Oceanus

REPORTS ON RESEARCH AT THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

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ARCTIC RESEARCH

WHOI Science at the Top of the World

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ED DENTON

Human researchers share their arctic space with polar bears. This footprint was left by a bear who was investigating the vicinity of two sleeping huts located about 300 meters from the main 1994 Sea Ice Mechanics Initiative (SIMI) camp. Calvert Eck saw the bear upon returning to the hut where Keith von der Heydt was sleeping. Cal made a dash for the hut, and the bear took off in the opposite direction.

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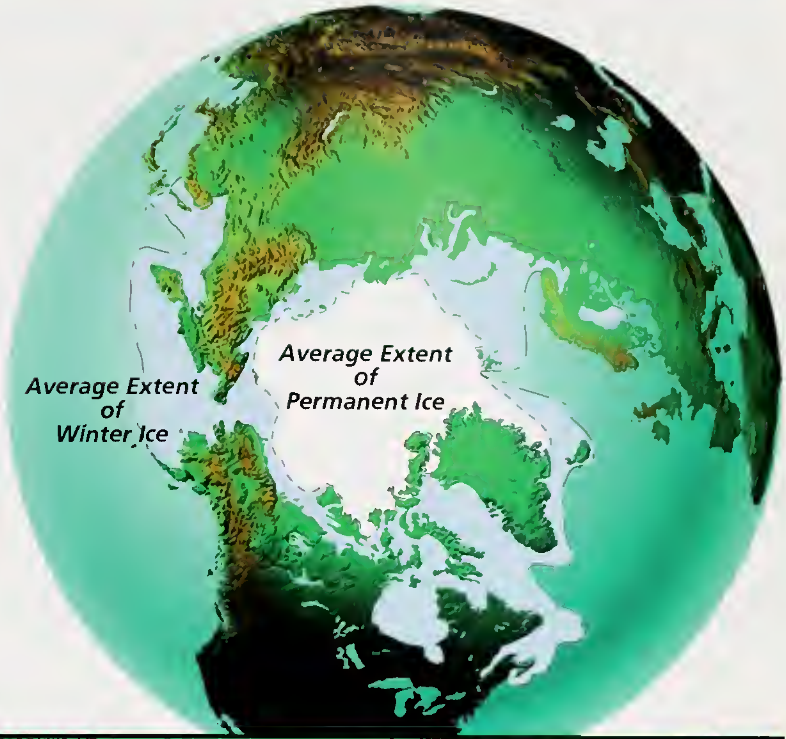
Arctic Research

COVER PHOTO: *An aerial view of the "downtown" section of the Office of Naval Research sponsored 1994 Sea Ice Mechanics Initiative (SIMI) camp located in the Beaufort Sea 200 miles north of Prudhoe Bay, Alaska.* BACK COVER: *During the SIMI project a helicopter provides fast, safe instrument deployment and camp logistical support. Photos by Ed Denton.*

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

WHOI Science At the Top of the World

The first five publications sponsored by the Woods Hole Oceanographic Institution in the early 1930s concerned work in the polar region, and Institution investigators have often plied arctic waters since then. This issue of *Oceanus* features recent acoustic studies of the Arctic, examines the region's circulation characteristics, and details work on radioactive contamination in an arctic river basin. Its authors, modern arctic explorers as well as WHOI staff, students, and colleagues, also discuss polar-area remote sensing techniques, logistics, and surface and submersible research vessels designed and adapted for icy northern waters.

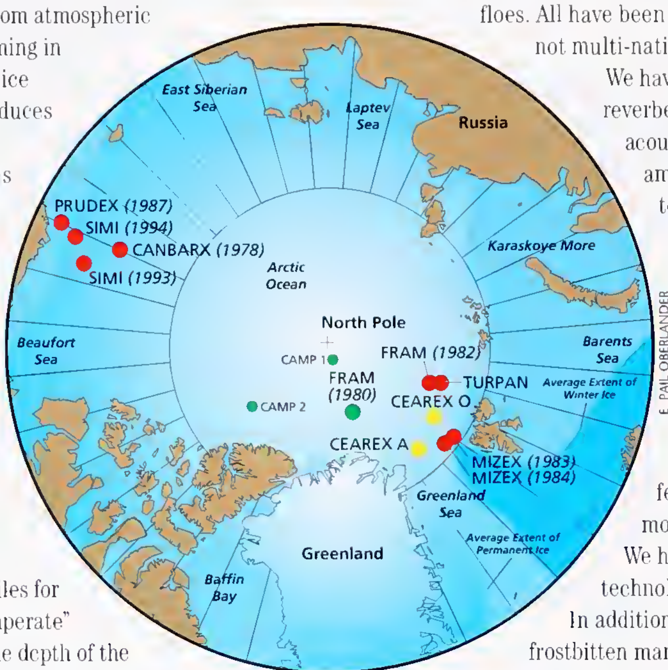


Fifteen Years of Arctic Acoustics and Ice Camps

Cold Region Technology Advances in Nine Expeditions to the Ice Cap

Keith von der Heydt
Senior Engineer, Applied Ocean Physics & Engineering Department
Arthur Baggeroer
Professor, Electrical & Ocean Engineering Department, Massachusetts Institute of Technology, and WHOI Guest Investigator

The Arctic Ocean is unique among the world's oceans because it is covered by pack ice with an average thickness of 3 meters for almost the entire year. It is the only ocean you can walk on or land a C-130 Hercules upon without flotation. More importantly, for acoustics, the ice pack has profound effects on transmitted signals and ambient noise. The ice insulates the water from atmospheric extremes, impeding warming in summer and moderating ice growth in winter. It introduces a strong haline (salinity) signature as brine leaches from newly frozen ice, and, because of the ice pack's continual presence, the coldest arctic water (as low as -2°C) typically occurs within the upper 100 meters of the water column rather than much deeper, as at lower latitudes.



Sites employed for nine arctic acoustic expeditions range across the top of the earth.

Acousticians often classify sound speed profiles for deep water as either "temperate" or "polar," according to the depth of the SOFAR axis. Since the speed of sound in the ocean varies primarily with temperature, the result is a duct of low sound speed (known as the SOFAR—Sound Fixing And Ranging—axis) just beneath the ice sheet; at lower latitudes, the SOFAR axis typically occurs at depths between 1,000 and 1,500 meters. This duct creates a wave guide that efficiently traps sound energy and leads to very long propagation ranges at low frequencies. Because of this channeling effect, sound interacts with the underside of the ice pack continually in a unique acoustic environment. In temperate waters, the sound in a SOFAR waveguide does not interact with the surface, but in the Arctic the presence of the duct near the surface leads to continuous interaction with the ice pack.

The authors have each logged nearly a year of their lives north of the Arctic Circle on nine expeditions sponsored by the Office of Naval Research (ONR). In 1977, we proposed a basin reverberation project in the Mediterranean—and instead found ourselves in the Canadian Basin. The temperature difference between the two sites was 120°F! Since then, seven of these experiments have been conducted from ice camps, while two were based aboard ships moored to ice floes. All have been multi-institutional, if not multi-national.

We have studied basin reverberation, long-range acoustic propagation, ambient noise, the tectonic structure of the arctic seafloor, and ice-floe dynamics at the edge of the year-round ice zone. Most recently (1994), we examined the acoustic and elastic radiation of ice fractures and the feasibility of acoustically monitoring arctic climate. We have advanced the technology of arctic acoustics. In addition, we have been frostbitten many times and have encountered a lot of polar bears, some at distances as close as 6 meters. (Though we always carry high-powered rifles, we seldom need to use them.) Our two- to six-week-long expeditions have occasionally included moments of excitement, when ice conditions have surprised us (such as having an ice crack open beneath one's bunk) or when a bear joins us for lunch.

Over these years, the motivations for arctic acoustic research and funding, as well as the technology employed, have changed dramatically in response to shifting national interests. Fifteen years ago, the Navy was most interested in using sound to detect non-US submarine activity under the ice. Today, its emphasis has shifted largely to environmental monitoring. Other motivations for arctic research are scientific and economic. The Arctic looms large in climate studies.

KEITH VON DER HEYDT

The Norwegian charter vessel Polarbjorn *was moored to an ice floe to serve as base for the summer 1983 Marginal Ice Zone Experiment (MIZEX). Author Art Baggeroer, right, and then Joint Program student Greg Duckworth (now at Bolt, Baranek, Newman) prepare to deploy equipment away from the ship. The small boats used to haul equipment across the ice allowed relatively easy crossing of ice floe boundaries.*

Arctic oceanography and seismic structure is hardly known. The variability of the ice pack and its causes are not well understood. The arctic region is important for shipping, especially for Russia, and there are large arctic areas that hold hydrocarbon potential.

Acoustic Research in the Arctic

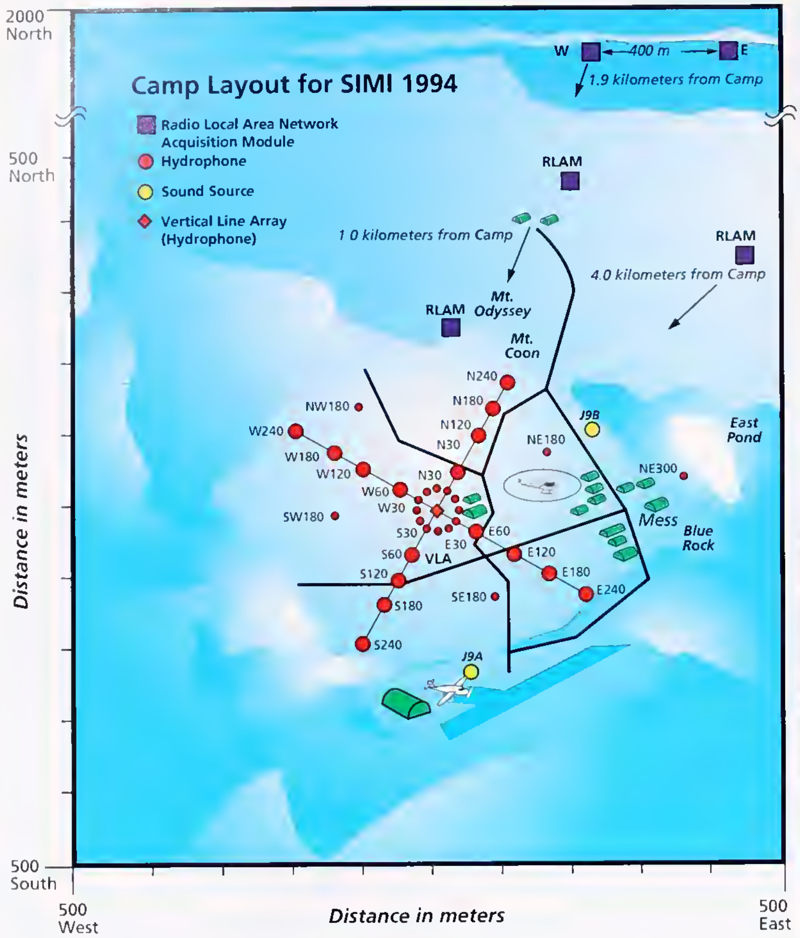
Our basic tools are sound sources, two-dimensional arrays of hydrophones as receivers and three-axis geophones accompanied by one or more systems for digitizing and recording their signals. Hydrophones, usually piezo-electric ceramic elements with amplifiers, convert pressure fluctuations to electrical signals. They couple efficiently to seawater and provide a direct measurement of the sound field. Geophones are velocity sensors commonly used in seismic research. We use them to sense small motions resulting from ice cracks or other ice flexing. Just as for shipboard oceanography, supporting measurements include navigation, basic meteorology, and water-column measurements of conductivity, temperature, and depth to monitor local environmental conditions.

In 1978, our introduction to ice camp life was the Canadian American Basin Reverberation Experiment (CANBARX). The notion of installing AC-powered racks of computer equipment at a camp 300 nautical miles north of Pt. Barrow, Alaska, was considered novel—if not foolhardy—by previous ice-camp scientists. They had always worked on a smaller technical scale, using only battery power, and questioned the sanity of introducing the level of complexity (computers and other power-hungry devices) proposed. To be sure, we acquired both data and practical ice camp know-how in equal quanti-

Fridtjof Nansen: The First Polar Oceanographer

After learning that shipwreck debris and driftwood of Siberian origin were found on Greenland coasts, Norwegian explorer and oceanographer Fridtjof Nansen theorized* "that a current flows…from the Siberian Arctic sea to the east coast of Greenland." He conceived a remarkable plan to freeze a ship into the ice and let it be carried all the way across the Arctic Ocean. Despite considerable disbelief in his theory, he secured support to build a stout, ice-strengthened ship called *Fram* that he allowed to freeze into the arctic ice pack near the New Siberian Islands in September 1893. He hoped winds and currents would carry it across the North Pole. When it became clear that the ship's drift would not cross the pole, Nansen and Frederick Johansen left *Fram* in March 1895 to attempt a 360-mile, dog-sled trek to the pole. Though they had to turn back 226 miles short of their goal and spent a lonely winter in a stone hut on Franz Josef Land, the *Fram* expedition continued under the leadership of the ship's captain, Otto Sverdrup. *Fram* emerged from the ice near Spitsbergen in August 1896, bearing the first arctic oceanographic and pack-ice data and proving Nansen's polar drift theory.

*The quotation and the photo are drawn from Nansen's book *Farthest North* (Westminster: Archibald Constable and Co., 1897), courtesy MBL/WHOI Library Rare Book Room.



ties while deploying and using our 12-channel hydrophone array. Nevertheless, we did establish the credibility of using sophisticated data-acquisition equipment in the arctic environment, and, more importantly, the experiment was a success.

