer - 23, and WHOI Ph.D. - 3).

Establishment of a Center for Marine Exploration, headed by Senior Scientist Robert Ballard of the Ocean Engineering Department, was formally approved by the Board of Trustees in January. The new Center will foster the continued development of unmanned deep ocean systems and provide a focal point for marine scientists and others to explore the deep sea.

The first W. Van Alan Clark Sr. and Jr. Chairs for Excellence in Oceanography were awarded to Senior Scientists William Jenkins of the Chemistry Department and G. Michael Purdy of the Geology and Geophysics Department. The permanently endowed chairs will be awarded for a five-year period to tenured members of the scientific staff who have distinguished themselves through extraordinary accomplishments in marine science and education.

An enthusiastic group of 55 Associates and Institution staff departed 21 January for a trip to Australia to view the America's Cup races off Fremantle, eventually won by American challenger *Stars and Stripes*. The WHOI flag flew prominently from their spectator boat.

Several major snowstorms hit Cape Cod in late January and February, forcing the Institution to close the afternoons of 26 January and 9 February and the morning of 10 February. Institution Facilities crews rose to the test to clear parking lots and paths of the more than 50 inches of snowfall.

Fifty-four employees donated blood at the annual Red Cross Blood Drive 2 February in Clark 507. Physical Oceanography Department Secretary May Reese was presented a plaque recognizing her contributions to the Red Cross blood drives in Woods Hole.

More than 110 attended a 26 February workshop on shellfish disease problems in the region, sponsored by the Institution's Sea Grant program. Scientists, shellfishermen and public officials gathered in Redfield Auditorium to discuss such issues as MSX oyster disease, brown tide and the risks of disease introduction and spread from the importation of shellfish from distant hatcheries.

Celebration of the U.S. Constitution's bicentennial was the topic of Black History Month activities. Robert Hayden, Executive Director of the Massachusetts Pre-Engineering Program, spoke 26 February on "Free Blacks and the Constitution, 1798 to 1900: Emphasis on Inventors." Black History Month activities were jointly sponsored once again by the Institution, the Marine Biological Laboratory and the National Marine Fisheries Service.

DSV Alvin's February dives off Loihi Seamount attracted considerable media attention as the sub explored the active volcano as it rises to the surface to one day become the newest Hawaiian island. Local press visited *R/V Atlantis II* during port calls at Hilo and Honolulu and converged at the dive site on chartered boats.

A $1,500 college scholarship was awarded by the Institution to Falmouth High School Junior Eric Hallstein as overall first place winner of the annual Falmouth Community Science Fair 14 March at Falmouth High School. Eric studied the impact of copper-based bottom paint on the environment. The award, the eighth science fair scholarship given by WHOI and an increase of $500 from previous years to keep pace with the rising cost of education, was presented by Dean Charles Hollister.

Rep. Claudine Schneider (R-Rhode Island) presented the 17th J. Seward Johnson Marine Policy Lecture 20 March in Redfield Auditorium on "What is the Future of the Oceans in the Absence of a U.S. National Ocean Policy?" A reception followed at Endeavour House.

More than 130 members of the Falmouth Chamber of Commerce attended the group's monthly breakfast meeting hosted by the Institution 26 March in Clark 507. Publications and Information Manager Shelley Lauzon presented a slide program on Institution research and education programs and WHOI's impact in the greater Falmouth area.

The 11th Annual Meeting of the Massachusetts Marine Educators was held 4 April in Redfield Auditorium, hosted once again by the Institution's Publications and Information Office. Scientific staff members Bruce Tripp, Geoffrey Thompson

ASHORE & AFLOAT


Photo by Shelley Lauzon

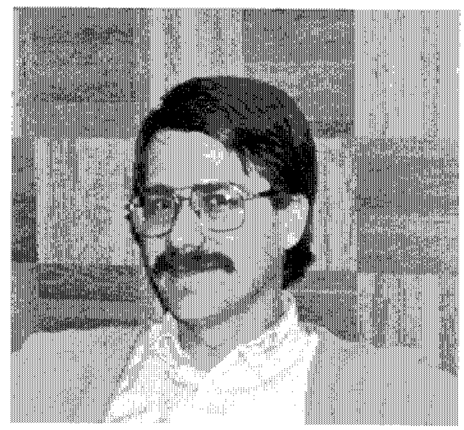

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Photo by Shelley Lauzon

Top: Rep. Claudine Schneider (R-Rhode Island) answered questions at a reception at the Exhibit Center after her Johnson Marine Policy lecture March 20. Middle: Van Alan Clark Chair recipient Bill Jenkins. Bottom: Van Alan Clark Chair recipient Mike Purdy.

and Peter Tyack presented lectures on their research activities to the more than 200 in attendance.

The spring Associates Dinners attracted more than 60 to New York City's Lotos Club 2 April and more than 180 to Boston's Museum of Science 9 April. Associate Scientist David Aubrey of the Geology and Geophysics Department spoke on "Sea Level Rise: Myth or Threat?"

Seventy-five attended a series of activities 6-10 April in celebration of the Marine Policy Center's 15th anniversary. Many former staff attended the reunion and participated in the symposia organized for the occasion.

Numerous Visiting Committees, composed of members of the Board of Trustees and Corporation, met with Institution staff during the spring to evaluate programs and suggest areas of improvement. Final Visiting Committee meetings were held 11-12 May; preliminary reports to all departments were discussed.

Wave modeling specialists from around the world gathered in Woods Hole 4-7 May to discuss the latest developments in computer modeling. Assistant Scientist Hans Graber of the Ocean Engineering Department convened the session, attended by more than 40 scientists and engineers.

The Marine Policy Center sponsored two workshops in early May. Science, economics and sea-level change were the focus of a 7-8 May meeting, while Arctic/Soviet maritime programs was the topic of a 10-13 May meeting, funded by a grant from the MacArthur Foundation.

Some 116 New and Guest Associates spent the day 22 May learning about Institution research and education programs and visiting laboratories as part of the annual New Associates Day program.

Sixty attended a Coastal Zone Management workshop 22 May convened by Arthur Gaines of the Marine Policy Center.

Senior Scientist Robert Gagosian, Chairman of the Chemistry Department since October 1982, began his new duties 1 June as Associate Director for Departmental Research. Senior Scientist Frederick Sayles was named Chemistry Department Chairman. Derek Spencer, who has

Photo by Shelley Lauzon

Top: New Associates view trays of *aplysia* at the Environmental Systems Laboratory May 22. Bottom: Entrance to the Quissett Campus after one of the winter snow storms.

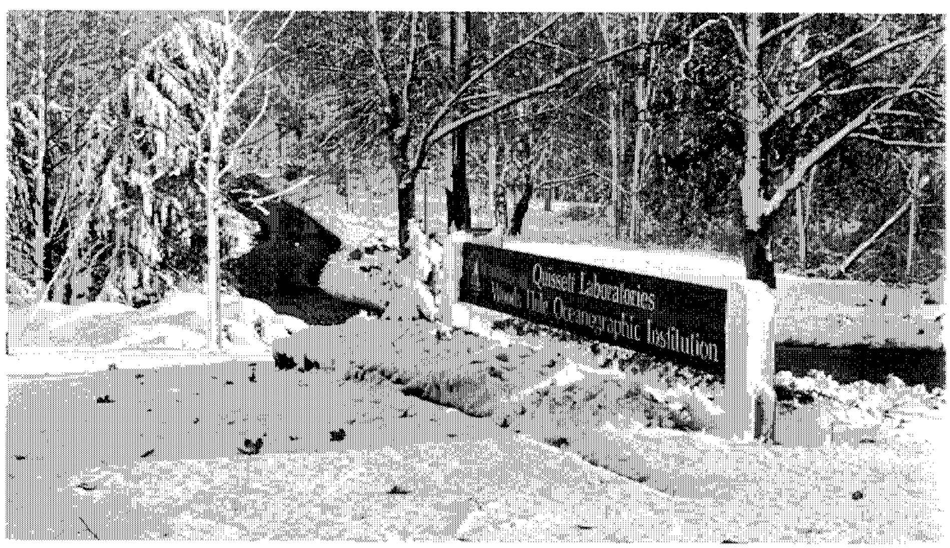


Photo by Shelley Lauzon

been the only Associate Director for Research, assumed the duties of Associate Director for Inter-Departmental Research, with responsibility for the development of major interdisciplinary programs and the individual programs within the Institution's three research centers.

Senior Scientist Brian Tucholke of the Geology and Geophysics Department received the Naval Research Laboratory's Alan Berman Research Publication Award in recognition of the technical merit and literary clarity of his publication "The Geology of North America, Volume M: The Western North Atlantic Region."

A 1972 research paper entitled "A Cenozoic Time-Scale: Some Implications for Regional Geology and Paleobiogeography" by Senior Scientist William Berggren of the Geology and Geophysics Department was cited by the Institute for Scientific Information as having achieved "classic" status among scientific publications. Berggren's paper had been cited in more than 260 publications.

The Boston Sea Rovers, the oldest diving group in the U.S., chose the Institution's prototype vehicle *Jason Jr.* as its 1987 "Person of the Year" in ceremonies 7 March in Boston.

Director John Steele accepted a plaque honoring the Institution staff responsible for the development of *Jason Jr.*.

More than 100 friends and colleagues gathered 12 June at Fenno House to honor departing Ocean Engineering Department Chairman Robert Spindel, who accepted a position at the University of Washington in Seattle as Director of the Applied Physics Laboratory. Senior Scientist Albert "Sandy" Williams was named Acting Department Chairman.

Assistant Scientist Deborah Smith of the Geology and Geophysics Department was chosen by the Office of Naval Research (ONR) as one of 15 recipients of its Young Investigator Award. Smith was chosen from more than 300 applicants for her research on characterizing seafloor topography and was the only oceanographer to win the award in 1987. A 1986 recipient, Cheryl Ann Butman of the Ocean Engineering Department, was also the only oceanographer to win the award.

Senior Scientist Holger Jannasch of the Biology Department was elected a Fellow of the American Academy of Arts and Sciences in May.

Associate Scientist Ellen Druffel of the Chemistry Department was selected to receive one of 24 National Science Foundation Visiting Professorships for Women for 1987-1988. Druffel spent the year at the University of California, Santa Cruz, and was recognized for her research in trace metal concentrations in banded corals as indicators of past enso activity.

Marine Policy Center (MPC) Advisor Robert Solow of MIT was awarded the 1987 Nobel Prize in Economics for his pioneering studies on economic growth. Solow, a member of the Senior Advisors Committee, is the father of MPC Social Scientist Andrew Solow.

Karen Rauss, the Institution's Manager of Benefits, was appointed Special Assistant to the Director 14 July. Rauss will be responsible for initiating and responding to all Institution affirmative action issues and concerns and will advise the Director on employee and student relations, including policies and programs to increase the diversity of the Institution's workforce and student body. Benefits Administrator Teresa Monroe was named Benefits Manager.

The 58th Annual Meetings of the Trustees and Members of the Corporation were held 19 June at Clark Laboratory. New Trustees and Members were elected during the morning sessions; Senior Scientist William Jenkins of the Chemistry Department gave the science report on "Tracers in the Ocean." Later in the day, Open Houses were held at the Coastal Research Laboratory, where demonstrations were given on the flume facility and the robotic vehicle *Jason Jr.*, and at Clark Laboratory, where mooring technology and remote sensing and modeling was explained in the Physical Oceanography Department. Following the Open Houses, more than 200 Associates and guests attended the annual Associates Lecture in Clark 507 given by Assistant Scientist Peter Tyack of the Biology Department on "Baleen Whales vs. Toothed Whales: Differences in Life History, Social Structure and Communication." The Woods Hole Associates dinner followed under a tent on the Fenno House grounds.

Two hundred sixty-five attended a bluefin tuna workshop 30 June sponsored by the Sea Grant program in Redfield Auditorium. The workshop was held to educate recreational fishermen on how to handle tuna once they are caught to get them to market in the best condition.

News of a French *Titanic* expedition caused considerable media attention for the Institution throughout the summer once the expedition was announced 22 July. Although WHOI was not involved in the expedition, reporters were anxious to learn the Institution's "position" on the event.

A satellite earth station was installed on the Central Heating Plant near Clark Laboratory in August, linking the Institution with the University Satellite Network (USAN) which in turn links seven educational institutions to each other and to the National Center for Atmospheric Research in Boulder. Through USAN Institution scientists now have access to the nation's supercomputers.

R/V Atlantis II and *DSV Alvin* spent a busy week in Tokyo 2-9

Photo by Shelley Lauzon

Photo by Shelley Lauzon

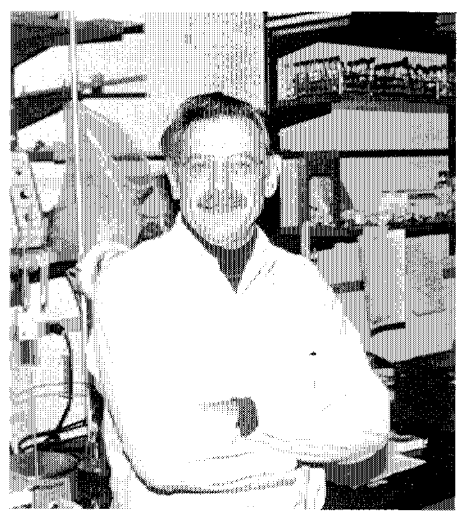


Photo by Shelley Lauzon

Photo by Shelley Lauzon

Top: Young Investigator Award recipient Deborah Smith. Second from top: Endeavour House (left), home of the Exhibit Center, and Shiverick House. Third from top: Holger Jannasch, elected a Fellow of the American Academy of Arts and Sciences. Bottom: *Knorr* Engineer Harry Oakes (left) and Radio Electronics Officer Ernest "Butch" Smith prior to *Knorr's* departure October 30 for a year-long cruise.

August for the ship's first port call in Japan since 1965. The port call marked the conclusion of highly successful U.S.-Japanese scientific collaboration in the western Pacific during which Japanese scientists made a number of *Alvin* dives in the Mariana Trough area. Highlighting the port activities was the 4 August visit by Crown Prince Akihito, who viewed displays, toured the ship and climbed into *Alvin* with Pilot Dudley Foster. Later in the week 12 specimens from the Mariana Trough dives were presented to Emperor Hirohito via his chamberlain for his private collection by the Institution on behalf of the U.S. marine research community. Other activities during the week included science discussions on the Global Ocean Flux Study and submersible technology with colleagues at the University of Tokyo and the Japan Marine Science and Technology Center, a media Open House, a VIP reception cosponsored by the Bank of Boston and WHOI, and visits by invited delegations from government, industry and academia. An estimated 1,500-2,000 people visited *Atlantis II* during the port call.

More than 300 employees and their families gathered 9 August on the Fenno House and Clark Laboratory grounds for the annual Employee Picnic. Activities included pony rides, volleyball and musical entertainment.

For the second year, the Institution donated its receipts from leasing the Dyer's Dock parking lot to the Woods Hole Businessmen's Association for the summer season to the Woods Hole Community Development Foundation. Director John Steele forwarded a check for $1,287 to the Foundation for its unrestricted use.

A small group of colleagues and staff gathered 2 October in Clark 206 to celebrate John Steele's 10th anniversary as Director. He became the Institution's fifth Director 3 October 1977, succeeding Paul Fye.

More than 400 attended the annual Day of Science 9 October at Clark Laboratory. Morning science presentations were given by Assistant Scientist Brian Howes of the Biology Department on "Nutrient Inputs in Buzzards Bay: Are We Looking at the Right Processes?" and by Associate Director for Departmental Research Robert Gagosian on "Scientists at WHOI: Why They Come; Why They Stay?" Following luncheon under a tent on the Fenno House grounds, lectures were given by Assistant Scientist Jules Jaffe of the Ocean Engineering Department on "Underwater Imaging and Image Processing" and by Visiting Investigator Ken Buesseler of the Chemistry Department on "Chernobyl Fallout and Its Implications for Oceanographic Studies in the Black Sea."

Captain Joseph Coburn began his new duties 12 October as Manager of Marine Operations, with responsibilities for the management and operation of the Institution's research fleet.

Space considerations for scientific needs in Physical Oceanography forced the Directorate to move from the second floor of Clark Laboratory to renovated quarters in Fenno and Bell Houses in mid-October. Director John Steele and his staff and the Development Office are now located on the second floor of Fenno House. Associate Directors Derek Spencer and Robert Gagosian and their staffs and Assistant Director for Finance and Administration Gary Walker and his staff are located in Bell House, along with the Ocean Industry Program. The Sea Grant Program offices were expected to move to Bell House in early 1988.

Friends and colleagues gathered 20 October in Smith Conference Room to honor *R/V Knorr* Boatswain Jerry Cotter for thirty years of service. The traditional December ceremony was rescheduled as *Knorr* would be at sea on a year-long cruise.

More than 40 Associates who served as Volunteers in the Publications and Information Office and the Exhibit Center at Endeavour House July through mid-October were honored at an appreciation luncheon 28 October at Carriage House. More than 20,000 visited the Exhibit Center during the summer season.

After nearly ten months in layup status due to lack of operating funds, *R/V Knorr* began its 1987 operating schedule 7 July with a cruise to the North Atlantic off Iceland to search for hydrothermal vents with the *ARGO* camera system and to conduct naval operations. Several short cruises followed before *Knorr* departed Woods Hole 30 October for a year-long cruise which will take the ship to South America, Africa and into the Mediterranean and Black Seas. Return to Woods Hole is scheduled for late October 1988.

The annual Institution holiday party was held 12 December at the Marine Biological Laboratory's Swope Center. Nearly 300 attended the gala, the first held in Woods Hole in many years.

Among the many visitors to the Institution in 1987 were staff members of Sea Grant College programs throughout New England, who met in Woods Hole 9 June; and thirty-five members of the New England Farm and Garden Association, who attended a slide presentation on Institution activities 11 June in Clark Laboratory. The group has supported a Summer Student Fellow for many years. The Marine Board of the National Academy of Sciences toured *R/V Knorr* and the dock area 11 June prior to a dinner hosted by the Institution. National Science Foundation Director Eric Bloch and Senior Science Advisor Mary Clutter visited WHOI 7 August, hosted by Associate Directors Derek Spencer and Robert Gagosian and Dean Charles Hollister. New Scripps Institution of Oceanography Director Edward Frieman toured Institution facilities and met with staff 2-3 September during board meetings at the National Academy of Sciences's facilities in Woods Hole.

The 1987-1988 Knight Science Journalism Fellows at MIT spent the day 25 September to learn about Institution research programs; many other print, radio and television reporters visited during the year. The Northeast Area Remote Sensing Association, of which WHOI is a member, met 13 November at Clark Laboratory. Annual visits were made by senior cadets at the U.S. Coast Guard Academy, who spent the day 28 April at WHOI, and four classes of mid-and senior level foreign naval officers from the Naval War College in Newport, each class representing more than 30 nations.

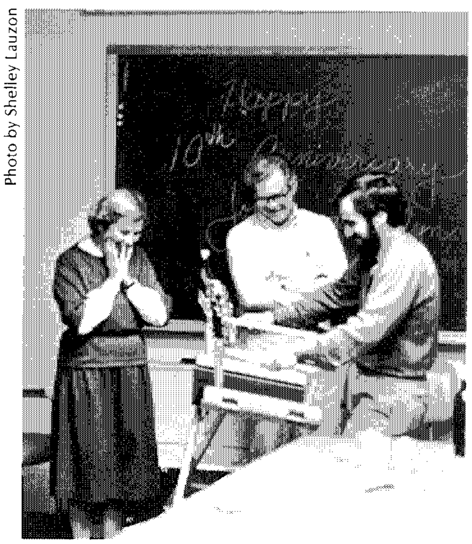
Photo by Linda Lee Andrews

Photo by Shelley Lauzon

Clockwise from top left: Personnel's Marsha Hjulstrom entertained the crowd at the employee picnic August 9; Liberal arts college educators chat with Dean Hollister at the conclusion of their week-long training session in June; Director's chairs were presented to John and Evelyn Steele on the occasion of his tenth anniversary as Director October 3; Associates try their hand at maneuvering *Jason Jr.* in the test tank at the Coastal Research Laboratory during Annual Meeting Open Houses; Senior Scientist Sus Honjo painted the ship's name in Japanese during the *Atlantis II/Alvin* port call in Tokyo in early August; Japan's Crown Prince Akihito (right) views biological specimens collected by *Alvin* in the western Pacific, which were later presented to Emperor Hirohito for his private collection. Director John Steele is at right, U.S. Ambassador to Japan Mike Mansfield is at left.

Photo by Shelley Lauzon

Photo by Shelley Lauzon



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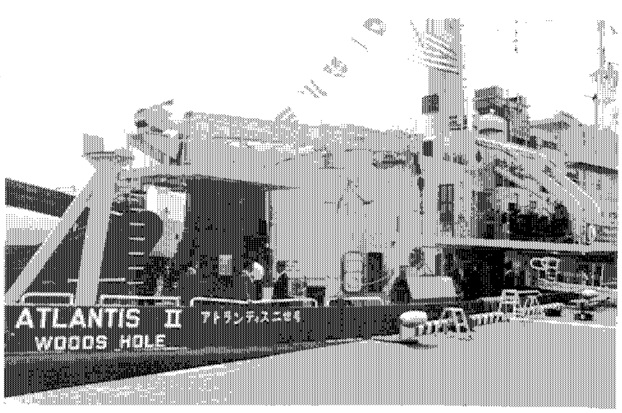

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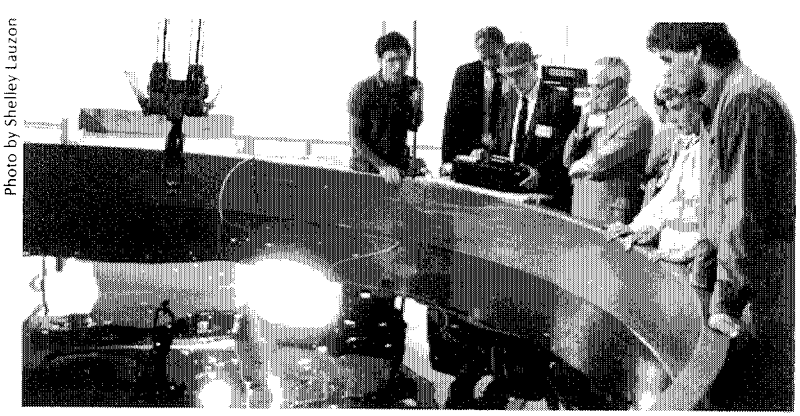

Publications

1987 Publications of record as of February 1, 1988. Entries are listed by department. Institution contribution number appears at the end of each entry. 1986 publications not listed in the 1986 Annual Report are included here.