The chief difficulties of our first two experiments were 60-hertz electrical and mechanical contamination of acoustic signals by our generator, and suppression of unwanted signals resulting from the strum of unfaired hydrophone cables. At the time, we eliminated the electrical contamination by shielding the sensors with aluminum foil pilfered from the mess hut. We have since figured out how to decouple the generator vibrations from the ice, and we manufacture hum-free hydrophones. We suspend the hydrophones through 2 to 5 meters of pack ice on 60 to 100 meters of lightweight, "faired" cable. (The fairing, short woven-in fibers, breaks up the flow about the cable, reducing cable motion and the unwanted strum signal.)

The principal goal of CANBARX and the 1980 and 1982 deep-arctic Fram experiments was to improve understanding of fundamental acoustic issues through use of modern research tools—arrays of hydrophones; wide-dynamic-range, multi-channel, data-acquisition systems; and new processing methods. During the three expeditions we detected backscatter, or reverberation, persisting for half an hour at low frequencies with some of the sound traveling across the entire Arctic Ocean. We examined acoustic propagation for signal coherence and multipath. We also made some of the few seismic refraction measurements for the structure of the arctic seafloor. Subsequent analyses established that, in the central Arctic, wind and current-induced ice stress leading to floe motion and fracture were the primary sources of ambient noise.

After three arctic expeditions, we were much wiser about planning our work. The Fram programs showed that acoustic measurements alone were inadequate for explaining responses of the acoustic environment to atmospheric and oceanographic forcing. A multidisciplinary sampling strategy that integrated oceanographic, meteorological, and acoustic measurements was needed. Also, after some near disasters with camp breakups and logistics, we were more appreciative of the tenuous nature of ice camps as we planned ambitious experimental programs.

The Marginal Ice Zone Experiments (MIZEX) of 1983 and 1984 were designed to construct a coherent view of the relationship between various energy fluxes at the ice edge. Their focus was large-scale, multi-ship sampling of short-lived (days to weeks), 10- to 50-kilometer eddies that form where the ice pack meets open water in the summer months. Our acoustically tracked hydrophone array proved difficult to maintain as we struggled to find, recover, and redeploy sensors before they moved out of range, all the while recording data (and avoiding an

ED DENTON

Keith von der Heydt (right) and MIT's Henric Schmidt prepare a hydraphone for deployment near the Sea Ice Mechanics Initiative camp in April 1994.

unexpected, icy swim!). Despite the difficulties, we were able to develop an understanding of ambient noise and sound propagation fluctuations at the ice edge.

After testing new techniques and instrumentation during the 1987 Prudhoe Bay Experiment (PRUDEX), we mounted the 1989 Coordinated East Arctic Experiment (CEAREX) north of the Fram Strait (between Greenland and Spitsbergen). CEAREX was, as the name implies, a coordination of ship and ice-camp sampling strategies. It was one of the few occasions when environmental parameters, including the acoustic ambient, were sampled during the winter months from a ship drifting with the ice pack. At the spring ice camp, designated "A," we had two main objectives. The first, undertaken as "A" camp drifted southward toward the ice edge, was to monitor the effect of changing oceanography on acoustic propagation using low-frequency signals received from a second ice camp, designated "O", about 100 kilometers to the northeast. The second objective was to simultaneously monitor the ambient noise field and meteorological and oceanographic parameters in a 100-kilometer-square area using portable buoy systems transported by helicopter. Unfortunately, the data we could take was limited because "A" camp had to be evacuated early when it drifted through the Fram Strait to within 30 kilometers of the open North Atlantic.

Following a four-year fieldwork hiatus, the 1993 and 1994 Sea Ice Mechanics Initiative (SIMI) consisted of back-to-back field programs in the Beaufort Sea, intended to gather data during the very much undersampled winter months. SIMI's focus is the study of ice-mechanical processes—including the evolution of processes that lead to catastrophic events such as ridging and rafting—over scales of millimeters to kilometers.

We used a horizontal hydrophone array to locate ice events and maintain a visual inventory of event statistics, and then, once a site of intense activity was selected, we quickly deployed a few portable three-axis geophone systems to telemeter data to the base camp. Collaborating with TURPAN, a joint Russian/US camp 2,600 kilometers away led by American Peter Mikhalevsky (Science Applications International Corp.), we also conducted a Trans Arctic Propagation (TAP) experiment to test the feasibility of using acoustics to monitor temperature changes in the arctic basin. The Russians transmitted a variety of signals that were centered at 19.6 hertz and designed to measure the stability of long-range propagation. The excellent data received by our sensors is currently being analyzed.

Over these 15 years, scientific objectives have evolved as a function of changing motivations but also as a function of improving technology. As an example, each of three portable Radio Local Area Network Acquisition Modules used at SIMI is capable of acquiring data at 10 times the rate of the system used for CANBARX, and each telemeters data over a radio-linked Ethernet. Similarly, the workstations used at SIMI are computationally thousands of times faster than the CANBARX computer.

KEITH VON DER HEYDT

A Norwegian participant in the 1980 Fram ice camp evaluates the situation of a hut partially consumed by formation of an ice ridge. The hut was eventually recovered—somewhat the worse for wear.

Arctic acoustics has led to many challenges, both scientifical and technical. We have had some exciting moments (a fire in a helicopter while carrying 1,000 pounds of explosives) and some very contemplative times (viewing the beauty of a midnight sunset in a unique part of the planet)—and we would pack in a flash for the next expedition.

The research described in this article was funded by the Office of Naval Research. It has been published in Institute of Electrical and Electronics Engineering journals, EOS, *the* Journal of the Acoustical Society of America, *and the* Journal of Geophysical Research.

Keith von der Heydt admits to starting work at WHOI in 1972 on a six-week cruise in the Caribbean as a green engineer. While visiting the Grand Canyon four years later, an old park ranger asked him if he knew anything about Arctic Ocean research. Having then just returned from a geophysical cruise north of Australia, arctic research was a remote notion. Now, after spending about a year of his life in ice camps, he could give that fellow a more interesting answer. Facing the challenges of the arctic environment, he has found that a megaton ice floe can be a superior "ship"—though he would still consider a research cruise to the Mediterranean.

As a youth in New England, Arthur Baggeroer never had the slightest interest in freezing his extremities north of the Arctic Circle. He came to ocean acoustics after obtaining an Sc.D. from MIT in electrical engineering. He has worked with colleagues at Woods Hole since 1972 and been active in the MIT/WHOI Joint Program from its start. After spending his first oceanographic cruise aboard *Atlantis II* between Capetown and Antarctica, he decided there were certain advantages to being able to walk on an ocean, and has since undertaken the extensive arctic work described in this article. He advises researchers in the Arctic to always keep a slow, fat friend with them when working near polar bears...

Tracking Radioactive Contamination in the Siberian Arctic

On the Adventures of a WHOI-Built Catamaran in the Ob River Basin

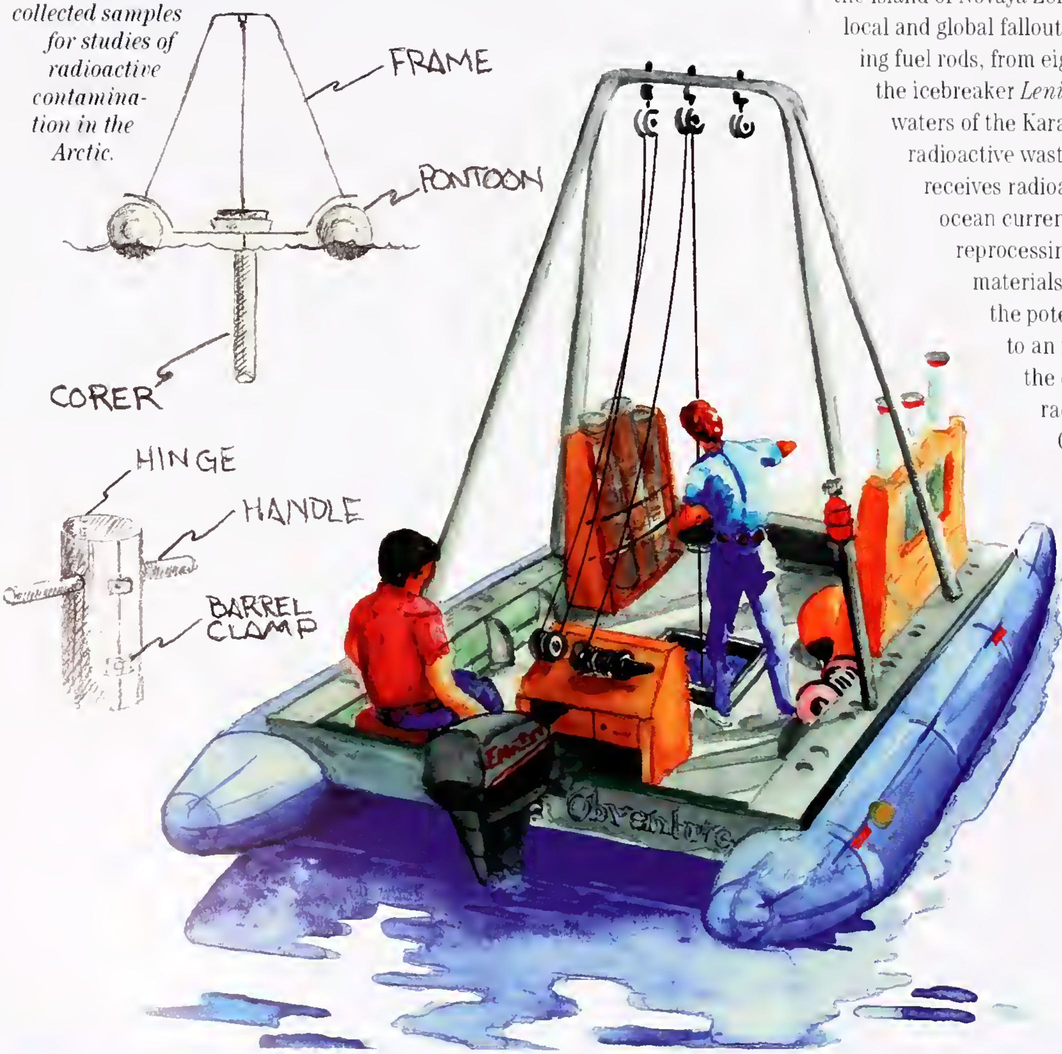
Frederick L. Sayles
Senior Scientist, Marine Chemistry & Geochemistry Department
George P. Panteleyev
MIT/WHOI Joint Program Student
Hugh D. Livingston
Senior Research Specialist, Marine Chemistry & Geochemistry Department

With the advent of Glasnost and the collapse of the Soviet Union, we have begun to learn of severe environmental problems that are one legacy of 70 years of Communist rule. These problems range from severe air pollution to industrial waste contamination and large-scale nuclear accidents. The release, both accidental and intentional, of radioactive materials to the environment, has perhaps garnered the most western-press attention. While the Chernobyl nuclear power plant fire is certainly the most well known, it is not alone in a catalog of serious incidents.

Radioactive materials from a number of sources have found their way to the Arctic Ocean, which is of particular concern because of its fragile ecology and the dependence of native populations on local fisheries. The rapid circulation of this ocean's surface waters can disperse contaminants around the Arctic in 10 to 20 years.

Known nuclear releases include weapons testing on the island of Novaya Zemlya, which resulted in both local and global fallout. Reactors, seven still containing fuel rods, from eighteen nuclear submarines and the icebreaker *Lenin* were dumped in the shallow waters of the Kara Sea, along with low-level radioactive waste. This area of the Arctic also receives radioactive materials transported by ocean currents from British and French fuel reprocessing plants. Concern over nuclear materials released to the Arctic as well as the potential for future releases has led to an international effort to assess the dispersal, fate, and effects of radioactive wastes in the Arctic Ocean and the rivers that flow into it. At the direction of the US Congress, and through the efforts of Senator Ted Stevens of Alaska, a US study was initiated by the Office of Naval Research to address a variety of issues related to the introduction and dispersal of arctic contaminants.

While there are many Arctic Ocean sources, the Ob River, one of the largest rivers draining into the Arctic Basin, is of special interest because of both past releases and the potential for future releases. The Ob's drainage

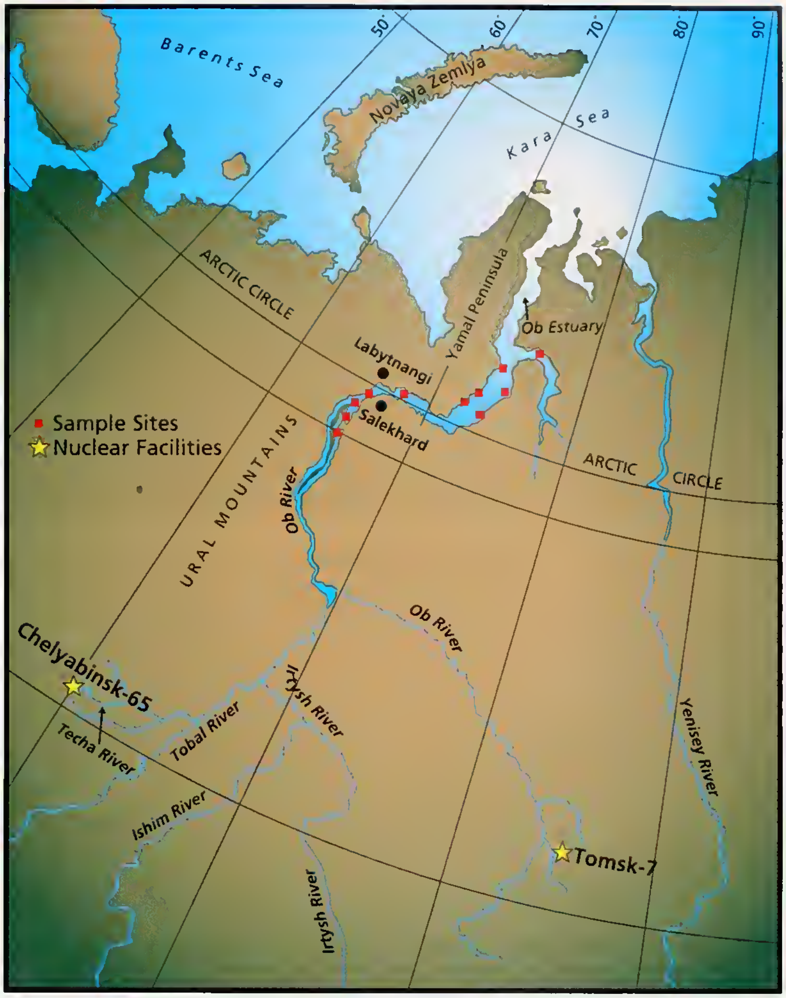


The specially built catamaran Obventure *plied the waters of the Russian river Ob at flood as its crew collected samples for studies of radioactive contamination in the Arctic.*

E. PAUL OBERLANDER

basin contains several nuclear facilities, including the weapons production plants Tomsk-7 and Chelyabinsk-65. There have been substantial releases of radioactivity from both of these plants including at least three serious ones from Chelyabinsk-65, and this plant remains a site of potential catastrophic release. For the period 1949 to 1952, medium and low-level wastes were simply dumped into the Techa River to make their way downstream. Beginning in 1952, the wastes were diverted into Lake Karachay, a small, shallow lake adjacent to the plant, which has become the "hottest" lake in the world. An hour's stroll along its shores would provide a lethal dose of radiation. It contains more radioactive cesium than the total released to the atmosphere from all of the weapons tests of the nuclear age combined. During a 1967 drought, much of its floor was exposed, and winds described as a "tornado" whipped the highly radioactive dust from the lake bed and spread it over the adjacent countryside. As a result, 45,000 people were evacuated from the affected area, and it remains deserted to this day. In 1957, a large Chelyabinsk-65 storage tank for high-level wastes exploded. At present, over 2 billion curies of radioactive material remain stored at Chelyabinsk-65, often under conditions of questionable security.

The history of large releases, the present storage of vast amounts of radioactive material, and the lack of knowledge about the fate of Chelyabinsk and Tomsk materials led us to organize an Ob River expedition. Our objective was to obtain a record of past contamination written in the sediments of the Ob delta in order to determine past delivery to the Arctic Ocean as well as predict the fate of future releases. The Ob delta is, for the most part, 56,000 square kilometers of marsh underlain by permafrost. In winter it is covered by several meters of ice and snow. The spring thaw floods the delta's thousands of lakes and channels. Settling of sediments from the flooding waters results in accumulation of annual bands of sediment that preserve a record of material brought down the river. Many radionuclides of interest are strongly adsorbed to sediment particles, and high deposition rates coupled with limited mixing make these sediments excellent candidates for studies of this record.



E. PAUL OBERLANDER

Radioactive contaminant sources in this area include weapons testing both globally and on the island of Novaya Zemlya, nuclear reactor dumping in the Kara Sea, weapons production plants, and ocean-current-borne materials from British and French fuel reprocessing plants.

The project started in 1992 when we began to develop contacts and support among Russian colleagues and science administrators. In the end, these contacts were to prove every bit as important to our expedition's success as our ability to handle the logistics of an expedition to a remote area of the Siberian Arctic. Without the help of Russian colleagues, institutes, and the Russian Academy of Sciences, we would never have mastered the labyrinth of overlapping and competing bureaucracies whose jurisdictions are more difficult to navigate than the Ob at flood. Dozens of permissions and applications were required from such organizations as customs, the KGB, the Ministry of Fisheries, the Ministry of Environment, and the Academy of Sciences. In particular, the sponsorship of Nikolai Laverov, a vice president of the Russian Academy, proved invaluable in cutting red tape and silencing objections. Valeriy Shishmarev of the Environment Protection Committee in Salekhard, a small town that straddles the Arctic Circle, agreed to provide our "mother" ship on the Ob and arrange safe


STEVE SMITH

While working in one marshy area, Olga Medkova, left, and Gera Panteleyev encountered two Russian fishers whose outboard had quit. The Obventure *crew summoned help by radio.*

STEVE SMITH

The crew of Obventure's *mother ship, a fisheries vessel, rigged a plywood platform to accommodate the catamaran.*

storage of our equipment. The responsibility for the crucial task of getting our equipment through customs and to the staging point in Salekhard was taken on by Olga Medkova, a colleague from the Russian Arctic and Antarctic Research Institute.

In addition to dealing with the labyrinth that is official Russia, we had to build a boat to very unusual specifications, at least for oceanographers. It needed to carry at least four people and handle a 600-pound coring frame, winch, and corer system, have a draft of less than one foot, collapse to a size suitable for air shipment, and be designed and built in two months. A narrow weather window and late-in-the-plan change to emphasize sampling in the small lakes off the main channels dictated the short time frame. Bob McCabe, WHOI's Supervisor of Mechanical Services, met our needs with an inflatable catamaran patterned after Navy Seal assault boats. *Obventure* was launched, tested in waters around Woods Hole, and shipped, all in about five days. That *Obventure* came into being and performed admirably in a remote corner of the world only a few months after its conception is a testament to Bob McCabe's dedication and that of the WHOI shops—there are few institutions in the world where this could have been achieved so successfully with such dispatch.

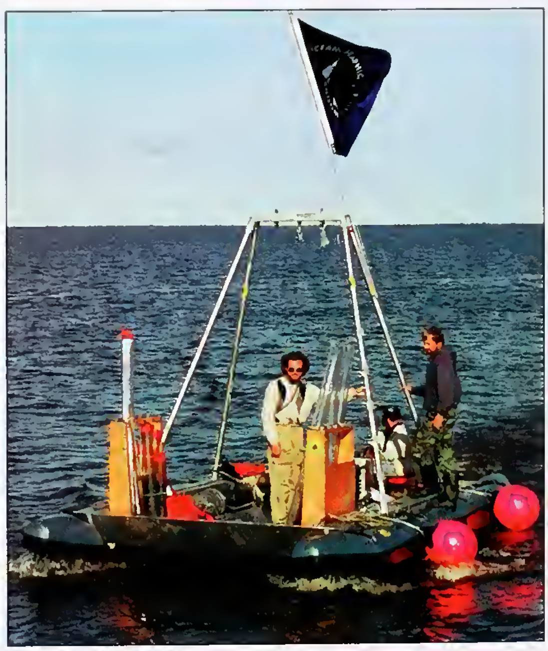
In late July *Obventure*, associated equipment, and the US contingent arrived in Salekhard. Leadership of the group fell to Gera Panteleyev, a Russian national in the MIT/WHOI Joint Program, and Steve Smith, a Marine Chemistry and Geochemistry engineer. The scientific party also included Matthew Monetti (Environmental Measurements Lab of New York), Brad Moran (Graduate School of Oceanography, University of Rhode Island), Boris Ilyachuk (Rincan, St. Petersburg), and Olga Medkova. In two days *Obventure* emerged from its shipping crates, was assembled and tested (no leaks in the pontoons), and loaded onto the Fisheries Protection vessel *RS300 #168*. The ship's fantail was too small to take *Obventure*, but a talented and willing crew soon remedied this situation with a ramp of plywood from undisclosed sources.

For two weeks *Obventure* and its dedicated cadre of scientists traveled the Ob. During the dusk hours, as the sun grazed the horizon but never really set, they moved from one sampling location to another along the river and estuary aboard *RS300 #168*. Days were spent on *Obventure*, picking their way along narrow channels through the marshes to inland lakes where cores were collected. In all, some 15 locations were visited and sampled. Three weeks after arriving in Salekhard, the team had *Obventure* and associated equipment back in the packing crates and on a railroad siding ready for return to St. Petersburg and, eventually, to WHOI. To protect against loss, Panteleyev and Smith each hand carried 75 pounds of samples on their homeward flight. The following shipment contains another 150 pounds of samples as well as each site's duplicate cores, which were sealed without being sectioned.

Analysis of a few samples to date tells us that these cores contain a history of the nuclear age as recorded in the distribution of cesium-137 from global fallout. Analyses over the next 12 to 18 months will tell us whether or not signals from the nuclear facilities in the Ob drainage basin have reached the delta and provide information on what and how much may have been delivered to the Arctic Ocean from these sources.

This work was funded by the Office of Naval Research.

The collaboration that led to this project was born of long-standing common interests and coincidence, in roughly equal measure. Fred Sayles has spent much of his career studying the geochemistry of sediments, including interactions with radionuclides. Hugh Livingston has spent much of his career studying the fate of radionuclides in the oceans. Gera Panteleyev, a native Russian, has worked previously on the geochemistry of Siberian rivers, acquiring the experience and knowledge essential to successful research in this remote region. The release of information on activities at the Mayak plant brought them together in an effort to apply their various skills to addressing the possible introduction of large amounts of radioactivity to the Arctic via the Ob River.



STEVE SMITH

Obventure *flew a WHOI flag during sampling activities.*

Deep Water Formation in the Greenland Sea

New Technologies Investigate an Old Mystery

Ryszard A. Pawlowicz
1994 MIT/WHOI Joint Program Graduate
James F. Lynch
Associate Scientist, Applied Ocean Physics & Engineering Department
W. Brechner Owens
Senior Scientist, Physical Oceanography Department
Peter F. Worcester
Research Oceanographer, Scripps Institution of Oceanography

Oceanographers love a challenge, and arctic oceanographers particularly so. One great challenge, which stood for over three quarters of a century, was to measure and explain the phenomenon of "Greenland Sea Deep Water Formation." In a few select spots in the world's oceans, the surface water cascades in plumes down to the ocean bottom, thousands of meters deep, to form new "deep water." This process is known to occur in the Weddell, Labrador, Greenland, and Mediterranean seas, but was only recently quantified and understood.

Why only recently? To begin with, this process occurs in short bursts over a brief season, generally in the late winter and early spring, during very cold and windy conditions. Shipboard observations during such periods are, for obvious reasons, sparse! Moreover, the deep water seems to form via a collection of very small plumes that originate over a relatively large area, so that a single sensor could perhaps be looking for a needle in an oceanographic haystack. Additionally, in the polar seas (that is, all except the Mediterranean), the process is not guaranteed to happen each year, as it is highly dependent on salinity conditions, which vary greatly from year to year. Finally, the ice caps make observation of the polar seas much more difficult. Thus it is *not* such a mystery that a process known to the Norwegian explorer Fridtjof Nansen in 1906 eluded measurement and description for so long!

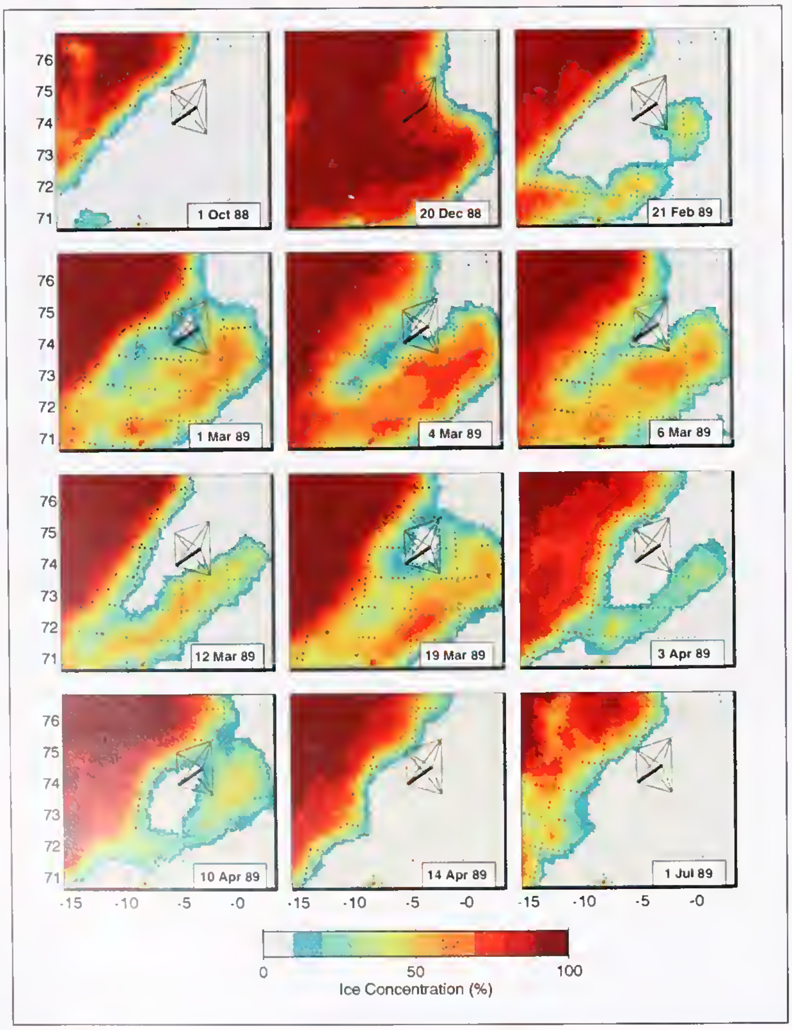
Given a dearth of data and an intriguing ocean mystery, it is also no surprise that theoretical efforts held the forefront for a number of years. The theoretical problem is, in its most basic form, simply stated: How do you get cold, fresh, less dense surface waters to sink below warmer, more saline, denser water ("Arctic Intermediate Water") underneath? There are two mechanisms for increasing the surface water's density, an increase in salinity or a decrease in temperature, and oceanographers have proposed a number of ways they might be accomplished. Earlier theories generally concentrated on mixing the surface and Intermediate Water via diffusion, turbulence, eddies, ice edge upwelling, and other processes. The mixed water, which was then saltier, further cooled at the surface and sank. More recent theories, also based on mixing of water masses, adds the "salinization" mechanism of brine rejection by early winter ice formation. The most recent picture of Greenland Sea Deep Water formation is drawn as follows: Ice forms at the surface in early winter, rejecting salt and thus increasing the density of the surface water. Arctic winds then blow the ice away, exposing the "preconditioned" surface water to cooling and mixing by the strong, cold winter winds. Deep convection then occurs in a series of short, episodic bursts.