Biology

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VOYAGE STATISTICS

R/V ATLANTIS II/DSV ALVIN

Total Nautical Miles for 1987 - 18,478 miles
Total Days at Sea - 259 days
Total Dives - 166 dives

Voyage	*Cruise Period*	*Principal Objective, Area of Operations*	*Ports of Call (Destination)*	*Chief Scientist*
118-VIII	9 Jan - 21 Jan	Twelve *Alvin* dives to implant instruments and collect samples: six dives in the San Diego Trough and six dives in the Santa Catalina Basin; box coring, pogo camera casts and the deployment/recovery of free vehicle samplers	San Diego, California	C. Smith (UW)
118-IX	26 Jan - 4 Feb	Transit from San Diego, California	Honolulu, Hawaii	
118-X	8 Feb - 17 Feb	Sampling vent fluids for chemical analysis and mapping the geological setting of hydrothermal vents near Loihi Seamount; seven *Alvin* dives, deep sea camera tows	Hilo, Hawaii	H. Craig (SIO)
118-XI	17 Feb - 22 Feb	Collection of basalt rock samples and mapping the geological setting of hydrothermal vents in the vicinity of the Loihi Seamount; four *Alvin* dives, SEA BEAM surveys and a rock dredge	Honolulu, Hawaii	M. Garcia (UH)
118-XII	28 Feb - 1 Apr	Ten *Alvin* dives on the Horizon Guyot and seven *Alvin* dives on the Magellan Rise to observe the fauna and collect specimens; CTD/rosette casts, MOCNESS tows, camera sled tows, Otter trawl tows, box core stations and the launch and recovery of sediment trap moorings	Piti, Guam	K. Smith (SIO)
118-XIII	5 Apr - 17 Apr	Collection of chemical, geological, biological and petrological samples and the investigation of hydrothermal vents in the Mariana Trough; ten *Alvin* dives, ANGUS camera tows	Tanapag, Saipan	H. Craig (SIO)
118-XIV	22 Apr - 12 May	Collection of geological/biological samples and studies of the geologic processes of a volcanic and tectonic spreading center in the area of the Mariana Trough; eighteen *Alvin* dives, dredge stations and 3.5 echo sounding surveys	Piti, Guam	P. Lonsdale (SIO)
118-XV	15 May - 2 Jun	Collection of samples to study the geologic processes and tectonic features in the northern Mariana fore-arc; fourteen *Alvin* dives, dredge and camera stations, and 3.5 echo sounding surveys	Piti, Guam	P. Fryer (UH)
118-XVI	8 Jun - 25 Jun	Studies of the geologic processes of an off-axis hydrothermal field on old crust west of the Mariana Trough spreading center; sixteen *Alvin* dives, piston and gravity cores and dredge stations	Tanapag, Saipan	M. Leinen (URI)
118-XVII	28 Jun - 12 Jul	Studies of the geologic and volcanic processes associated with submarine volcanoes in the Mariana Trough spreading center; ten *Alvin* dives, collection of rock and vent water samples, 3.5 echo sounder surveys, and dredge, box core and camera tow stations	Piti, Guam	P. Fryer (UH)
118-XVIII	15 Jul - 2 Aug	Investigation of the structural, volcanic and hydrothermal processes associated with back-arc spreading of the Bonin Island Arc; twelve *Alvin* dives to collect rock, sediment and vent water samples, SEA BEAM surveys, camera tows and rock dredge stations	Tokyo, Japan	B. Taylor (UH)
118-XIX	9 Aug - 24 Aug	Transit from Tokyo, Japan	Astoria, Oregon	

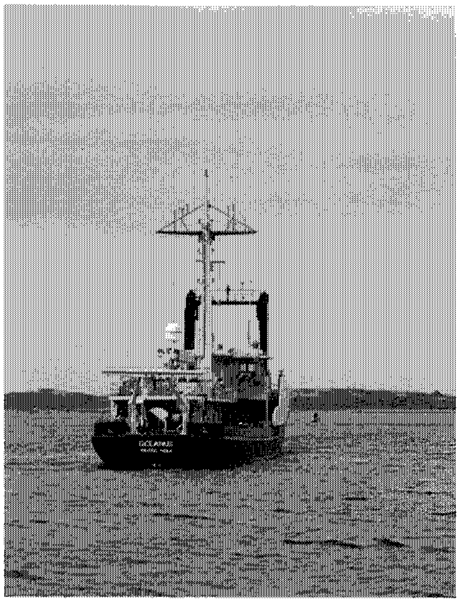
118-XX	28 Aug - 10 Sep	Studies of active fluid vents on the crest of the Juan de Fuca Ridge and of the structure, lithologies and fluid conduits of adjacent canyons; twelve *Alvin* dives, gravity and box coring, rock dredging, SEA BEAM and seismic surveys, air guns and deep-tow hydrophones	Newport, Oregon	L. Kulm (OSU)
118-XXI	14 Sep - 5 Oct	Continuation of the Vents Program involving investigations on the hydrothermally active spreading center composed of the Gorda, Juan de Fuca and Explorer Ridges in the northeastern Pacific Ocean Basin; twenty *Alvin* dives, SEA BEAM surveys, rock dredge stations, current meter/sediment trap recovery, deployment of deep-sea tide gauges and dragging for a failed instrumented mooring	Newport, Oregon	S. Hammond (NOAA/PMEL)
118-XXII	9 Oct - 16 Oct	Operational testing of in-situ "smoker" samplers used in the study of the relationship between hydrostatic pressure and bacterial activity in hydrothermal environments; five *Alvin* dives, SEA BEAM surveys and rock dredging	Seattle, Washington	J. Baross (UW)
118-XXIII	19 Oct - 24 Oct	Transit	San Diego, California	
118-XXIV	27 Oct - 12 Nov	Collection of samples in the Santa Catalina Basin and San Diego Trough; fourteen *Alvin* dives, camera lowerings, deployment and recovery of free vehicle samplers	San Diego, California	C. Smith (UW)

R/V KNORR

Total Nautical Miles for 1987 - 18,532 miles
Total Days at Sea - 134 days

Voyage	*Cruise Period*	*Principal Objective, Area of Operations*	*Ports of Call (Destination)*	*Chief Scientist*
129-I	7 Jul - 17 Jul	Transit from Woods Hole	Reykjavik, Iceland	R. Ballard
129-II	18 Jul - 1 Aug	Deep Submergence Laboratory, ARGO Support	Bodo, Norway	R. Ballard
130-I	2 Aug - 20 Aug	Investigating hydrothermal properties of active vents on the Mohns Ridge between Greenland and Jan Mayen Fracture Zones; ARGO camera tows, SEAMARC side scan surveys	Reykjavik, Iceland	W. Schwab (USGS)
130-II	20 Aug - 30 Aug	Transit from Reykjavik, Iceland	Woods Hole	
131	4 Sep - 9 Sep	Operational testing of Dynamic Positioning System, Western North Atlantic	Woods Hole	D. Yoerger
132	16 Sep - 3 Oct	Deployment of instrumented sub-surface moorings, CTD station, Western North Atlantic	Woods Hole	S. Worrilow
133	14 Oct - 14 Oct	INSURV Inspection	Woods Hole	
134-I	30 Oct - 4 Nov	Collection and analysis of water samples for intercomparison of at-sea techniques for Freon concentration during the South Atlantic Ventilation Experiment (SAVE) program in the Western North Atlantic; Niskin bottle casts	St. George's, Bermuda	W. Smethie (LDGO)
134-II	6 Nov - 19 Nov	Continuation of monitoring the water collection system for the SAVE program	Recife, Brazil	P. Salameh (SIO)
134-III	23 Nov - 13 Dec	South Atlantic Ventilation Experiment (SAVE): Investigation of the rates of mixing, ventilation, interocean exchange and ocean circulation of carbon, oxygen and nutrient cycling on an ocean basin scale; large volume water sampler, CTD/rosette system and Gerard bottle casts	Abidjan, Republic of the Ivory Coast	T. Takahaski (LDGO)
134-IV	18 Dec - 23 Jan 1988	Continuation of SAVE Program	Rio de Janeiro, Brazil	W. Smethie (LDGO)

Photo by Shelley Lauzon



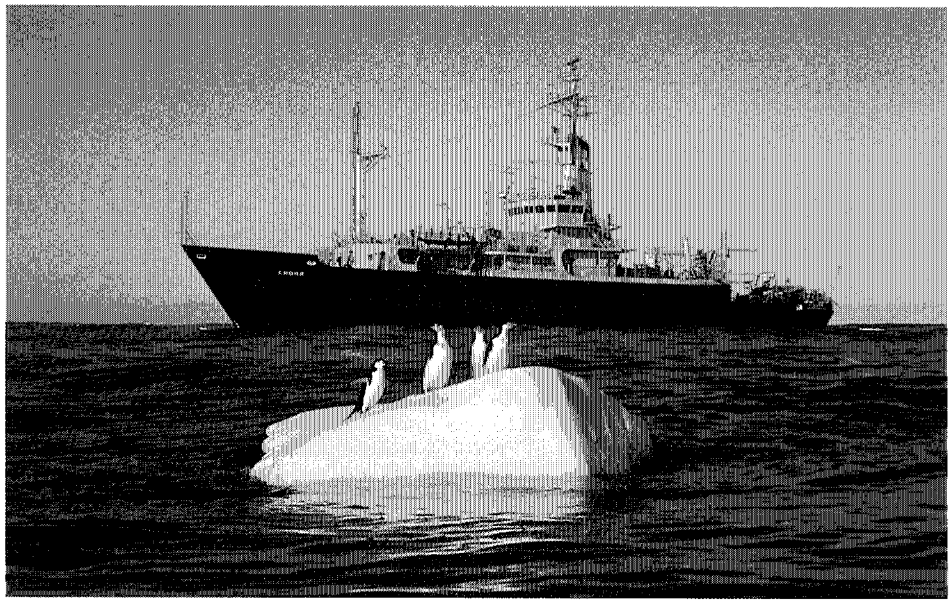


Photo by Richard Bowen

Top left: *Oceanus* departs Woods Hole on another cruise. Top right: *Knorr* in the Antarctic, 1984. Bottom: *Atlantis II* maneuvers to recover *Alvin*.

Photo by Perry Thorsvik©National Geographic Society

R/V OCEANUS

Total Nautical Miles for 1987 - 31,230
Total Days at Sea - 240 days

Voyage	*Cruise Period*	*Principal Objective, Area of Operations*	*Ports of Call (Destination)*	*Chief Scientist*
181-I	5 Feb - 10 Feb	Hydrographic survey of water masses in the Gulf of Maine and Northeast Channel of Georges Bank; CTD casts, deployment and recovery of current meter moorings, deployment of instrumented tripods and guard buoys in Massachusetts Bay off Boston Harbor	Portsmouth, New Hampshire	B. Butman (USGS)
181-II	10 Feb - 20 Feb	Survey of benthic bacteria and meiofauna production and grazing in the Gulf of Maine; collection of larval fish and hydrographic surveys of inshore waters, box cores, CTD and hydrographic stations	Woods Hole	L. Cammen (IOS)
182-I&II	26 Feb - 10 Mar	Initiation of seasonal variability experiment of the Biowatt Program, designed to understand optical variability and bioluminescence patterns from the dynamics of plankton populations in the Western North Atlantic; deployment of instrumented surface mooring, CTD/rosette casts, MOCNESS tows, Bio-Optical Profiling System (BOPS) lowerings, Bathy-Photometer (B/P) casts and XBT stations	Woods Hole	J. Marra (LDGO)

183	14 Mar - 19 Mar	Collection of many species of deep-sea grenadier fishes to obtain tissue and blood samples for use in a systematic study of the genus south of Cape Cod; Otter net and mid-water trawls and one-meter net tows	Woods Hole	R. Wilson (SIO)
184	21 Mar - 10 Apr	Continuation of studies of gelatinous zooplankton and microzooplankton in the Eastern North Atlantic; SCUBA diving, mid-water trawling, plankton tows and hydrocasts	Woods Hole	R. Harbison
185	26 Apr - 5 May	Evaluation and use of a lander to determine spatial variability of chemical gradients near the sediment-water interface on the Continental Rise southeast of Bermuda	Woods Hole	F. Sayles
186-I&II	9 May - 22 May	Deployment of instrumented surface moorings to continue the Biowatt Program; CTD stations, BOPS lowerings and XBT stations	Woods Hole	J. Marra (LDGO)
187	27 May - 29 May	Engineering tests of the R-TEAM mooring southeast of Bermuda; CTD casts	St. George's, Bermuda	P. Clay
188	1 Jun - 6 Jun	Engineering and operational tests of the "Flying Fish" profiling instrument south of Cape Cod and engineering tests of the R-TEAM mooring	Woods Hole	A. Bradley
189	11 Jun - 24 Jun	Collection of samples to measure the abundance, distribution and activity of photosynthetic pico-plankton, identification and culturalization of these organisms in the Sargasso Sea; hydrocasts, Bodman Bottle casts, XBT stations, underwater light measurements and the deployment/recovery of free drifting incubator buoy systems	Woods Hole	R. Olson
190	30 Jun - 9 Jul	Determination of the distribution and abundance of chloroplast-retaining ciliates in the vicinity of Georges Bank; CTD casts, hydrocasts and light measurements.	Woods Hole	D. Stoecker
191-I	14 Jul - 30 Jul	Observation and conduction of experimental studies on gelatinous zooplankton, micro-zooplankton and marine snow in the Gulf Stream waters, Continental Slope and Sargasso Sea north of Cape Hatteras and west of Georges Bank; diving, plankton tows and mid-water trawling for sample collection	New London, Connecticut	R. Harbison
191-II	2 Aug - 16 Aug	Continuation of experimental studies in waters of the Continental Slope in the vicinity of Atlantis, Veatch, Lydonia and Hydrographer Canyons; diving, plankton tows and mid-water trawling for sample collection	Woods Hole	K. Hartel (Harvard)
192-I	21 Aug - 27 Aug	Continuation of the Biowatt Program's seasonal variability experiment in the Western North Atlantic	Woods Hole	J. Marra (LDGO)
192-II	28 Aug - 2 Sep	Continuation of the Biowatt Program	Woods Hole	T. Dickey (LDGO)
193	9 Sep - 20 Sep	Study of the distribution, concentration, primary production and grazing rates of nitrifying bacteria and cyanobacteria, in the Gulf Stream; Niskin bottle casts	Woods Hole	S. Watson
194-I	23 Sep - 24 Sep	To shipyard	Brooklyn, New York	
194-II	22 Oct - 23 Oct	Return from shipyard	Woods Hole	
195	27 Oct - 15 Nov	Recovery and deployment of Antonomous Listening Station (ALS) moorings for the Newfoundland Basin Circulation Experiment; operational tests of the "Fast-fish" profiling vehicle	Woods Hole	J. Valdes
196-I&II	20 Nov - 4 Dec	Continuation of the Biowatt Program's seasonal variability experiment and recovery of instrumented surface mooring in the Western North Atlantic; CTD/ rosette stations, BOPS lowering, XBT casts, Bathy-Photometer (B/P) casts and MOCNESS tows	Woods Hole	J. Marra (LDGO)