JAMES LYNCH

Orange subsurface floats and yellow glass ball floats crowd the fantail of R/V Knorr *during deployment of one of the two-mile-long Greenland Sea moorings.*

Such theories are "pretty pictures" in an intellectual sense, but which, if any, is true? Data intended to either verify or disprove these theories was collected during a large multinational, multiyear project called the "Greenland Sea Project." It encompassed a large number of crucial measurements, particularly during an "intense"period in 1988 to 1989. In addition to meteorological information provided by both the British Meteorological Office and the European Center for Medium Range Weather Forecasting, satellite microwave imagery yielded pictures of the ice cover throughout the year; shipboard CTDs (Conductivity (salinity)–Temperature–Depth sensors) provided intermittent looks at the salinity, temperature, and thus density profiles during late winter; moored current meters and temperature sensors recorded long-term oceanographic measurements that, in one fortunate instance. included an individual plume.

A steady stream of science party members from WHOI, Scripps, and University of Washington Applied Physics Laboratory walk back and forth from the galley coffee machine to the fantail during an eight-hour-long deployment in freezing temperatures.



Sampling of 1988-1989 Greenland Sea ice cover maps made by Special Sensor Microwave Imager (SSM/I) satellite. Features of note are the initial December coverage of the tomography array by ice, which has disappeared by February, and the later surrounding of the array by ice, except for the open bay right over the region of deep convection.

Of most interest to this article is the "acoustic tomography" array deployed jointly by researchers from the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution. This array, which consisted of six moored acoustic "transceivers" (combination source and receiver units) surrounding the Greenland Sea, made three-dimensional pictures of the ocean temperature and current field every day using the travel times of acoustic pulses as data in a scheme that is the oceanographic analog of a medical CAT scan. This rather new technology provided the "when, where, and how deep" information about the deep-water formation. The ice cover, wind, air temperature, surface heat flux, and (occasional) ocean salinity and temperature profile data, when combined with the tomography, completed the suite of measurements needed to constrain the theoretical models.

Two scant figures here must represent the vast amount of data collected toward deciphering the riddle of Greenland Sea Deep Water formation. One shows the yearly evolution of the ice that formed over the array, and the other shows the average temperature profile, as measured by tomography, of the water between a pair of moorings in the center of the Greenland Sea.

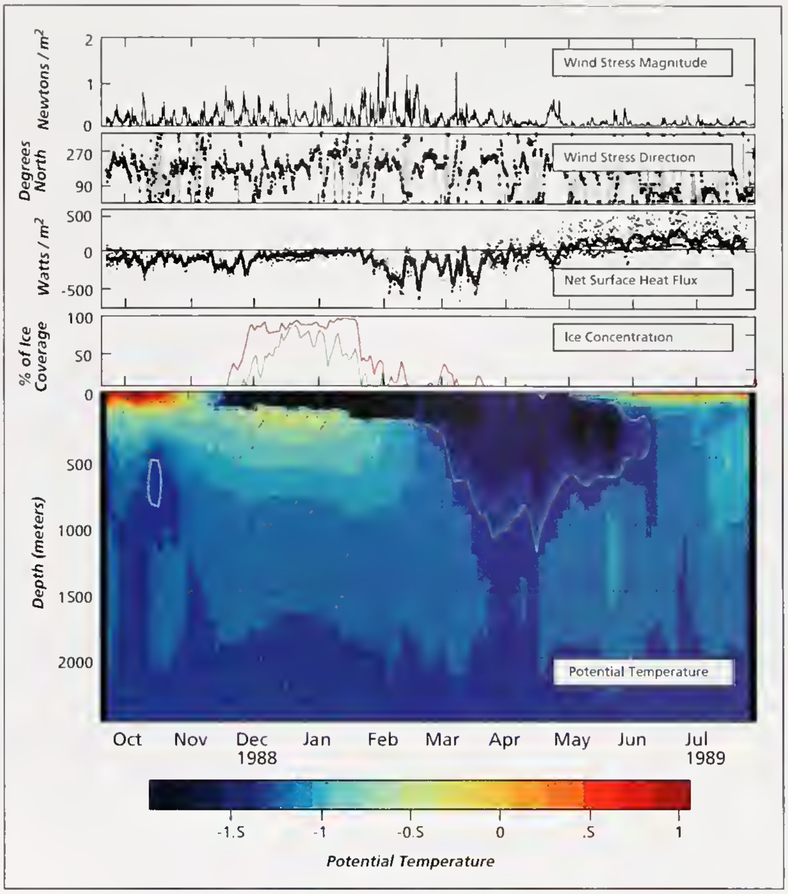
In the figure at left, which illustrates the growth of the ice cover, two features are critical to understanding deep-water formation. First, we see in the top three panels that winter ice forms over the array, increasing the salinity of the near-surface waters; it is then pushed away from the array by winds. (CTD and meteorological data help provide us with this interpretation). Ice then reforms around the array during early March to early April except for over the dark-line acoustic path, which is just where we will see the deep water form in the next picture! Thus, after getting its "salt dollop" from the winter ice, the region is opened up to wind mixing and cold-air cooling, as the prevalent theory proposes.

The second figure, at right, shows the tomography results, the average temperature along the path that appears as a heavy line in the first figure. An annual cycle of temperature, ice cover ("concentration"), heat flux from the surface, and wind direction and speed is laid out here, and tells an interesting story. During autumn, a layer of warm surface water (if you care to call just above the freezing point warm!) lies above cooler Intermediate Water. As winter comes on, this water cools; as the ice cover develops, the near surface water (down to 100 meters) cools drastically, leaving a cold, now saltier layer over warmer, salty water. After the ice cover blows away in mid January, the surface water warms slightly while the water below cools as the surface and Intermediate Water mix. Finally, from around early March to mid April, the surface layer mixes deeply in a series of steps (via the convective plumes) to a depth of 1,600 meters or so—completing the so-called deep water formation! After mid-April, the surface heat fluxes begin to turn positive (the water begins to heat up, rather than cool), and so a warm buoyant surface layer is reestablished, and downward convection is shut off.

In addition to these pictures, a great deal of other data indicates how deep convection works. It includes full three-dimensional temperature field images from the tomography array, a beautiful Doppler current profiler picture of a convective plume made by the University of Kiel group, and conductivity (salinity)-temperature-depth profiles, to name a few. All of these measurements, by and large made possible by ocean technology developments of the past 25 years (tomography, satellite oceanography, and the Acoustic Doppler Current Profiler are particularly new), were necessary pieces to explain what turns out to be a rather intricate phenomenon of nature.

Thus, we should not be too hard on ourselves or our forebears for taking so long to solve the puzzle of deep-water formation. Sampling the ocean adequately is a hard job, and in this case we only recently crossed the technological threshold required to do it properly. Many ocean mysteries yet defy our best attempts to sample and explain them. It is these continuing challenges that make oceanography as exciting today as when Nansen discussed the formation of Greenland Sea Deep water in 1906.

The work described was funded jointly by the Office of Naval Research and the National Science Foundation. "Thermal Evolution of the Greenland Sea Gyre in 1988-89" by R. Pawlowicz, J.F Lynch, W.B. Owens, P.F Worcester, W.M.L. Morawitz, and P.J. Sutton is "in press" in the Journal of Geophysical Research.



E PAUL OBERLANDER

Tomographic temperature profile of the region of deep-water formation during 1988-1989, along with ice concentration and meteorological time series. The rapid deepening of the cold-water region by surface convection is quite striking during March.

Rich ("Grumpy") Pawlowicz received his Ph.D. from the MIT/WHOI Joint Program in Oceanography and Oceanographic Engineering in January 1994 for his work on the Greenland Sea deep convection analysis presented here. He is presently a postdoctoral investigator at the Institute of Ocean Sciences in his native Canada, working on long range acoustic transmissions across the Arctic. Rich's main hobbies are bicycle racing and grousing. Jim Lynch and Breck Owens were Rich's Ph.D. advisors. Peter Worcester is "one of those Scripps guys" (Research Oceanographer) and a longtime friend and collaborator in acoustic oceanography

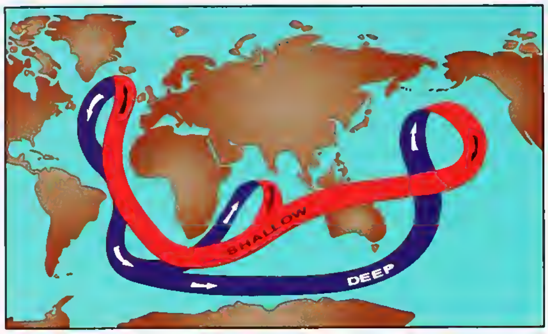

JAMES LYNCH

R/V Knorr *departs from Longyearbyen Fjord, Spitsbergen, for an emergency mooring pickup, leaving the Greenland Sea tomographers aboard the Norwegian M/V* Polar Syssel *at the end of the deployment cruise.*

Maintaining the Thermohaline Circulation

Alternative Arctic Circulation Scheme Provides Continuous Source of Deep Water

Cecilie Mauritzen
1994 MIT/WHOI Joint Program Graduate
W. Brechner Owens
Senior Scientist, Physical Oceanography Department



A schematic view of the thermohaline circulation of the world oceans.

The idea that ocean currents connect the world is very appealing—who wouldn't be thrilled to find a letter in a bottle from some unknown friend far away? For the people of northern Europe, "information" carried by currents from far away, more specifically heat from southern latitudes, makes their climate not only livable, but pleasing. The idea that this current system may be sensitive to small changes in the environment, and that it could even be "turned off," is naturally disturbing. Yet this prospect has been intensely debated in the oceanographic literature over the past few years.

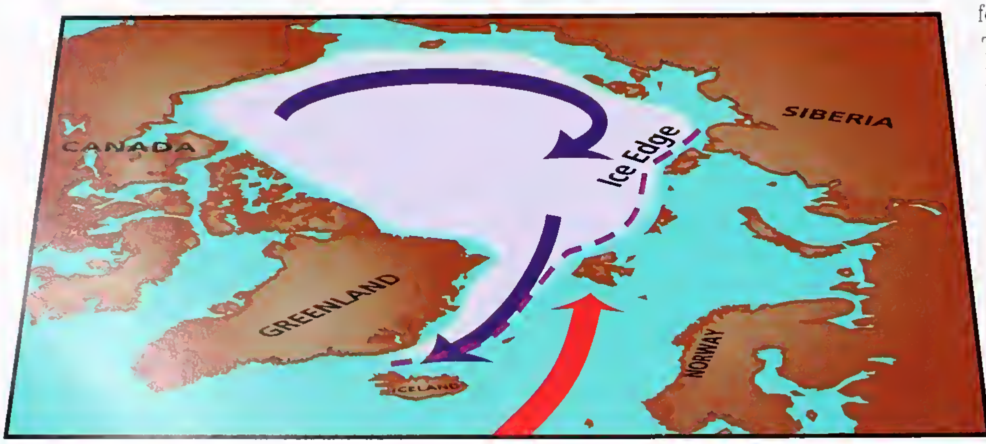
The sun heats the Earth nonuniformly, delivering most of the heat to the equatorial regions. Both the atmosphere and the oceans participate in redistributing the heat. The oceans' role is often referred to as the thermohaline circulation: a meridional overturning cell with warm water flowing poleward in the upper layers, converting to dense water, and returning equatorward as cold, deep water that gradually upwells to complete the circuit. Since the ocean basins are connected, this circulation scheme encompasses all the major world oceans.

An important part of the thermohaline circulation occurs in the North Atlantic, and includes the warm Atlantic flow along northern European coasts. This water becomes dense as it cools within the Nordic Seas and Arctic Ocean, and leaves the region by flowing across the Greenland-Scotland Ridge. This dense water outflow is well observed and known to be remarkably constant, both interannually and seasonally.

To examine the issue of dense water conversion, let us consider the thermohaline conditions of the Nordic Seas and the Arctic Ocean. The average surface temperature is very close to freezing (-1.9°C), and the central Arctic is permanently ice covered. In the Nordic Seas, ice conditions are closely related to surface currents: In the west, the southward flowing East Greenland Current brings cold Polar Water and ice toward the Denmark Strait, while, in the east, the northward flowing Atlantic Water inflow brings water that is well above freezing. The Greenland and Iceland seas fall between these two domains. Within each sea, the circulation forms counterclockwise gyres (see figure opposite)

The conversion from light to dense water is commonly thought to occur in the waters of the Greenland and Iceland sea gyres. Since these seas contain the densest surface waters of the entire Arctic Ocean system, conditions are favorable for vertical convection of dense surface waters to great depths (see the previous article for observations of this phenomenon). The dense water is thought to accumulate in the lower portion of the gyres, then "spill" out by crossing the gyre boundaries and exiting over the Greenland-Scotland Ridge.

Surface thermohaline conditions in the Nordic Seas and the Arctic Ocean.



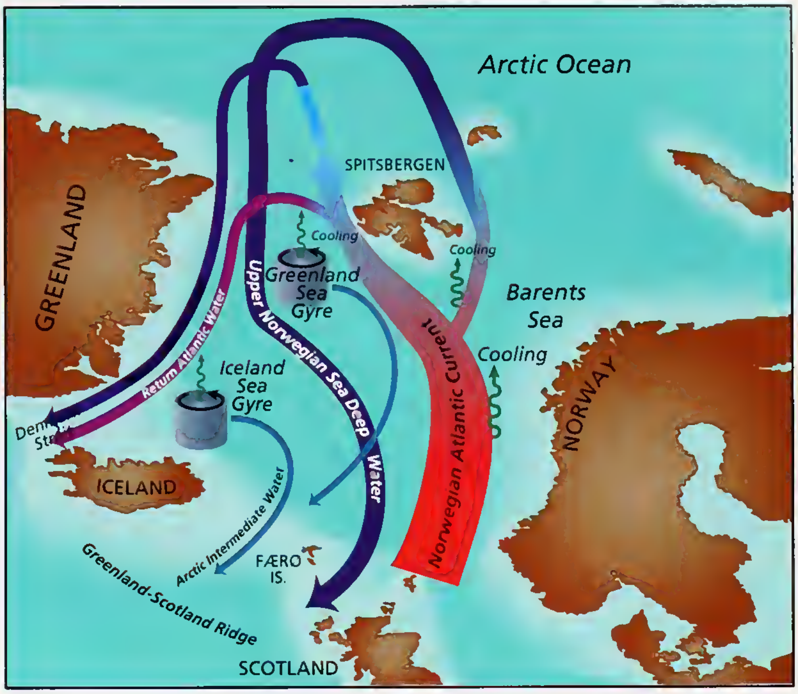
Although the dense water produced in the Greenland and Iceland seas is locally important, the conversion of surface waters to dense water in these seas is neither steady enough nor sufficient to constitute principal sources of dense water for the thermohaline circulation. The surface wind and ice conditions are highly variable from year to year, and recent observations show that dense water formation in the Greenland Sea has a tendency to turn on and off. This and other findings have led some researchers to postulate that the thermohaline circulation could "switch off," or significantly change its spatial pattern. But, curiously, there is no indication of such variability in data on the Greenland-Scotland Ridge overflow. Additionally, quantitative estimates of dense water production rates in these seas are considerably less than transport estimates of dense water flow into the North Atlantic across the Greenland-Scotland Ridge.

An alternative circulation scheme was presented in author Mauritzen's thesis work for the MIT/WHOI Joint Program. It resolves these apparent conflicts and produces an overflow with the observed characteristics. According to this scheme, dense water forms along the path of the Norwegian Atlantic Current east of the Greenland and Iceland Seas. The Atlantic Water loses heat to the colder air and becomes progressively denser as it moves north toward the Arctic. The water's properties are further modified as the Norwegian Atlantic Current splits into three branches, each bringing dense water with slightly different characteristics back to the Greenland-Scotland Ridge along boundary currents surrounding the Greenland and Iceland seas.

The scheme is simple—water properties are continually modified during the transit of the Arctic Ocean system, rather than being mixed across gyre boundaries into and out of the Greenland and Iceland seas. The scheme is also consistent with the various water masses and currents in the region. The formation rate of dense water is consistent with transport estimates of dense flow across the ridge, and the three southward-flowing branches account for the observed variation in overflow water properties at different locations along the ridge.

A closer look at the mechanisms for dense water formation explains why the Norwegian Atlantic Current scheme results in a more steady conversion to dense water than occurs in the Greenland and Iceland seas. Water becomes dense either by a decrease in temperature or an increase in salinity, and there is a lower limit to how cold the water can get: the freezing temperature. In the Greenland and Iceland seas the water is already close to this limit, so if the salinity is too low, the water cannot cool sufficiently to sink before it freezes. Therefore, a small freshwater anomaly can effectively halt thermal convection by allowing for the formation of an ice cap in the region. However, freezing doesn't necessarily halt dense water formation, because when ice forms salt is released to the water column, increasing the density of the water below. But to maintain dense water formation by freezing requires continual removal of newly formed ice from the area by a more steady windfield than is typical in the Greenland and Iceland seas.

Within the Norwegian Atlantic Current, on the other hand, the temperatures are always far above freezing when the dense water forms. Any local decrease in salinity may therefore be overcome by further cooling



JACK COOK

Modification and pathways of Atlantic water in the Nordic Seas and the Arctic Ocean, from warm and light inflow to dense overflows.

without chance of freezing, so light water is continually converted to dense water. Thus the formation of dense water within the Norwegian Atlantic Current is not likely to shut down. As Atlantic Water residence time in the Norwegian Atlantic Current is several years and the net annual atmospheric heat loss dominates seasonal variations in heat loss, the seasonal signal associated with dense water formation in this region is insignificant.

That said, there certainly are anomalies in the temperature and salinity fields of the Norwegian Atlantic Current—interannual (two- to ten-year) variations in Atlantic Water properties are as large as, or perhaps larger than, anywhere else in the arctic system. These variations may well correlate with small climate anomalies that are observed on similar time scales (like the cold winters "everyone" seems to have experienced in their childhood), but they are minor modifications in a system that steadily produces dense water.

Thus the scheme implies a robust thermohaline circulation in the Arctic Ocean system, more robust than suggested by the marginal conditions in the Greenland and Iceland seas, and this is consistent with the knowledge that the climate in Europe hasn't changed in any dramatic manner since the last ice age.

This work was partly funded by a NASA Global Change Fellowship. Two articles have been submitted to a scientific journal.

Cecilie Mauritzen is a native of Norway. After completing studies at the University of Bergen, she came to Woods Hole as a graduate student in the MIT/WHOI Joint Program where her thesis advisor was Breck Owens. Her interest is polar oceanography, although she contemplates, almost daily, how she might join a tropical (warm!) oceanographic cruise. This year she made what she calls "the cardinal error" of marrying another oceanographer, Joe LaCasce, a Joint Program student in physical oceanography. Cecilie currently holds a postdoctoral position at the National Aeronautics and Space Administration in Maryland.

Dense Water Formation on Arctic Shelves

Model Tracks Coastal Ocean Response to Arctic Ice Conditions

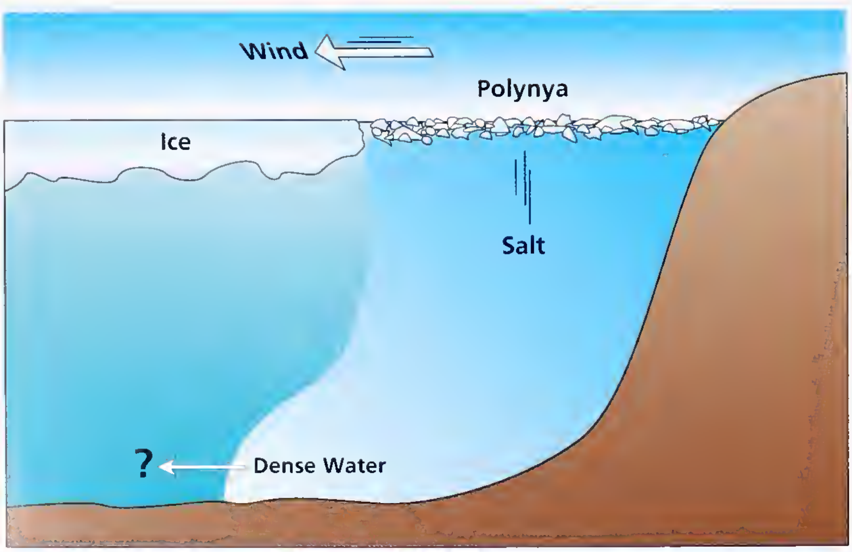
Glen Gawarkiewicz
Assistant Scientist, Physical Oceanography Department
David C. Chapman
Associate Scientist, Physical Oceanography Department

Water in the upper 100 to 200 meters of the deep arctic basins is cooled by the atmosphere to freezing or near-freezing temperatures. Consequently, ice readily forms and covers most of the arctic. On the other hand, the deeper waters are several degrees warmer. In fact, the heat stored in the deeper waters would be enough to melt all of the arctic ice, if it were to mix with the surface waters. Separation of the colder surface layer from the warmer deep water is thought to be maintained by lateral injection between the two layers of relatively salty water formed over the continental shelves.

The proposed scenario is as follows. As sea ice forms from salt water, most of the salt is dropped out (rejected) into the water column beneath the ice, reducing the salinity of the ice by a factor of three or more relative to the seawater. The rejected salt mixes with underlying water, thereby substantially increasing the water density. The amount of salt added is proportional to the rate of ice formation, so the greatest changes in water density are found in areas where ice formation rates are largest. One such area is called a coastal polynya, or ice-free region adjacent to the coast, where offshore winds tend to blow the ice away from the coast, leaving open areas exposed to rapid atmospheric cooling (see figure below). As the winds weaken, a new ice cover forms, rejecting more salt into the coastal waters before being blown offshore again, and so on. This process can increase the water density beneath the polynya to such an extent that the dense water begins to flow away from the polynya and interact with less-dense surrounding waters. Eventually, this dense shelf water is thought to leave the shelves and enter the deep basins at the depth of the boundary between colder surface waters and warmer deep waters.

Though there are numerous observations of dense water near coastal polynyas on record, the details of these dense shelf-water flows are difficult to ascertain because of observational limitations in the Arctic. Dense water has typically been identified either from hydrographic surveys that produce a spatial snapshot of ocean conditions over a short time interval, or from long-term measurements at a fixed location. The first method provides little information about the time evolution of dense water flows, while the second provides little information about the spatial patterns.

As an alternative to direct observations, we have been using a sophisticated numerical model to study the dynamics of the formation and transport of dense water on arctic shelves. Our goals are to understand the various factors contributing to dense-water formation over arctic shelves, to identify the offshore-transport processes for dense water, and to learn how the dense water leaves the shelves and enters the deep basins. The model, developed by Dale Haidvogel (Rutgers University) and others, allows us to study the response of coastal waters to a coastal polynya and the resulting circulation over the continental shelf in highly idealized settings.



JAYNE DOUCETTE

A schematic diagram of a wind-driven coastal polynya, or ice-free area. Offshore winds blow ice away from the coast, leading to high rates of ice formation adjacent to the coast. The salt rejected as the ice forms collects in the underlying water, increasing its density.

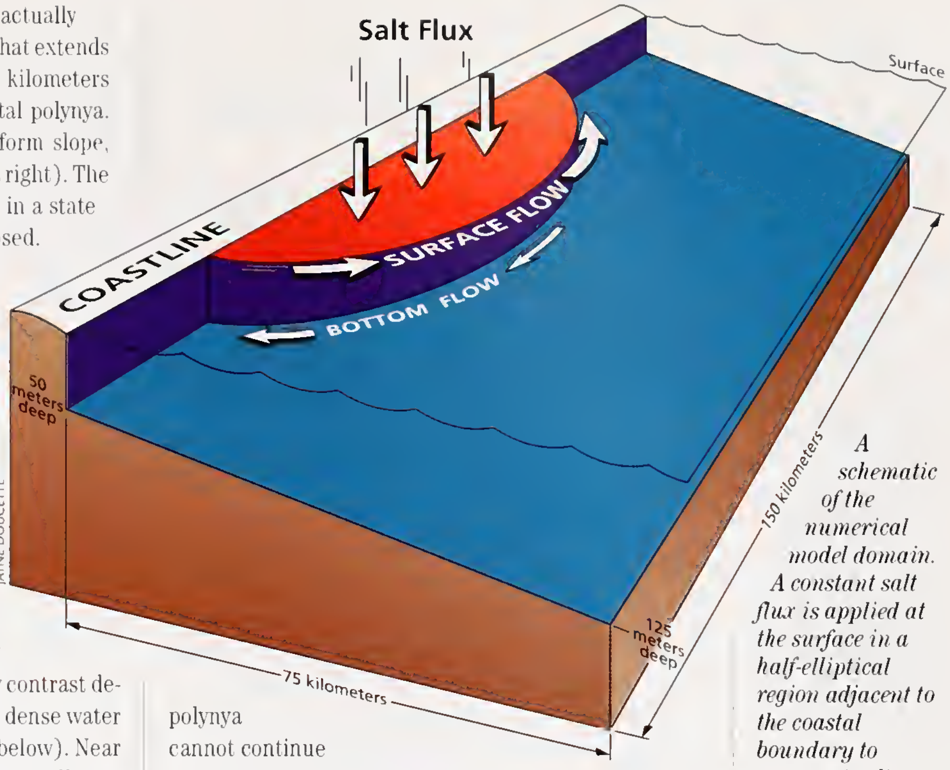
We began by representing a coastal polynya as a constant surface salt flux (to mimic the formation of ice without actually modeling the ice) over a half-elliptical area that extends 60 kilometers along a straight coast and 10 kilometers offshore, reasonable dimensions for a coastal polynya. The bathymetry is assumed to have a uniform slope, deepening away from the coast (see figure at right). The ocean begins with a constant density and is in a state of rest when the surface salt flux is imposed. Despite the apparent simplicity of the model configuration and forcing, the induced flow displays remarkable complexity. To aid our understanding of the flow, we divide the evolution of flow around the polynya into three stages, each dominated by different dynamics.