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James S. Coles
Charles A. Dana, III
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Thomas A. Fulham
*Paul M. Fye
Kenneth S. Safe, Jr.
Marjorie M. von Stade

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Paul Dudley Hart
Guy W. Nichols
John H. Steele

*Deceased March 11, 1988

Joseph V. McKee, Jr.

Major Challenges

In education, in science, persons make the difference. Persons who are dedicated, informed, creative, and willing to chart new courses. Two successful projects undertaken by the Development Office during 1987 centered on ensuring that such persons—and there are many of them on WHOI's science roster—will have the opportunity and funding to explore new paths, especially those that require multidisciplinary collaboration.

Our first challenge was to raise $800,000 to match funds from the Penzance Foundation for the endowment of two W. Van Alan Clark Chairs for Excellence in Oceanography. This effort was completed one full year ahead of schedule and the first two recipients were named: Senior Scientist in Geology and Geophysics, G. Michael Purdy, and Senior Scientist in Chemistry, William J. Jenkins.

The second challenge came from The Andrew W. Mellon Foundation last spring in the award of $1 million, contingent upon WHOI raising $1.5 million, to endow a fund to provide Joint Initiative Awards for multidisciplinary research. One major objective in the natural sciences is to understand the trends and extent of global environment change, the principal source and first indications of which lie in the ocean. These Joint Initiative Awards will allow WHOI scientists the flexibility to establish unconventional collaborative research partnerships, and will bring individuals from different fields together to grapple with the complex processes that support the oceanic and global environment.

There are two phases to The A. W. Mellon challenge grant. To qualify for the first $500,000, an initial $1 million needed to be raised from other sources; during the second phase WHOI must raise $500,000 to be matched by the remaining $500,000 from the Foundation, bringing the total endowment to $2.5 million. Thanks to many generous donors—individuals as well as foundations and trusts—one million dollars in cash and pledges were raised in 1987, and every effort will be made to complete the challenge in 1988.

Associates Made the Difference

By providing support to match the Penzance Foundation and the Andrew W. Mellon Foundation challenges, by renewing commitments to specially named funds, and by generously donating their time, Associates made the difference in 1987.

In addition to annual contributions for membership, over 27% of the donations made to the fund for Joint Initiative Awards came from Associates. They also generously supported opportunities for students through the Ocean Ventures Fund, the Frank W. Tchitcherine Student Opportunities Fund, and Summer Student Fellowships in the names of Christopher Haebler Frantz, William D. Grant, Sidney T. Knott, the New England Farm and Garden Club, William B. Richardson, and Virginia Walker Smith.

Associates' support was not limited to financial commitments. Over 40 members donated their time during the summer of 1987 providing invaluable assistance to the Institution and the staff. Answering requests for information on research underway and the many inquiries that continue to be received regarding the TITANIC expeditions of 1985 and 1986 kept the volunteers in the Public Information Office busy. They also helped compile the large number of press materials, working against a tight schedule, that were required for the August visit of the ATLANTIS II and ALVIN to Tokyo. As the public interest in the Institution and its scientists increases, so does the number of information requests we receive. Many more of these requests are now answered due to the great help provided by the Associates.

The volunteers who staffed the Exhibit Center, located in the historic Endeavour House, greeted over 25,000 visitors, answered a myriad of questions, and sold copies of WHOI publications and WHOI gift items. These ad hoc ambassadors of the Institution literally provided an open door for visitors to learn about the work of WHOI scientists.

Recognizing that there are possibly other areas that would benefit from the help of volunteers, additional volunteer positions, both on a seasonal and year-round basis, will be explored.

In Addition...

The Ocean Industry Program continues to serve as a resource to member companies in the petroleum industry. Six of these major oil companies are members of the Geosciences Section of the Program, and five are members of the Ocean Dynamics and Engineering section. Income from the Program, in excess of providing membership services, is used for postdoctoral fellowships and research funding.

The research activities of the Marine Policy and Ocean Management Center were significantly aided during 1987 by a generous grant from the Pew Charitable Trusts. Other organizations that contributed generously to WHOI are listed in the "Sources of Support for Research and Education" section of this report.

TRUSTEES & CORPORATION

Photo by Shelley Lauzon

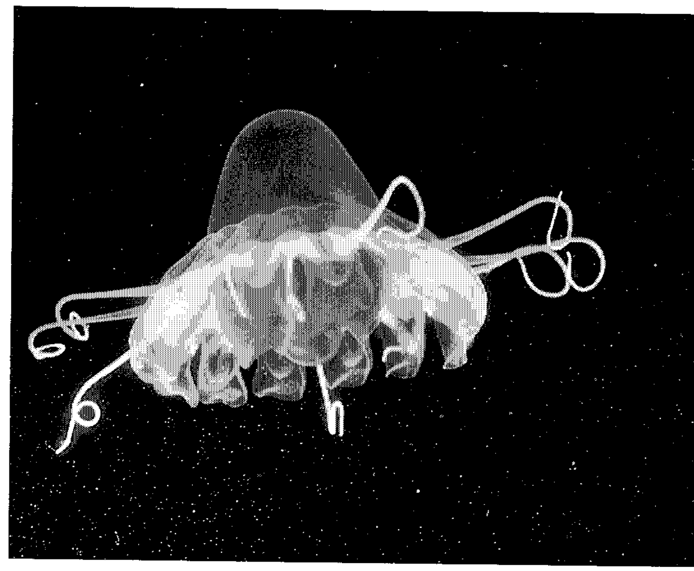

Photo by Laurence P. Madin

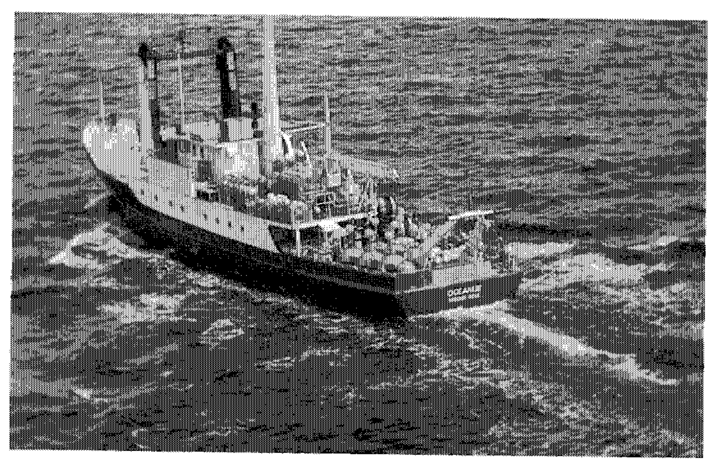

Photo by James Valdes

Top: *Alvin* Pilot Dudley Foster explains boarding procedure to Crown Prince Akihito prior to descending into the submersible during the *Atlantis II* port call in Tokyo August 2-9. Middle: Gelatinous plankton *Periphylla*. Bottom: No room to spare on the *Oceanus* fantail as the ship heads to sea to deploy a series of moorings.

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In Memoriam

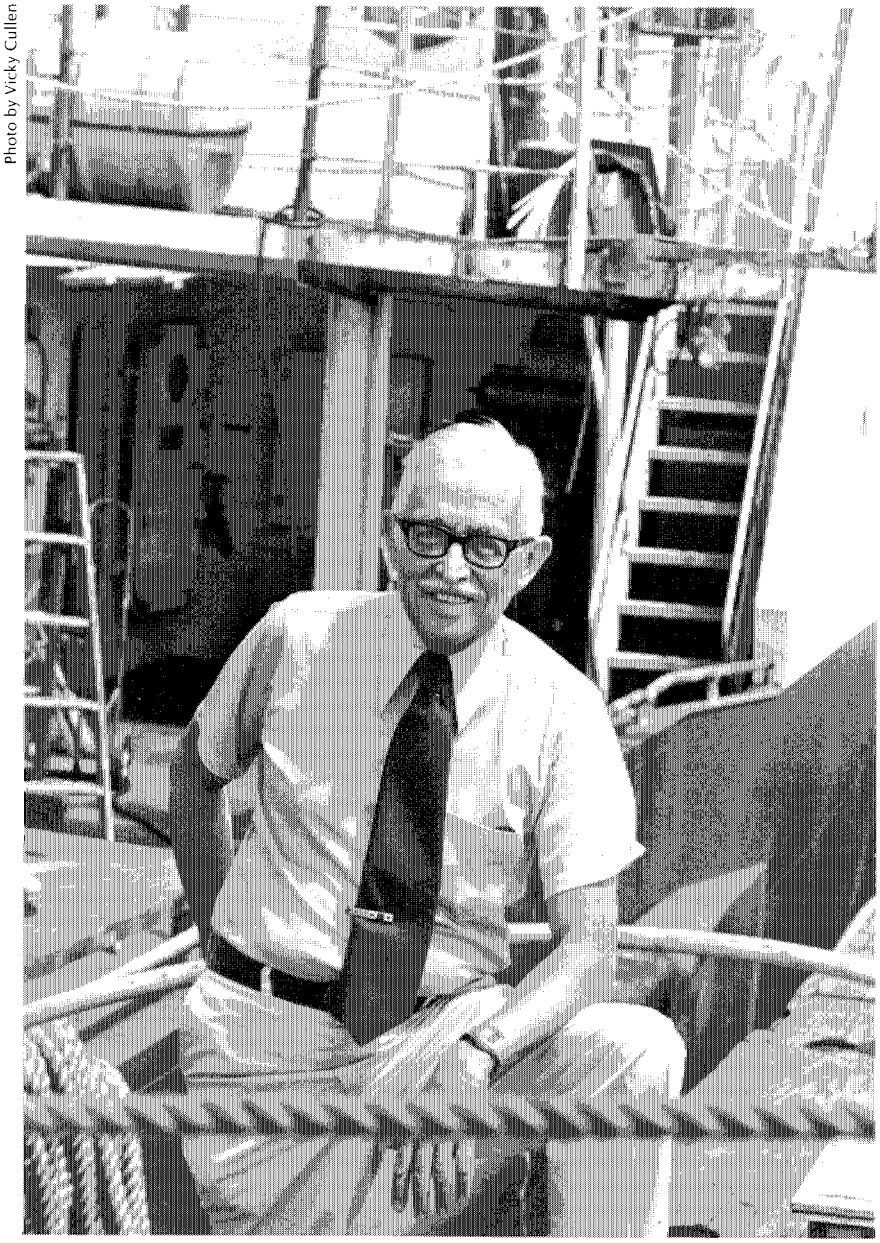
The Institution gratefully acknowledges the service and support of John C. Kiley, Jr., Augustus B. Kinzel, and Roger L. Nichols who passed away in 1987, and Paul M. Fye, who passed away in early 1988.