During the initial phase, which we call geostrophic adjustment, the salt entering from the surface mixes with and increases the density of underlying water. There is no offshore transport of salt, so the density of the water beneath the polynya simply increases linearly with time. A sharp density contrast develops at the edge of the polynya, where the dense water meets the ambient ocean water (see figure below). Near the bottom, the dense water then begins to slump offshore under the ambient water and turns to the right because of Earth's rotation. Similarly, the ambient water near the surface begins to move shoreward over the dense water and turns to the right. The net result is flow primarily along the edge of the polynya, in opposite directions at the surface and bottom. The flow near the bottom is retarded by friction, creating an asymmetry, with stronger flow near the surface.

The second phase, eddy development, begins after roughly six days. Since flow along the edge of the polynya cannot continue through the coast, the boundary between dense and ambient waters begins to deform, developing several waves near the coastal boundary. The boundary is unstable, that is, variations along the boundary will grow rapidly in time, no matter how small they are initially. These waves have horizontal scales of about 15 kilometers, and within four more days develop into a pair of isolated features called eddies that begin to propel each other offshore, across the isobaths.

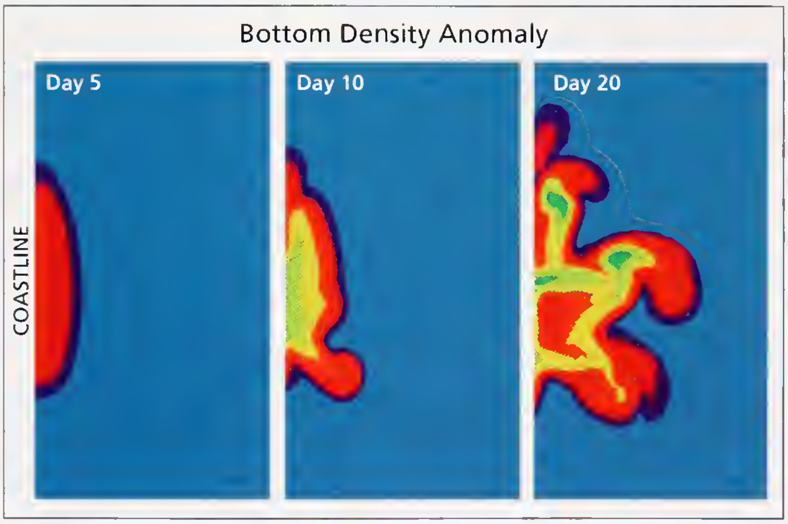
During the final phase, the eddies transport the dense water well offshore of the polynya. The flow within each eddy is counterclockwise near the surface and clockwise near the bottom. These counter-rotating structures bear a striking resemblance to a theoretical flow structure known as a "heton," investigated by WHOI physical oceanographers Nelson Hogg and Henry Stommel in the early 1980s. They showed that pairs of hetons can transport mass (or salt) by propelling themselves in a direction perpendicular to the line between the two eddy centers, which, in our case, is nearly directly offshore. The dense water is carried offshore within the eddies at a typical offshore velocity of about 2 centimeters per second for an eddy center.

The results of our numerical calculations have



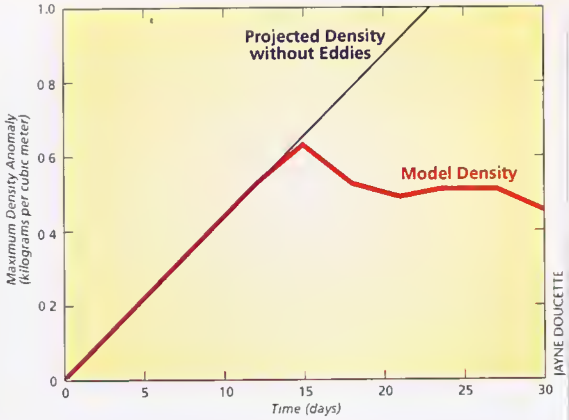
JAYNE DOUCETTE

A schematic of the numerical model domain. A constant salt flux is applied at the surface in a half-elliptical region adjacent to the coastal boundary to represent salt rejected from a coastal polynya. The bottom depth increases gradually, from 50 meters depth to 125 meters, away from the coast. The salt flux increases the water density within the polynya, and Earth's rotation causes the water to flow along the edge of the polynya in opposite directions at surface and bottom.



Plan view of water density at the bottom of the numerical model domain after 5, 10 and 20 days of imposed salt flux. The ambient water is blue, and the densest water is green. The left boundary in each panel is the coast. After 5 days, the dense water is still confined to the polynya. By day 10, however, an eddy composed of dense fluid forms near the lower edge of the polynya. Eddies continue to form, and by day 20, they carry the dense fluid directly offshore from the polynya.

A plot of the maximum density within the model domain versus time. The blue line shows the increase in density that would occur if no eddies formed to carry dense water offshore. The red line shows the actual model density. Initially, the water density increases linearly, but after day 10, when eddies begin forming, the density remains roughly constant because the eddies carry the dense water offshore as fast as it is formed in the polynya.



several important implications concerning dense water formation and offshore transport on arctic shelves. For example, the maximum density of the water formed in the polynya is apparently limited by the offshore motion of the eddies and not by the rate of ice formation. The eddies tend to transport dense water offshore as fast as new dense water can form, so the maximum water density remains roughly constant after about 10 days (see figure above). The maximum density depends on factors that affect eddy formation and movement, such as the bottom slope, but not solely on the magnitude of the salt flux. The short spatial scales and highly variable nature of the dense water flows suggest that observing these features will continue to be difficult. Localized measurements in either space or time may completely miss the eddies, despite their presence over the shelf. Finally, although the model is idealized, the eddy scales (15-kilometer diameter, 20-centimeter-per-second radial velocity) are consistent with those commonly identified within the central basins of the Arctic Ocean. This suggests that eddies formed by the processes involved in the model may be able to penetrate across the shelf and shelf edge into the deep basins.

We do not presently have sufficiently well-resolved observations to test some of the important features of our model results. However, we are working closely with Tom Weingartner (University of Alaska, Fairbanks) who will soon be deploying moored current meters and conductivity cells to measure salinity and detect eddies of dense water forming in the Chukchi Sea north of Alaska. Some of his previous observations show dense water moving offshore directly across isobaths at speeds of 1 to 2 centimeters per second, similar to our model results. Through this collaboration we hope to test some of our ideas and gain a better appreciation for aspects of the dynamics we have so far neglected, including variations in bathymetry such as submarine canyons, background stratification of the ambient ocean, steady flows along the shelf, changes in bottom slope at the shelf edge, and time variations in ice production.

Overall, there is still much to learn about the dynamics of dense water formation and transport on arctic shelves, and close collaboration between observationalists and modelers will be essential to gain new insight into the interaction of continental shelf water masses with the central basins.

This work was supported by the Office of Polar Programs of the National Science Foundation under the Ocean-Atmosphere-Ice Interactions initiative of the Arctic Systems Science program. It is dicussed in an article entitled "A Numerical Study of Dense Water Formation and Transport on a Shallow, Sloping Continental Shelf" that is in press for the March 1995 issue of the Journal of Geophysical Research-Oceans.

Glen Gawarkiewicz became interested in polar problems after a trip to the Dry Valleys of Antarctica, where he accompanied a team of geochemists who were studying the ice-covered lakes. During this field season, he was the team leader in falling through thin lake ice into waist-deep water, and also specialized in paddling the (leaky) inflatable raft from the shore onto the ice cover over the lake. In his spare time, he enjoys playing basketball and canoeing with his wife, Connie, and children, Ellen and Thomas.

Dave Chapman has been using numerical models to address oceanographic as well as other problems for almost two decades. However, he never truly appreciated the benefits of studying the ocean from his office computer until he began modeling Arctic flows. Brrrr...

What's a numerical model?

Many physical processes occurring in a fluid, like the ocean, can be represented as mathematical equations that express the conservation of mass, heat, and momentum. These differential equations describe changes in velocity, temperature, and salinity caused by external forces such as wind, atmospheric heating and cooling, and Earth's rotation.

The complexity of the equations and forcing often precludes analytical solutions, so the equations must be solved in approximate form on a computer, that is, numerically. In essence, the numerical equations express a set of well-defined rules by which fluid properties are thought to change in response to external forces. The computer keeps track of the fluid changes at many locations, called grid points, within the region of interest, or model domain. The time histories of fluid properties at grid points are then used to reconstruct the behavior of the entire model ocean.

The model characteristics are chosen by the scientist, allowing great flexibility in model applications—from idealized situations with a limited number of processes at work, as in the case this article describes, to highly complex simulations that include many processes and realistic bathymetry and forcings. Numerical models have become useful tools for advancing our understanding of the many ocean processes that are difficult and expensive to observe directly.

—Dave Chapman

Where the Arctic Meets the North Atlantic:

Exploring the Barents Sea Polar Front

Surprises Still Await Those Who Study Arctic Circulation

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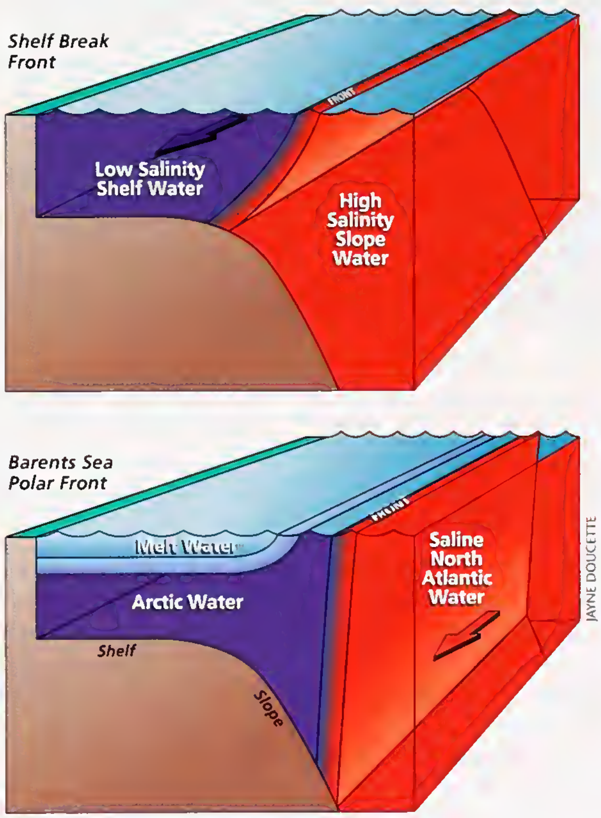
Albert J. Plueddemann
Associate Scientist, Physical Oceanography Department

Fronts are among the ocean's most fascinating and complex general features. They are sharp water-mass boundaries marked by large changes in temperature, salinity, or both over short horizontal distances. Fronts occur in a variety of deep- and coastal-ocean contexts. Significant roles of coastal ocean fronts are thought to include inhibiting cross-shelf transport of matter and enhancing local biological productivity.

In the arctic and sub-arctic marginal seas, a variety of fronts are associated with different physical processes. For example, near the mouths of major rivers, coastal-current fronts divide the river outflow water from the ambient shelf water. Sharp fronts often occur at the transition between ice and open water. At the shelfbreaks or edges of the continental shelves, fronts normally separate cool, fresh shelf or arctic surface water from warm, saline slope waters that typically originate in the North Atlantic.

The frontal systems dividing cool, fresh Arctic Water from warm, saline North Atlantic Water in the Barents Sea are particularly interesting (see figure on page 18). Two major inflows affect the central basins: North Atlantic Water flows northward from the continental slope west of Norway into the southwest corner of the Barents Sea through the Bear Island Trough, and Arctic Surface Water enters the Barents Sea from the north and northeast and flows to the southwest. The Arctic Surface Water then exits the Barents Sea into the Norwegian Sea via the northern portion of the Bear Island Trough. The Polar Front, or boundary between Arctic Water and North Atlantic Water, is a persistent, large-scale feature of the Barents Sea that is associated with the ice extent. The presence of warm, North Atlantic Water prevents the formation of ice over much of the southern Barents Sea. (The ice-free zones were important strategically during World War II as Allied convoys carried supplies to the Soviet Union at the port of Murmansk, which remains ice free year-round.)