Dr. Paul M. Fye, fourth Director of the Institution and President Emeritus of the Corporation, died March 11, 1988 at his home in Falmouth at age 75. With his passing the Institution has lot a great friend and leader, and the international marine research community a tireless statesman and supporter.

A 1935 graduate of Pennsylvania's Albright College with a degree in physical chemistry, Paul Fye received his Ph.D. from Columbia University in 1939. Through the years he was awarded seven honorary degrees, the most recent posthumously by the University of Massachusetts, Boston. His professional career began in 1939 as Assistant Professor at Hofstra College; in 1941 he was appointed Research Associate at the Carnegie Institute of Technology, serving for one year until the war effort called him to the Woods Hole Oceanographic Institution. He served as Research Supervisor and Research Director of the Underwater Explosives Research Laboratory at the Institution until 1948, when he briefly returned to teaching at the University of Tennessee. He joined the Naval Ordinance Laboratory in Washington, D.C., in late 1948, serving in various capacities until 1958, when he was named Director of the Woods Hole Oceanographic Institution. Three years later he was also elected President of the Corporation. During his career he served on numerous national and international boards, committees and advisory bodies, and was a member of many scientific societies and organizations.

The Woods Hole Oceanographic Institution is today a leader in marine scientific research and engineering, much to the credit of Paul Fye. During his tenure as Director the Institution budget grew from $2.5 million to $25 million and is today $55 million. The number of personnel doubled, endowment funds increased sixfold, and the number of scientific journal articles more than equalled all those published in the Institution's prior history. The research fleet expanded to include large modern ships like *Atlantis II*, the first ship built since 1930 (the Institution's first vessel, *Atlantis)* from the keel up for oceanographic research. The first manned research submersible in the

Photo by Vicky Cullen



In MEMORIAM

Paul McDonald Fye
1912-1988

Director 1958-1977
President 1961-1986

"The sea will yield its bounty only in proportion to our wisdom, our boldness and determination, and our knowledge."

United States, *Alvin*, joined the fleet in 1964 and *Knorr*, one of the largest vessels in the U.S. academic research fleet, was delivered to Woods Hole in 1970.

Other changes were made under Paul Fye's leadership. Copyright and patent policies were adopted, science department structure was established, and the directorate and staff council were organized. Visiting committees to evaluate research and education programs were activated, a tenure system for senior staff members was adopted, and a full-time development director hired to seek unrestricted funds for research and education.

Although students had been involved in research activities since the Institution's founding in 1930, Paul Fye, with the Board of Trustees' support, inaugurated the joint graduate program with the Massachusetts Institute of Technology in 1968. Since then more than 200 students have received doctoral and engineering degrees in various disciplines, and more than 120 students from around the world are presently enrolled in the program. Hundreds of undergraduate and high school students are involved in less formal education programs.

Aware that facilities were needed to house the growing education and research programs, Paul Fye directed the expansion of the Institution's physical plant with the 1968 acquisition of the Quissett Campus, a 183-acre tract comprised of two adjoining estates just outside Woods Hole. The Institution's largest research facility, the five-story Clark Laboratory, was completed in 1974, and a number of smaller buildings have since been constructed. In 1983, Paul Fye was honored by the Institution with the dedication of an advanced chemistry laboratory named in his honor. A plaque located in the lobby of the building reads: "Paul M. Fye, dedicated scientist, educator, administrator and statesman, whose wisdom and foresight led the Institution and international marine science into a new era."

Paul Fye was not unaware of the human reaction to the many changes taking place. Although some were critical of the expansion and the loss of informality and flexibility that had characterized the Institution's first three decades, most also realized the need to broaden the scope of research activities and maintain the Institution's leadership in the field. Throughout his tenure as Director, he tried to maintain a sense of "family", frequently stopping by offices to see how things were going, offering encouragement to struggling students and frustrated researchers, sending notes of appreciation for a job well done, and greeting ships upon their return to port. He knew most employees by name, and his door was always open.

During the 1970s growth slowed. The Commission of Marine Science, Engineering and Resources, better known as the Stratton Commission, proposed many challenges for the years ahead. Paul Fye spearheaded efforts to respond to these challenges, working tirelessly to raise more private funds. In the late 1970s, he would note: "Ten years ago I did not dream that oceanography could accomplish in so short a time what it has achieved to date. My views of the future, though optimistic at the time, now turn out to have been embarrassingly modest."

Paul Fye believed the future of marine science as well as of mankind lay in cooperation not only among scientists but among nations. He and many Institution staff were involved in the first International Oceanographic Congress at the United Nations; *Knorr* was brought to New York for Law of the Sea meetings in 1973 and is the only marine research vessel to hold that honor. "Research is an activity that flourishes only if it is freely permitted to determine its own priorities," he said of the need for nations to unite in the pursuit of knowledge about the oceans. "Nature knows no political boundaries and ocean phenomena do not stop at the continental shelf."

His dreams of bringing people together involved in the social, economic and political aspects of our use of the oceans was realized in 1970 with the establishment of the Marine Policy and Ocean Management program. Policy Associates and Research Fellows from many nations come together to study and work at the Institution, and the program has assisted developing nations to plan for the wise use of their marine resources. Paul Fye served as Director of the Marine Policy program during its first ten years and again as Acting Director in 1985-1986. In recent years he served in an advisory capacity, working nearly every day until his death.

In 1977, when he stepped down as Director, more than 700 employees and friends honored Paul and Ruth Fye with presentations including the establishment of the Paul McDonald Fye Fellowship and the Ruth and Paul Fye Award for Excellence for the best scientific or technical paper written by a graduate student.

A memorial service was held March 17 at the Falmouth United Methodist Church. Survivors include his wife, Ruth; a son, Dr. Kenneth Fye; a daughter, Elizabeth Fye Murphy; three step-grandchildren; and two sisters.

Paul Fye, more than any other individual, left his mark on the Woods Hole Oceanographic Institution. He will be sorely missed, but his unofficial motto, "to use the oceans wisely through better understanding", will live on.

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As of 31 December 1987

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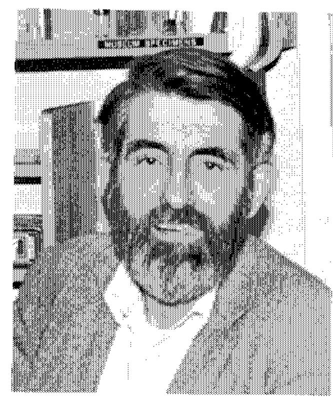
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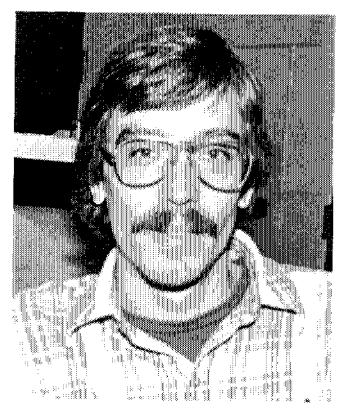
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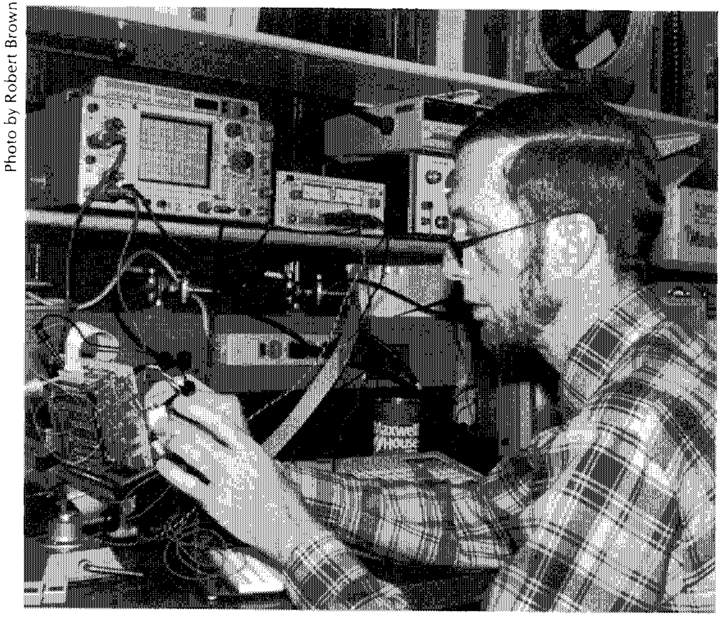
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*Deceased December 10, 1986
**Deceased June 17, 1987

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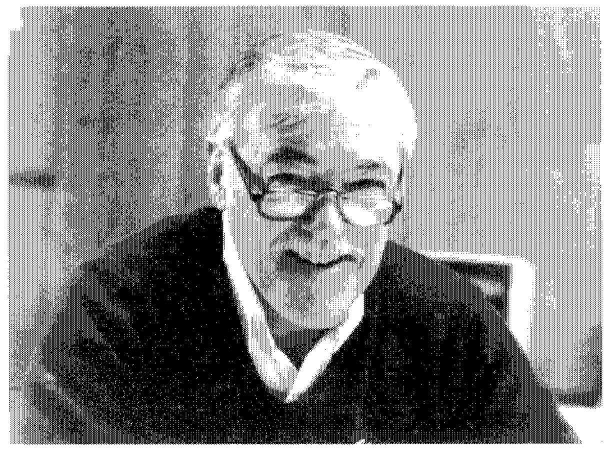

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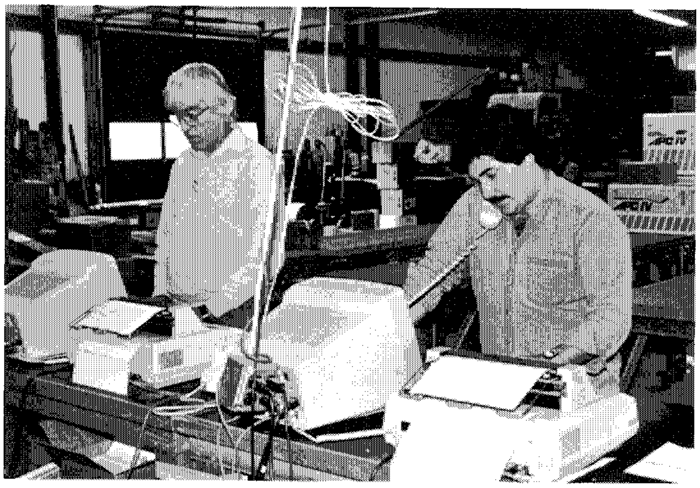

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John K. Sweet, Jr.
Evelyn C. Tayag
Herman Wagner
Stephen A. Walsh

EMPLOYEES RETIRING DURING 1987

Alvin L. Bradshaw
Donald A. Croft
Loretta M. Martin
John H. Ryther
Thomas H. M. Smart
Gordon H. Volkman
Clifford Winget
Grace M. Witzell
Warren E. Witzell, Sr.