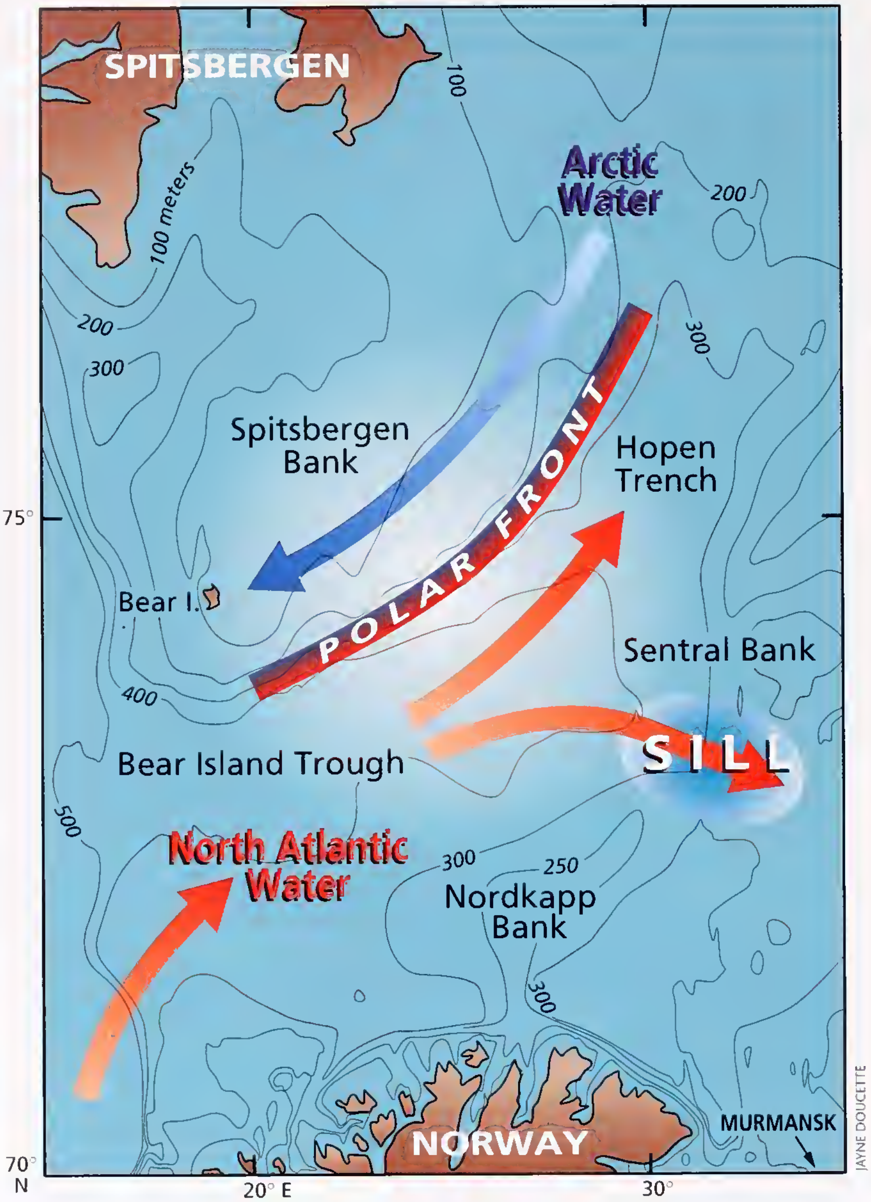


A schematic view contrasting the shelfbreak front in the Middle Atlantic Bight with the Barents Sea Polar Front on the south flank of Spitsbergen Bank. In the Middle Atlantic Bight there are moderately strong mean flows over the shelf and the front intersects the bottom at the shelfbreak. In the Barents Sea the mean flows are strong over the slope, and the front forms a nearly vertical "wall" that intersects the bottom well down the slope. Melt water from sea ice forms a second, shallow front on the shelf in summer.

In the eastern portion of the Barents Sea, the Polar Front shifts its latitudinal position both seasonally and interannually. The maximum southward extent may vary by up to 600 kilometers, depending on the severity of the winter and the ice conditions. In the western portion of the Barents Sea, within the Bear Island Trough and the Hopen Trench area, the Polar Front is topographically trapped, and is always located near the shelfbreak at the edges of the various banks.

Previous work in this region suggested that the frontal structure and dynamics might be somewhat analogous to the shelfbreak front on the Middle Atlantic Bight off the east coast of the United States. Recent numerical modeling work by author Gawarkiewicz and David Chapman identifies two key elements necessary for shelfbreak formation:

A map of the Barents Sea showing the bottom topography and the two major current systems as depicted by previous researchers. North Atlantic Water enters from the Norwegian Sea and flows to the east and northeast, while Arctic Water enters from the Arctic Ocean and flows southwest. The Polar Front, which divides these two water masses, is topographically trapped at approximately the 250-meter isobath on the south flank of Spitsbergen Bank.



despite large temperature and salinity differences. Instead of a strong westward flow of Arctic Water over the shelf, a westward flow of North Atlantic Water was observed over the slope at depths greater than 250 meters, with a mean velocity of 10 centimeters per second. One of the most curious features was that the front separating North Atlantic Water from Arctic Water was located at the 250-meter isobath, over the middle of the slope. Usually, shelfbreak fronts are located close to the shelfbreak.

Why was the core of North Atlantic Water bounded by the 250-meter isobath where the westward velocity was concentrated? After looking carefully at the bathymetry of the Barents Sea, we realized that there was a sill or opening at the eastern end of the Bear Island Trough, at a depth of roughly 250 meters. What effect might this sill have on the frontal structure downstream?

In order to answer this question, we used a numerical model developed by Dale Haidvogel (Rutgers University) and co-workers. The model's idealized bathymetry contained the two essential elements we felt were responsible for the frontal structure: a large, bowl-shaped indentation similar to the Bear Island Trough, and a sill at its eastern edge connecting the trough to an idealized central basin. We then imposed an inflow with water mass characteristics typical of the North Atlantic Water entering the trough from the Norwegian Sea. Initially, the entire basin was filled with Arctic Water. The inflow, which lacks vertical stratification and vertical structure in the along-shelf currents, tends to follow isobaths, or lines of constant depth. Half of the inflowing Atlantic Water enters the trough at depths less than the sill depth, and half at depths greater than the sill depth. At the sill, the inflowing water splits into two branches, one that enters the central basin and continues east, and one that recirculates to the west. Because the flow follows isobaths, the recirculat-

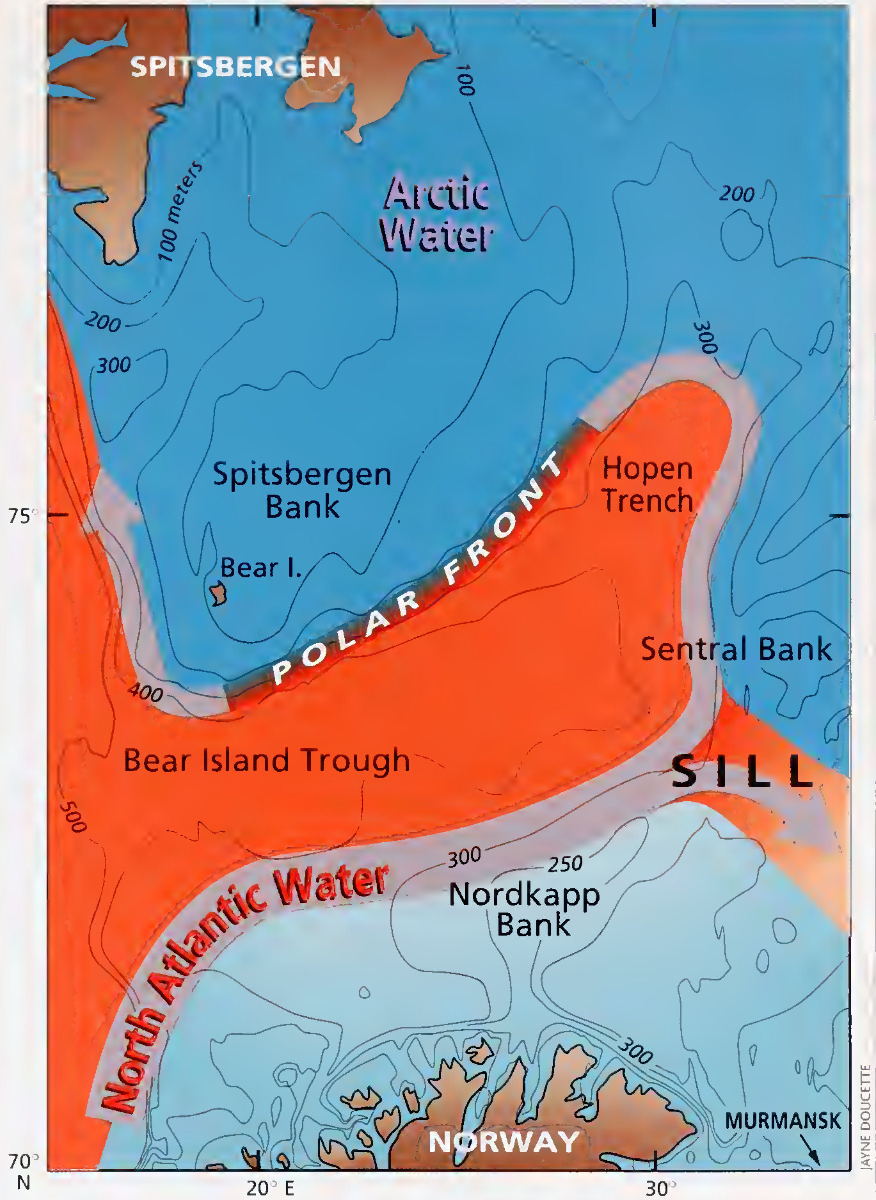
1) a mean flow over the shelf of at least 5 to 10 centimeters per second, and
2) a strong density contrast near the bottom at the shelfbreak, allowing the bottom boundary layer to detach.

We anticipated, based on prior work in this region, that the Arctic Water on the south flank of Spitsbergen Bank would be similar in structure to the shelf water in the Middle Atlantic Bight (see figure on page 17), with westward flowing Arctic Water providing the mean flow over the shelf. We also anticipated that there would be an eastward flow of North Atlantic Water into the Barents Sea from the Norwegian Sea, counter to the westward flow of the Arctic Water.

However, observations made by a group of investigators led by Robert Bourke (Naval Postgraduate School), showed:
1) there was little or no mean flow over the shelf beneath the upper 20 meters of the water column, and
2) there was no density contrast across the front,

ing water is constrained to flow only at depths greater than the sill depth, or 250 meters. This explains the core being offset from the shelfbreak, where the region of maximum gradients normally are found.

Remarkably, despite simple bathymetry and idealized inflow conditions, the model was able to reproduce the observed salinity structure beneath the surface mixed layer with a surprising degree of detail. Examination of historical data showed that this boundary is extremely stable; an 11-year average position (from data taken on 66 cruises in the 1960s and 1970s!) shows the core of North Atlantic Water bounded by the 250-meter isobath, and data from more recent cruises, in the 1980s, also show the front in this same position.



A new circulation scheme proposed for the western Barents Sea. North Atlantic Water enters from the Norwegian Sea and flows eastward along the southern edge of the Bear Island Trough. At the sill between Nordkapp Bank and Sentral Bank the flow splits, with one branch continuing east through the sill and the other turning north towards the Hopen Trench and eventually exiting the Barents Sea to the west. The latter branch forms the North Atlantic Water recirculation, which is bounded to the east and north by the sill depth, roughly the 250-meter isobath.

Thus, the observed density and velocity structure of the Barents Sea Polar Front differed drastically from our hypothesis, and, even more surprisingly, the dynamics turned out to be much simpler than expected. Instead of finding a shelfbreak front similar to that of the Middle Atlantic Bight, we found an entirely different type of shelfbreak front. The distinguishing feature of the Barents Sea Polar Front is that the upstream processes of the slope flow (through the current bifurcation), rather than the local processes over the shelf, determine the frontal structure.

This work points out two important issues for studying shelf and slope processes in the Arctic:
1) Because our observational data base is quite limited, in many arctic shelf and slope regions we are uncertain even of the direction of the mean flow, and
2) fundamental studies of the underlying dynamics are extremely useful in making sense of fragmentary observations from regions of complex bathymetry. As a result of this highly idealized modeling work, we have been able to formulate specific hypotheses for flows in several other regions within the Barents Sea, and we are presently collecting more historical data to test them. There is much to learn about the arctic shelves—in these areas, we are still at the exploration level of scientific endeavor, where a single cruise with well-resolved sampling can change our entire conceptual picture of a frontal system and the regional circulation that accompanies it.

This work was supported by the Office of Naval Research. It is described in an article in press for the March 1995 issue of the Journal of Geophysical Research-Oceans *entitled "Topographic Control of the Thermohaline Structure of the Barents Sea Polar Front."*

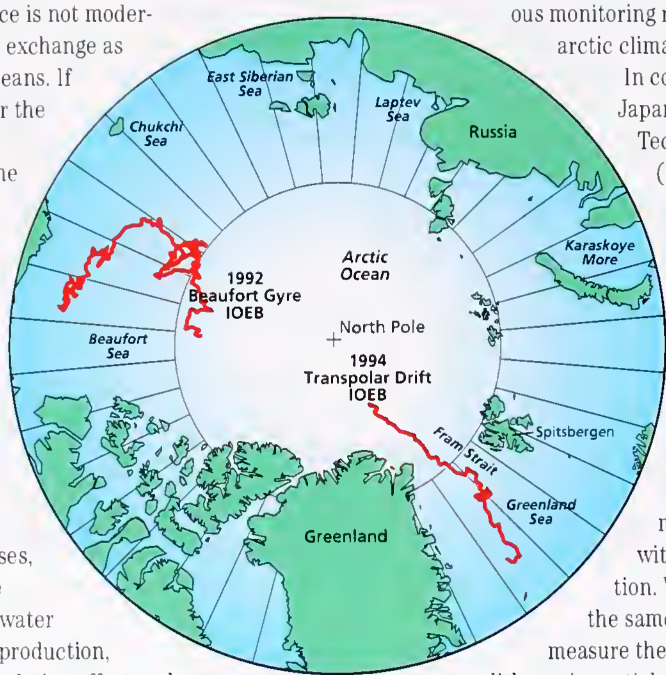
Author notes appear with other articles in this issue.