FELLOWS, STUDENTS & VISITORS

MIT/WHOI Joint Graduate Program 1987-1988

Elizabeth V. Armbrust
Stanford University
Carol Arnosti
Lawrence University
John A. Barth
University of Colorado, Boulder
Diane E. Bennett
Dartmouth College
Sara L. Bennett
Colorado State University
Gaboury Benoit
Yale University
Esther C. Brady
University of Massachusetts, Amherst
Erik T. Brown
Princeton University
Michael W. Byman
United States Naval Academy
Jeffrey W. Campbell
United States Naval Academy
Antonietta Capontondi
Liceo Scientifico, Italy
University Pisa, Italy
Kevin D. Casey
United States Naval Academy
Changsheng Chen
Shandong College of Oceanography, People's Republic of China
David B. Chester
Long Island University, Southampton
Joon Won Choi
Seoul National University, Korea
Daniel T. Cobra
University of Brazil, Massachusetts Institute of Technology
John A. Collins
University College, Cork, United Kingdom
University College of North Wales, United Kingdom
Debra C. Colodner
Yale University
Noellette M. Conway
Trinity College, United Kingdom
John G. Cooke
United States Naval Academy
Matthew J. Cordery
University of Chicago
Mary Carla Curran
University of South Carolina, Columbia
Victoria University, Australia
Peter H. Dahl
University of Washington
John R. Daugherty
United States Naval Academy
David M. Delonga
United States Naval Academy, University of Maryland, Massachusetts Institute of Technology
Carol E. Diebel
Humboldt State University
David M. Di Pietro
Massachusetts Institute of Technology
Daniel T. Diperna
Lafayette College
Scott C. Doney
University of California, San Diego
Martin E. Dougherty
Winona State University
Cynthia J. Ebinger
Duke University
Thomas Ehrendorfer
University of Vienna, Austria
Kelly K. Falkner
Reed College
Joyce M. Federiuk
University of California, Berkeley
Peter J. S. Franks
Queens University, Canada
Dalhousie University, Canada
Clark B. Freise
United States Naval Academy
John R. Fricke
Vanderbilt University
Carl T. Friedrichs
Amherst College
Ichiro Fukumori
University of Tokyo, Japan
Tanya H. Furman
Princeton University
Paula C. Garfield
Mt. Holyoke College
University of Delaware
Ramnarayan Golpalkrishnan
Indian Institute of Technology, India
Elisabeth A. Gray
Washington University
Sarah A. Green
University of Minnesota
Janet G. Hering
Cornell University
Harvard University
Kristine Holderied
United States Naval Academy
Franz S. Hover
Ohio Northern University
William R. Howard
Brown University
John P. Jasper
University of Chicago
John P. Jemsek
University of Notre Dame
Harry L. Jenter, II
University of Michigan
Andrew T. Jessup
University of Michigan
Gregory C. Johnson
Bates College
Kevin T. M. Johnson
Pennsylvania State University, University of Hawaii
Anne V. Judge
Williams College
Michael A. Kaminski
Rutgers University
Jagiellonian University, Poland
Linda L. King
Mary Washington College
Deborah D. Klatt
United States Naval Academy
Barry A. Klinger
Massachusetts Institute of Technology
Pamela J. Kloepper-Sams
University of California, Irvine
Laura S. L. Kong
Brown University
Wendy B. Lawrence
United States Naval Academy
David W. Lea
Haverford College
Kathleen M. Ledyard
Columbia University
Barnard College
Sang-Mook Lee
Seoul National University, Korea
Alan J. Lewitus
Rutgers University, Moss Landing Marine Laboratories
Sarah A. Little
Stanford University
Zheng Y. Liu
Academia Sinica, Nanjing Institute of Meteorology, People's Republic of China
Cecilie Mauritzen
University of Bergen, Norway
Mark A. McCaffrey
Harvard University
James D. McLaren
Dalhousie University, Canada
Michael J. Moore
Cambridge University, United Kingdom
Mark H. Murray
Massachusetts Institute of Technology
John W. Nicholson
United States Naval Academy
Neil R. Nickolaisen
Utah State University
Kirby S. Olson
Eckerd College
Martha T. O'Neil
Tulane University
Brian P. Palenik
Princeton University
Lorenzo M. Polvani
McGill University, Canada
Kurt L. Polzin
Whitman College
Rui V. Ponte
University of Rhode Island
John M. Richardson
United States Naval Academy
Stephen R. Rintoul
Harvard University

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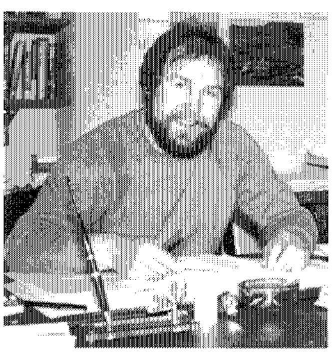

Top: Associate Scientist Dave Aubrey (right) discusses research work with Joint Program student Carl Friedrichs. Second from top: Research Assistant Kathryn Elder. Third from top: Joint Program student Sarah Little prepares her dissertation. Bottom: Assistant Scientist Hans Graber.

Elizabeth A. Rowe
United States Naval Academy

Markku J. Santala
University of Massachusetts, Amherst

Laela S. Sayigh
University of Pennsylvania

Jill V. Scharold
Michigan Technological University

Hagen Schempf
Stevens Institute of Technology

Christopher A. Scholin
University of California, Santa Barbara

Rebecca R. Schudlich
University of Michigan

Peter N. Schweitzer
University of Maryland, University of Kansas

Robert M. Sherrell
Oberlin College

Richard P. Signell
University of Michigan

Elisabeth L. Sikes
Wesleyan University, University of North Carolina, Chapel Hill

Niall C. Slowey
Tufts University, University of North Carolina, Chapel Hill

Wendy M. Smith
Rensselaer Polytechnic Institute

Paul V. R. Snelgrove
McGill University, Canada
Memorial University, Canada

Jonathan E. Snow
Indiana University, University of Rochester

Kevin G. Speer
University of California, Santa Barbara

William S. Spitzer
Harvard University

W. Kenneth Stewart
Florida Atlantic University, Cape Fear Technical Institute

Dajun Tang
University of Science and Technology, Institute of Acoustics, People's Republic of China

LuAnne Thompson
University of California, Davis, Harvard University

D. Andrew Trivett
Dalhousie University, Canada, Technical University of Nova Scotia, Canada

Thomas W. Trull
University of Michigan

Lisa A. Urry
Tufts University

Cindy L. Van Dover
Rutgers University, University of California, Los Angeles

Alexander F. M. J. van Geen
University of Washington

Gregory M. Vaughn
United States Naval Academy, Marymount College of Virginia

Padmaraj Vengayil
Indian Institute of Technology, India University of Florida

M. Ross Vennell
University of Auckland, New Zealand

Sophie Wacongne
University of Pierre & Marie Curie, France

David Walsh
Earlham College

Xiaoming Wang
Shandong College of Oceanography, People's Republic of China
University of Rhode Island

Nathalie A. Waser
University of Pierre & Marie Curie, France

Susan E. Wijffels
Flinders University, Australia

William S. D. Wilcock
Cambridge University, United Kingdom, Imperial College, United Kingdom

John L. Wilkin
University of Auckland, New Zealand

Joanne M. Willey
University of Pennsylvania School of Nursing

Anthony J. Withnell
Indiana University

Jan C. Zemba
University of California, Irvine

Postdoctoral Scholars 1987-1988

Daniel L. Distel
Scripps Institution of Oceanography

Mark E. Hahn
University of Rochester School of Medicine

Remy J.C. Hennett
Princeton University

Scott J. Lehman
University of Colorado

Mary E. Putt
University of California, Santa Barbara

Daniel L. Rudnick
Scripps Institution of Oceanography

Randall S. Wells
University of California, Santa Cruz

Visiting Scholars 1987

Michael F. Land
The University of Sussex, United Kingdom

Karel F. Liem
Harvard University

William Menke
Lamont-Doherty Geological Observatory

Julian P. McCreary
Nova University

Kenneth W. Bruland
University of California, Santa Cruz

Willard S. Moore
University of South Carolina, Columbia

Chia-Shun Yih
University of Michigan, University of Florida

Robin S. Keir
Scripps Institution of Oceanography

D. Van Holliday
Tracor Applied Sciences

Dean H. Roemmich
Scripps Institution of Oceanography

Marine Policy and Ocean Management Research Fellows 1987-1988

Tundi M. Agardy
University of Rhode Island
Jack H. Archer
University of Washington
Cynthia C. Beckham
University of Virginia School of Law
Garry Brewer
Yale University
Richard A. Kenchington
University College of North Wales

Summer Student Fellows

Andrea L. Arenovski
University of North Carolina
Samuel E. Bramhall
University of Virginia School of Law
Takumi Furuya
Texas A & M University
Donna J. Glassbrenner
Yale University
Zoltan F. Kanyo
Ohio State University
Kimberly K. Kelly
Ft. Lewis College
Sara M. Lindsay
Smith College
Michael J. Masterson
Michigan State University
Geraldine A. Miceli
Wagner College
Donald T. Miller
Xavier University
Maureen T. Muck
University of Missouri
Cynthia D. Nevison
University of California, Berkeley
Rodney D. Priddy
University of Oklahoma
Sandra J. Rosenthal
Valparaiso University
Daniel S. Sage
Harvard University
Ayse A. Sahin
Mt. Holyoke College
Steven M. Shroyer
Ball State University
Rachel Somerville
Reed College
Stephanie A. Stotland
University of Southern Mississippi
Catherine C. Weisman
Haverford College

Geophysical Fluid Dynamics Summer Seminar

Fellows:

Lorna C. Brazell
Emmanuel College, University of Cambridge
Andrew D. Gilbert
Gonville & Caius College, University of Cambridge
Rainer Hollerbach
Scripps Institution of Oceanography
Bin Bin Hu
Columbia University
Richard L. Jennings
University of Newcastle Upon Tyne, United Kingdom
Isaac Klapper
Courant Institute of Mathematical Sciences
Jack F. McMillan
University of Hawaii
Jun-Ichi Yano
Kyoto University, Japan

Staff Members & Lecturers:

Bruce J. Bayly
Courant Institute of Mathematical Sciences
Mel S. Berger
University of Massachusetts, Amherst
Jeremy Bloxham
Harvard University
Edward W. Bolton
Yale University
Fausto Cattaneo
University of Colorado, Boulder
Stephen Childress
Courant Institute of Mathematical Sciences
George B. Fields
Harvard University
Glenn Flierl
Massachusetts Institute of Technology
Annalisa Griffa
Scripps Institution of Oceanography
Raymond Hide
Meteorological Office, Brachnell, United Kingdom
David Hughes
DAMTP, University of Cambridge
Glenn Ierley
Michigan Technological University
Robert Krasny
Courant Institute of Mathematical Sciences
Willem V.R. Malkus
Massachusetts Institute of Technology
Michael Proctor
Cambridge University
Rick Salmon
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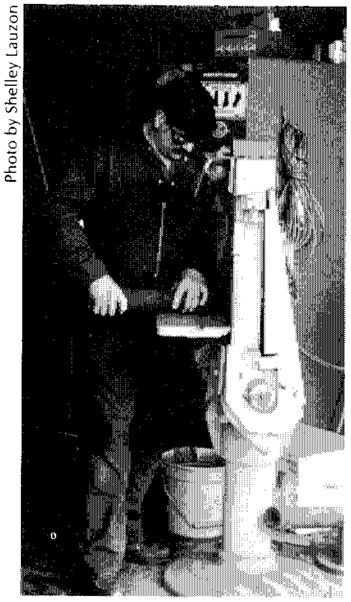
Theodore G. Shepherd
DAMTP, University of Cambridge
Joel Sommeria
University of Grenoble
Andrew M. Soward
University of Newcastle Upon Tyne, United Kingdom
Edward Spiegel
Columbia University
Melvin E. Stern
Florida State University
Henry Strauss
Courant Institute of Mathematical Sciences
George Veronis
Yale University
Nigel Weiss
Cambridge University
William Young
Massachusetts Institute of Technology

Visiting Investigators

Ken O. Buesseler
Chemistry Department, Woods Hole Oceanographic Institution
Shimshon Frankenthal
Tel Aviv University Ramat Aviv, ISRAEL
Arthur G. Gaines, Jr.
Marine Policy & Ocean Management, Woods Hole Oceanographic Institution

Photo by Shelley Lauzon



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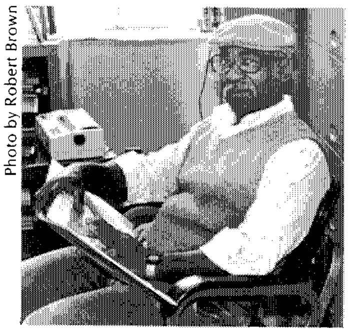

Photo by Robert Brown

Top: Senior Mechanic John Clement. Middle: Traffic Supervisor Bernie Crampton. Bottom: Barbara Martineau (left) and Shawna DiPetta of Marine Operations.

David G. Gallo
University of Rhode Island
Charles H. Greene
Cornell University
David A. Johnson
Geology and Geophysics Department, Woods Hole Oceanographic Institution
Daniel E. Kelley
Dalhousie University, Halifax, Nova Scotia
Zofia J. Mlodzinska
Biology Department, Woods Hole Oceanographic Institution
Bryce Prindle
Ocean Engineering Department, Woods Hole Oceanographic Institution
Victoria R. Starczak
Biology Department, Woods Hole Oceanographic Institution

Guest Investigators

Marie-Pierre Aubry-Berggren
National Center of Scientific Research, Paris
Arthur B. Baggeroer
Massachusetts Institute of Technology
Joseph P. Bidwell
Howard Hughes Medical Institute
Frederic Bisshopp
Brown University
Cmdr. Lawson W. Brigham
U. S. Coast Guard, Washington, DC
Bradford Butman
U. S. Geological Survey, Woods Hole
Thomas R. Capo
Howard Hughes Medical Institute
John F. Casey
University of Houston
Colleen Cavanaugh
Harvard University
Jerry Cheney
Biology Department, Woods Hole Oceanographic Institution
Mark W. Clark
Southeastern Massachusetts University
Phil Clarner
Biology Department, Woods Hole Oceanographic Institution
Robert Commeau
United States Geological Survey, Woods Hole
Mao-chang Cui
Institute of Oceanology, Qingdao, People's Republic of China
Felicita d'Escrivan
Harvard University
John M. Dvorak
Howard Hughes Medical Institute
Michelle J. Dzierzeski
Biology Department, Woods Hole Oceanographic Institution
Adria A. Elskus
University of Rhode Island
Changle Fang
Memorial University of Newfoundland, St. John's, Newfoundland
Elizabeth D. Garland
Florida Institute of Technology
John H. Gentile
U. S. Environmental Protection Agency, Rhode Island
Catherine Goyet
Universite Pierre et Marie Curie, Paris
George F. Heimerdinger
Environmental Data Service, NOAA
Ruth E. Keenan
Science Applications, Inc., McLean, Virginia
E. Douglas Kutney
Howard Hughes Medical Institute
An-Chun Li
Institute of Oceanology Qingdao, People's Republic of China
Fengye Li
Institute of Oceanology Qingdao, People's Republic of China
Douglas A. Lipka
U.S. Environmental Protection Agency, Washington, DC
Lloyd Nadeau
Marine Biological Laboratory, Woods Hole
Iwao Nakano
Japan Marine Science & Technology Center, Yokosuka, Japan
Frederick Olmsted
Biology Department, Woods Hole Oceanographic Institution
John A. Paige
Howard Hughes Medical Institute
Kiliparti Ramakrishna
Marine Policy Center, Woods Hole Oceanographic Institution
Donald C. Rhoads
Yale University
Brian J. Rothschild
University of Maryland
Amelie Scheltema
Biology Department, Woods Hole Oceanographic Institution
Marie-Alexandrine Sicre
Laboratoire de Physique et Chimi Marines, Paris, France
Jean G. Smith
Howard Hughes Medical Institute
Fred S. Stevens
Aquaculture Research Corp., Dennis
Jacek K. Sulanowski
Bridgewater State College
Armando Tamse
Boston University Marine Program, Woods Hole
Catherine T. Tamse
Marine Biological Laboratory, Woods Hole
Rodman E. Taylor
University of Washington
Maura G. Tyrrel
Stonehill College
Paul M. Vermette
Lt., U. S. Navy
Hans-Christoph Waldmann
Institut fur Angewandte Physik, Federal Republic of Germany
Qing Xia
Institute of Oceanology, Qingdao, People's Republic of China
Baoren Zhao
Institute of Oceanology, Qingdao, People's Republic of China
Jie-Zau Zhuang
Insitute of Oceanology, Qingdao, People's Republic of China
Lu-Ping Zou
Rutgers University

Guest Students

Luc Beaufort
University of Lyon
Michael Blundin
Colgate University
Roswitha E. Braunstein
University of Vienna
Alakananda Chatterjee
Smith College
Yvonne A. Coursey
Rollins College
Daniel Gerzon
Wesleyan University
Marc A. Hackel
Deerfield Academy
Timothy Hawley
University of Wisconsin, Madison
Jennifer R. Hoffman
Brown University
Kerry Jo Kreiton
Florida Institute of Technology
Ee Lin Lim
Smith College
David A. Schlezinger
Amherst College
Lisa Seaman
Colorado College
Holly Sheltry
Hamilton-Wenham High School
Jeannie S. Swift
Noble and Greenough Preparatory School

1987 SOURCES OF SUPPORT FOR RESEARCH AND EDUCATION

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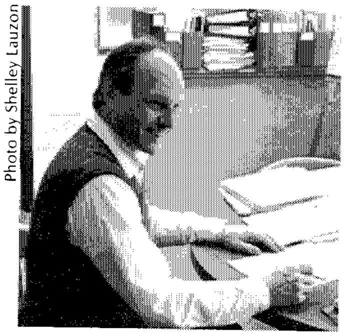

Photo by Robert Brown

Photo by Robert Brown

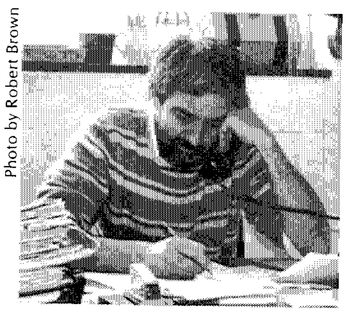

Photo by Shelley Lauzon

Top: Assistant Dean & Registrar Jake Peirson. Second from top: Payroll Administrator Laurie Murphy (seated) and Business Programmer Beverly Harper. Third from top: Assistant Facilities Manager Ernie Charette. Bottom: Special Assistant to the Director Karen Rauss.

AFG Industries, Inc.
ALCOA Foundation
Alden Electronic & Impulse Recording Equipment Company, Inc.
Alden Products Company
Alumni of WHOI/MIT Joint Program in Marine Geology & Geophysics and Ocean Engineering
American Chemical Society
Amoco Production Company
Anonymous Donors
The Arundel Foundation
Associates & Corporation Members of the Woods Hole Oceanographic Institution
Associates of Cape Cod
Avon Products Foundation
Babylon Tuna Club
Bank of Cape Cod
Bank of New England, NA
The Bank of New York
Benthos, Inc.
The Boston Company, Inc.
Cabot Corporation Foundation, Inc.
Camp, Dresser & McKee
Citibank, NA
Colgate-Palmolive Company
COMSAT Corporation
Conoco, Inc.
Corning Glass Works Foundation
Jessie B. Cox Charitable Trust
Cox Foundation, Inc.
Charles E. Culpeper Foundation, Inc.
Fred Harris Daniels Foundation, Inc.
Oliver S. and Jennie P. Donaldson Charitable Trust
Dynatech R/D Company
EDO Corporation
EG&G Foundation The Environmental Preservation Support Trust
EXXON Education Foundation
Falmouth Coal Company, Inc.
Five Colleges, Inc.
Friends of Pleasant Bay
The Horace W. Goldsmith Foundation
The Green Foundation
Harbor Capital Management Company, Inc.
The Hartford Insurance Group Foundation, Inc.
International Business Machines Corporation
International Light Tackle Tournament Association
International Paper Company Foundation
Island Foundations, Inc.
John Hancock Mutual Life Insurance Company
The Henry J. Kaiser Foundation
The Arthur D. Little Foundation
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Massachusetts Centers of Excellence Corporation
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R. K. Mellon Family Foundation
The Millipore Foundation
The MITRE Corporation
Mobil Foundation, Inc.
Mobil Exploration and Producing Services, Inc.
Monsanto Fund
Morgan Guaranty Trust Company
The Charles Stewart Mott Foundation
National Geographic Society
National Life Insurance Company Charitable Trust
New England Biolabs
New England Electric System
New England Farm and Garden Association, Inc.
New England Power Service Company
Norfolk Southern Foundation
Norton Company Foundation, Inc.
Ocean City Marlin Club, Inc.
Olin Corporation Charitable Trust
Peabody Lions Club
Penzance Foundation
The Pew Charitable Trusts
Phelps Dodge Foundation
Phillips Petroleum Company
Pitney Bowes
PneumoAbex Foundation
Port Aransas Rod and Reel Club
PPG Industries Foundation
R. D. Instruments
Raytheon Company
Sailfish Club of Florida
Sanders Associates, Inc.
The Florence and John Schumann Foundation
Richard B. Sellars Foundation
Shawmut Bank of Cape Cod
Sippican Ocean Systems, Inc.
Walter A. & Hope Noyes Smith Fund
SmithKline Beckman Foundation
SOHIO Petroleum Company
The South Atlantic Foundation
The Standard Oil Company
State Mutual Life Assurance Company
The Stevens Club of Cape Cod
Sun Exploration & Production Company
Texaco Inc.
Textron, Inc.
Town of Chatham, MA
Truro Conservation Trust
United States Government
- Department of Commerce
  - National Oceanic and Atmospheric Administration
  - National Marine Fisheries Service
  - National Sea Grant Program
- Department of Defense
  - Department of the Navy
    - Office of Naval Research
- Department of Energy
- Department of the Interior
  - U.S. Geological Survey
- Environmental Protection Agency
- National Aeronautics & Space Administration
- National Institutes of Health
- National Science Foundation

United Technologies Corporation
The Upjohn Company
The G. Unger Vetlesen Foundation
Edwin S. Webster Foundation
West Point-Pepperell Foundation, Inc.

GIFTS MADE IN MEMORY OF:

William Airlie
James R. Britton, Jr.
James J. Gerowin
William D. Grant
Christopher Haebler Frantz
Earl Hays
Sidney T. Knott
Richard Kobusch
John Coleman Pickard
William B. Richardson
Helen C. Roth
Virginia Walker Smith
Frank W. Tchitcherine

Financial Statements

Highlights:

The Institution's total operating revenue increased 8.1% in 1987 to $53,844,403 compared with a 2.5% decrease and total revenues of $49,787,948 in 1986. Excess current unrestricted funds of $800,000 were transferred to unexpended plant funds, $741,605 to endowment funds and $500,000 to replenish the Director's Innovative Fund.

Funding for sponsored research programs increased 10% in 1987 as compared to 1986 and summarized below. Government sponsored research increased 9% to $42,231,000 in 1987 compared to $38,664,000 in 1986, mainly because of the more favorable funding environment at the National Science Foundation for oceanographic research. Non-Government research increased 17% to $5,099,000 in 1987 from $4,377,000 in 1986, due primarily to increased use of our vessels by other organizations.

	1987	*1986*	*Increase (Decrease)*
National Science Foundation	$23,029,000	$20,332,000	13.3%
Office of Naval Research	15,728,000	15,465,000	1.7%
Department of Energy	505,000	529,000	(4.5%)
National Oceanic & Atmospheric Administration	1,816,000	1,581,000	14.9%
Other government	1,154,000	757,000	52.4%
Restricted endowment income	519,000	360,000	44.2%
Other gifts, grants and contracts	4,580,000	4,017,000	14.0%
	$47,331,000	$43,041,000	10.0%

Gifts and grants from private sources, including generous support from over 1,500 WHOI Associates, totaled $2,912,000 in 1987:

Gifts to Endowment	$1,598,000
Ocean Ventures Fund	122,000
Coastal Research Programs	270,000
Education Program	22,000
Marine Policy & Ocean Management	200,000
Young Scientists Program	58,000
Bowhead Whale Program	63,000
Brown Tide	100,000
Study of Buzzards Bay	70,000
Miscellaneous	106,000
Unrestricted Gifts	303,000
	$2,912,000

Capital expenditures in 1987 were $1,636,000, a 13.4% increase over 1986, and included $798,000 for the acquisition of computer equipment. Funds for capital expenditures were derived from depreciation recovery and other unrestricted income.

Other statistics of interest are:

	1987	*1986*	*Increase (Decrease)*
Number of Employees	777	781	(0.5%)
Total Compensation (including overtime and benefits)	$28,261,000	$27,768,000	1.8%
Endowment Income (net)	3,333,000	3,544,000	(6.0%)
Gifts to Endowment	1,598,000	2,177,000	(26.6%)
Endowment Principal (year-end market value)	84,162,000	82,174,000	2.4%
Sponsored Programs Backlog	24,615,000	26,568,000	(7.4%)

Funds used to support the education program were derived principally from endowment income totaling $1,917,000. In addition to other funds restricted for education, unrestricted funds of $595,000 were also expended. Student tuition and stipend support of $1,574,000 was provided either directly by charges to research grants and contracts or indirectly through the general and administrative overhead rate.

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

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

Balance Sheet December 31, 1987 and 1986

ASSETS	1987	1986
Current Fund Assets (Note A):		
Cash	$ 6,405	$ (685,794)
Short-term investments, at cost which approximates market	16,794,495	17,428,255
Accrued interest and dividends	665,759	900,948
Reimbursable costs and fees:		
Billed	1,125,917	384,911
Unbilled	638,672	683,941
Other receivables	787,312	390,689
Inventories	315,118	313,720
Deferred charges and prepaid expenses	411,889	427,172
Deferred fixed rate variances	(438,744)	(629,817)
Due to other funds	(8,983,739)	(7,665,874)
	11,323,084	**11,548,151**
Endowment and Similar Fund Assets (Note A):		
Investments at market (cost $67,005,747 in 1987 and $60,976,802 in 1986) (Note B)	70,720,967	72,423,940
Cash and cash equivalents	12,704,369	9,701,653
Pooled income fund investments, at market	154,964	153,744
Due from (to) current fund	581,983	(105,785)
Total endowment	84,162,283	82,173,552
Annuity fund investments, at market	136,980	136,245
	84,299,263	**82,309,797**
Plant Fund Assets (Note A):		
Land, buildings, and improvements	25,062,278	24,546,048
Vessels and dock facilities	7,432,532	7,442,492
Laboratory and other equipment	4,380,001	3,710,294
Construction in progress	132,632	65,963
	37,007,443	35,764,797
Less accumulated depreciation	15,989,654	14,481,605
	21,017,789	21,283,192
Due from current fund	8,401,756	7,771,659
	29,419,545	**29,054,851**
	$125,041,892	**$122,912,799**

LIABILITIES AND FUND BALANCE	1987	1986
Current Fund Liabilities and Fund Balances		
Accounts payable, accrued expenses and deferred revenues	$ 2,350,404	$ 1,744,956
Accrued payroll related liabilities	2,783,078	2,293,328
Unexpended balances restricted for:		
Sponsored Research	2,824,501	4,273,293
Education Program	809,850	847,880
Total restricted balances	3,634,351	5,121,173
Unrestricted balances designated for:		
Director's Innovative Fund	829,248	648,961
Ocean Industry Program	201,666	151,308
Total designated balances	1,030,914	800,269
Unrestricted current fund	1,524,337	1,588,425
	2,555,251	2,388,694
	11,323,084	**11,548,151**
Endowment and Similar Fund Balances		
Endowment:		
Income restricted	49,863,091	48,355,583
Income unrestricted	955,767	944,202
Quasi-endowment:		
Income restricted	12,244,647	11,470,444
Income unrestricted	21,098,778	21,403,323
Total Endowment	84,162,283	82,173,552
Annuity	136,980	136,245
	84,299,263	**82,309,797**
Plant Fund Balances		
Invested in plant	21,017,789	21,283,192
Unexpended, unrestricted	8,401,756	7,771,659
	29,419,545	**29,054,851**
	$125,041,892	**$122,912,799**

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

Statement of Current Fund Revenues, Expenses and Transfers for the years ended December 31, 1987 and 1986

	1987	1986
Revenues:		
Sponsored research:		
Government	$42,231,433	$38,664,406
Nongovernment	5,099,457	4,376,959
	47,330,890	43,041,365
Education funds availed of	2,087,889	2,203,120
Total restricted	49,418,779	45,244,485
Unrestricted		
Fees	438,021	460,488
Endowment and similar fund income	964,968	965,602
Gifts	303,232	400,186
Tuition	1,189,051	1,025,881
Investment income	991,104	1,049,389
Oceanus subscriptions	270,544	339,305
Other	268,704	302,612
Total unrestricted	4,425,624	4,543,463
Total revenues	**53,844,403**	**49,787,948**
Expenses:		
Sponsored research:		
Salaries and fringe benefits	14,202,927	13,809,940
Ships and submersibles	7,718,893	7,323,171
Materials and equipment	6,635,030	6,116,117
Subcontracts	2,500,674	2,034,696
Laboratory overhead	4,308,591	3,871,336
Other	7,036,200	5,725,025
General and administrative	4,928,575	4,161,080
	47,330,890	43,041,365
Education:		
Faculty expense	927,713	996,812
Student expense	727,603	789,080
Postdoctoral programs	331,728	420,664
Other	278,713	270,076
General and administrative	416,657	239,428
	2,682,414	2,716,060
Unsponsored research	628,990	549,915
Oceanus magazine	350,784	341,793
Other activities	745,584	676,482
General and administrative	192,079	158,526
Total expenses	**51,930,741**	**47,484,141**
Net increase before transfers	**1,913,662**	**2,303,807**
Transfers – to (from):		
Director's Innovative Fund	500,000	500,000
Designated reserves	(63,855)	(46,763)
Endowment fund	741,605	175,000
Plant fund, unexpended	800,000	800,000
Total	**1,977,750**	**1,428,237**
Net increase (decrease) – unrestricted current funds	**$ (64,088)**	**$ 875,570**

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

Statement of Changes in Fund Balances for the year ended December 31, 1987

	Current Fund				Endowment and Similar Funds	Plant Fund		Total All Funds	
	Restricted	Designated	Unrestricted	Total		Invested In Plant	Unexpended	1987	1986
Increases:									
Gifts, grants and contracts:									
Government	$40,876,863			$40,876,863				$ 40,876,863	$ 39,153,660
Nongovernment	4,614,788		$ 303,232	4,918,020	$ 1,597,916			6,515,936	6,927,635
Endowment and similar funds investment income (Note D)	2,367,666		964,968	3,332,634				3,332,634	3,543,791
Net increase (decrease) in realized and unrealized appreciation					(538,422)			(538,422)	7,380,219
Other	54,891		3,157,424	3,212,315	616			3,212,931	3,262,995
Total increases	47,914,208		4,425,624	52,339,832	1,060,110			53,399,942	60,268,300
Decreases:									
Expenditures	(49,418,779)		(2,511,962)	(51,930,741)				(51,930,741)	(47,484,141)
Depreciation (Note A)						$(1,727,765)	$1,465,951	(261,814)	(261,814)
Plant asset additions						1,635,854	(1,635,854)	—	—
Other						(173,492)		(173,492)	(2,004)
Total decreases	(49,418,779)		(2,511,962)	(51,930,741)		(265,403)	(169,903)	(52,366,047)	(47,747,959)
Net change before transfers	(1,504,571)		1,913,662	409,091	1,060,110	(265,403)	(169,903)	1,033,895	12,520,341
Transfers - additions (deductions):									
Current revenues:									
Plant funds			(800,000)	(800,000)			800,000	—	—
Endowment funds			(741,605)	(741,605)	741,605			—	—
Director's Innovative Fund		$ 500,000	(500,000)					—	—
Other		(63,855)	63,855					—	—
		436,145	(1,977,750)	(1,541,605)					
Director's Innovative Fund to endowment		(187,751)		(187,751)	187,751			—	—
Other	17,749	(17,749)						—	—
Total transfers	17,749	230,645	(1,977,750)	(1,729,356)	929,356		800,000	—	—
Change in fund balance	(1,486,822)	230,645	(64,088)	(1,320,265)	1,989,466	(265,403)	630,097	1,033,895	12,520,341
Fund balance, December 31, 1986	5,121,173	800,269	1,588,425	7,509,867	82,309,797	21,283,192	7,771,659	118,874,515	106,354,174
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**

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

Report of the Certified Public Accountants

To the Board of Trustees of Woods Hole Oceanographic Institution:

We have examined the balance sheet of Woods Hole Oceanographic Institution as of December 31, 1987, and the related statement of changes in fund balances, and of current fund revenues, expenses and transfers for the year then ended. Our examination was made in accordance with generally accepted auditing standards and, accordingly, included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances. We previously examined and reported upon the financial statements of the Institution for the year ended December 31, 1986; totals for that year are shown for comparative purposes.

In our opinion, the financial statements referred to above present fairly the financial position of Woods Hole Oceanographic Institution as of December 31, 1987, 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 applied on a basis consistent with that of the preceding year.

Coopers & Lybrand

Boston, Massachusetts
April 4, 1988

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.

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. Investments for which a readily determinable market value cannot be established are stated at cost. The amount of such investments carried at cost is not material.

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 attributed to the principal balance of the funds involved.

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 an adjustment 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.

Non-cash gifts are generally recorded at market value on the date of gift, although certain non-cash 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 8½% on buildings, 3½% on Atlantis II and 5% to 33⅓% on equipment. Depreciation expense on plant assets purchased by the Institution amounting to $1,465,951 in 1987 and $1,208,950 in 1986, has been charged to operating expenses. Depreciation on certain government funded facilities (Atlantis II, 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.

B. Endowment and Similar Fund Investments:

The cost and market value of investments held at December 31, 1987 and 1986, are as follows:

	December 31, 1987		December 31, 1986	
	Cost	Market	Cost	Market
Government and government agencies	$18,951,382	$19,252,899	$15,374,873	$16,123,155
Convertible bonds	282,969	253,688	1,170,903	1,332,750
Corporate bonds	5,658,389	5,413,084	7,048,912	7,387,932
Municipal bonds	250,000	238,750	—	—
Common Stocks	39,384,883	43,145,739	35,659,364	45,857,353
Other	2,478,124	2,416,807	1,722,750	1,722,750
Total Investments	**$67,005,747**	**$70,720,967**	**$60,976,802**	**$72,423,940**

C. Investment Units:

The value of an investment unit at December 31, 1987 and 1986 was $1.6900 and $1.7144, respectively. The investment income per unit for 1987 and 1986 was $.0682 and $.0761, respectively.

	1987	1986
Unit value, beginning of year	$1.7144	$1.5343
Unit value, end of year	1.6900	1.7144
Net change for the year	(.0244)	.1801
Investment income per unit for the year	.0682	.0761
Total return per unit	**$ .0438**	**$ .2562**

D. Endowment and Similar Fund Income:

Income of endowment and similar funds consisted of the following:

	1987	1986
Dividends	$1,210,917	$1,059,090
Interest	2,547,918	2,868,373
	3,758,835	3,927,463
Investment management costs	(426,201)	(383,672)
Net investment income	**$3,332,634**	**$3,543,791**

E. Retirement Plan:

The Institution maintains two noncontributory defined benefit pension plans covering substantially all employees of the Institution. In 1987, the Institution adopted Statement of Financial Accounting Standards No. 87 (SFAS No. 87) "Employers Accounting for Pensions." Pension benefits are earned based on years of service and compensation received.

Combined net pension expense for the two plans includes the following:

Service cost	$2,176,503
Interest cost	3,166,808
Actual return on plan assets	(1,005,719)
Net amortization and deferral	(2,764,704)
Net pension expense	**$1,572,888**

Below is a reconciliation of the combined funded status of the plans at December 31, 1987:

Accumulated benefit obligation:	
Vested benefits	$29,197,941
Nonvested benefits	1,880,798
Total accumulated benefit obligation	**$31,078,739**
Projected benefit obligation	49,355,249
Market value of plan assets	54,786,573
Plan assets in excess of the projected benefit obligation	(5,431,324)
Unrecognized net transition asset	7,249,699
Unrecognized prior service costs	(780,241)
Unrecognized net loss	(844,964)
Accrued pension cost	**$ 193,170**

The discount rate and rate of increase in future compensation used to determine the projected benefit obligation as of December 31, 1987 were 7.5% and 7.2%, respectively. The expected return on plan assets was 7.5%.

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 $169,359 in 1987 and $143,144 in 1986.

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