A Buoy for All Arctic Seasons: The Ice-Ocean Environmental Buoy

Drifting Instrument System Provides Long-Term Arctic Measurements

Susumu Honjo
Senior Scientist, Geology & Geophysics Department

In the unique Arctic Ocean thermodynamic setting, heat contained in the ocean is insulated from the frigid atmosphere by a relatively thin and mobile canopy of sea ice. Consequently, the atmospheric heat balance is not moderated by constant air-sea exchange as it is in lower-latitude oceans. If the air temperature over the Arctic Ocean were to increase as a result of the greenhouse effect or other causes, it is likely that sea ice would be less extensive and thinner, accelerating the release of heat from the ocean. Should global warming at the same time induce a drier climate over the circum-Arctic land masses, particularly Siberia, the reduced supply of river water would diminish sea-ice production, further reducing the insulating effect and allowing more heat to escape from the ocean to the atmosphere. Because of this unique accelerating mechanism, changes in the Arctic Ocean environment could provide early warning of a warming Earth. Numerical models predict that the rate of air-temperature increase could be several times more rapid than in temperate zones.



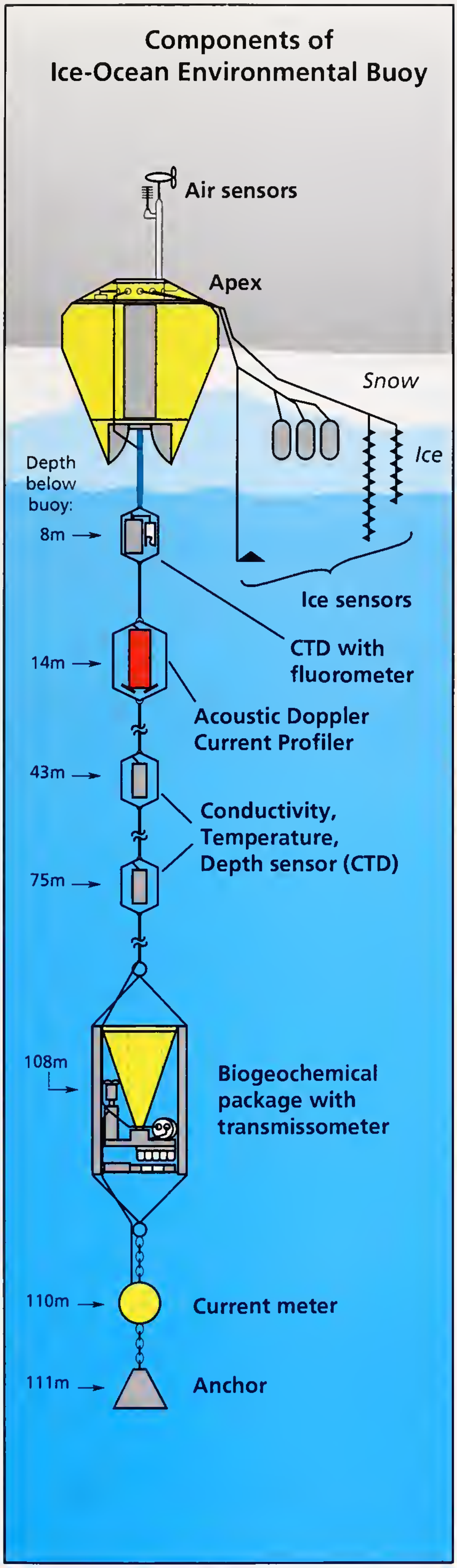
E. PAUL OBERLANDER

Red lines track the courses of two Ice-Ocean Environmental Buoys. The Beaufort Gyre buoy follows a complex, looping track, while the Transpolar Drift buoy takes a nearly steady southward course.

In order to detect changing environmental conditions in the Arctic, coherent sets of frequent atmospheric, oceanographic, and ice-physics data are urgently needed through all seasons, but particularly during the winter when the air-sea temperature contrast is largest. Accelerating environmental change would occur on a time scale of several years to decades; therefore frequent observations should be made continuously into the next century at critical Arctic Ocean locations. Some arctic conditions can be remotely assessed by satellite-based sensors, scientists can make critical short-term measurements at ice camps, and small satellite-tracked buoys allow monitoring of Arctic Basin ice movement. However, none of these methods provide the broad, continuous monitoring required to capture arctic climate changes.

In collaboration with the Japan Marine Science and Technology Center (JAMSTEC), we set out in late 1980s to develop a platform with many sensors capable of telemetering critical atmospheric and upper-ocean data in real time, while, once installed, surviving the harsh Arctic Ocean environment for months and years without human intervention. We also wanted to use the same platform to collect and measure the flux of biogenic and lithogenic particles in Arctic basin waters, where no such data had ever been taken.

The apex of our Ice-Ocean Environmental Buoy (IOEB) houses meteorological sensors, data-management computers, and transmission electronics linked to satellite communication systems. In order to withstand harsh ice dynamics and low temperatures, the apex is constructed of material that maintains flexibility in arctic temperatures. Its tapered conical design allows the buoy to slip upward when surrounding ice exerts excessive lateral force. When an IOEB alternately encounters surface water and ice, it is designed to return to the ice surface after refreezing. Ice-profiling thermistors and other ice sensors are embedded in the ice near the apex to feed signals to the IOEB. The underwater mooring, connected to the apex by a strong electro-mechanical cable, consists of oceanographic and biogeochemical sensors, time-series sediment traps, and a particle filtering pump station. IOEB



JACK COOK

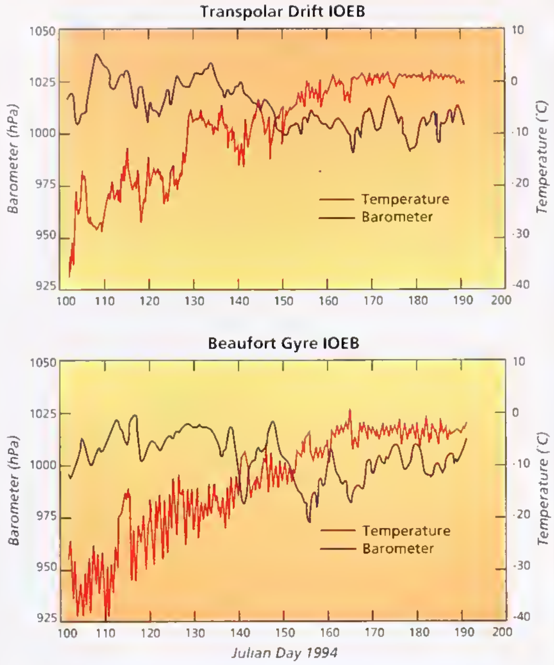
PHOTOS BY SUSUMU HONJO

Deployment of an Ice Ocean Environmental Buoy begins (top photo) with drilling a 1-meter-diameter hole using a hot-water augur under a special lightweight gantry crane that is airlifted to the camp along with buoy components. A sediment trap (middle left), an automated suspended particle and plankton collector (middle right), and many other instruments are lowered through the hole in the ice to make up an instrumented buoy similar to the one drawn at left. Placement of the yellow apex and attendant ice sensors (bottom photo) completes the deployment. Author Sus Honjo is the red-jacketed figure in the photos.

components are designed to be transported to large off-shore ice floes in such aircraft as the DeHavilland Twin Otter commonly used for scientific arctic expeditions. The buoy system can be deployed in a few days' time by a team of three or four technicians using a portable gantry crane and a hot-water ice augur. When an IOEB moves into a mixed-ice zone or open ocean, it will float until recovered by a ship.

Following successful launch (1987) and recovery (1988) of a test IOEB (see next article by Al Plueddemann), a fully instrumented platform was deployed in the Beaufort Gyre of the Canada Basin at 73°N, 142°W on a large multi-year ice flow 3.2 meters thick in April 1992. In mid April 1994 we deployed a second IOEB at 85.8°N, 12°W, also on a large multi-year ice floe 2.8 meters thick, at about the axis of the Transpolar Drift. The overlapping field lives of the two IOEBs allows us to compare ice movement in these two contrasting Arctic Basin environments. Although some sensors on the Beaufort Gyre IOEB ceased transmission early due to noise from underwater sensors, the remainder have transmitted data for over two years. The diverse sensors are all synchronized to collect data according to a single precision timetable, allowing us to identify interrelationships among events and variables

Daily temperature and barometer measurements from the Transpolar Drift and Beaufort Gyre IOEBs for the spring and summer of 1994. Overall seasonal changes are surprisingly similar in the two areas, though they differ in detail.



JACK COOK

that may appear to be unrelated, for example, turbidity of seawater and the drift of an ice floe.

A number of exciting features of the Arctic's natural environment are being revealed by this experiment. Except for a relatively long, conspicuous, early May warming period in the Beaufort Bay, which was not seen in the Transpolar Drift area, the atmospheric pressure and temperature measured by the Transpolar Drift and the Beaufort Gyre IOEBs correlate strongly despite the 1,000 miles that separate them. High-arctic, under-ice phytoplankton blooms were first recorded by this experiment as the Beaufort Gyre IOEB drifted over the Chukchi Plateau area: In the late summer of 1992, the fluorometer 8 meters below the ice registered a sudden increase of chlorophyll pigment in the water at the same time as the transmissometer at 108 meters showed an increase in turbidity. About 50 days later, in late September, a second chlorophyll peak began and lasted more than two months. This was unexpected and is difficult to explain because at this high latitude solar radiation diminishes in October—and no increase in turbidity was observed during this time. These twin peak blooms were repeated in 1993 during the corresponding time periods, but the relationship between the fluorometry and turbidity was somewhat different.

While the Beaufort Gyre IOEB moves slowly (0.27 kilometers per hour on average), making numerous complex loops, the Transpolar Drift IOEB proceeds southward in a more linear fashion and at a higher speed (0.32 kilometers per hour on average). By comparing synchronized wind-vector, ice-floe drift, and current speed measurements, we have uncovered a number of interesting features. Most of the ice-floe-drift vectors in the Transpolar Drift area can be explained by wind forcing. The ice floe itself hardly rotated to the north of the Arctic Mid-Ocean Ridge, as it headed steadily through the Nansen Basin; however, it rotated as much as 90° counterclockwise when it passed over the Mid-Ocean Ridge. While drifting through the Fram Basin toward the Fram Strait, it frequently rotated 20° to 30°, interacting with the West Spitsbergen Current moving northward into the Arctic Ocean.

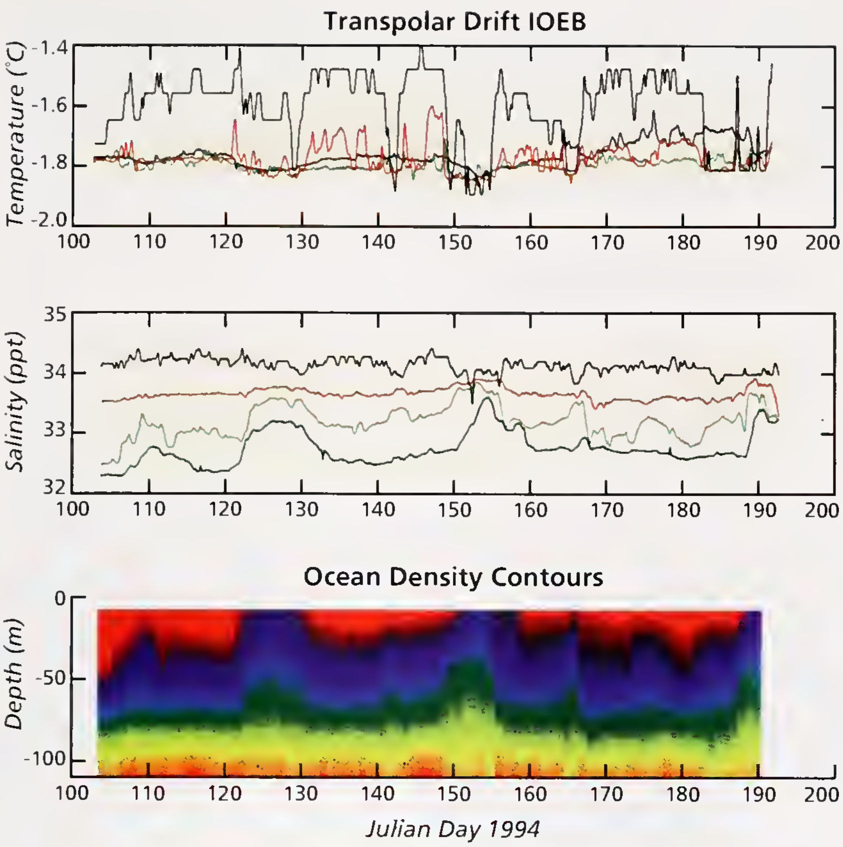
With the IOEB measurements we were able to observe long-term changes in drifting sea-ice thermal structure and to compare the changes in the Transpolar Drift and the Canada Basin areas. The temperature gradient in the ice profile began to reverse in the upper ice layers at the onset of summer, and a distinct summer thermal structure was evident by the end of June. Melting ponds on the top, warm-ice layers (-0.2 to -1.6°C) replaced the upper cold core, and there was a mildly cold core of -1.7°C in the middle, which gradually migrated to the deeper layers of ice (-0.2 to -1.7°C). Until mid May the ice at the bottom of the floe grew at the rate of 3 to 4 millimeters per day, but this growth

RICK KRISHFIELD

International participants in 1994 Transpolar Drift IOEB deployment display their colors. From left, they are the Japan Marine Science and Technology Center (JAMSTEC), Polar Associates (logistics providers), the Woods Hole Oceanographic Institution, and the US government Cold Regions Research and Engineering Laboratory.

SUSUMU HONJO

Researchers relax in an insulated hut after a taxing day on the ice. Sus Honjo is seated in the foreground, John Kemp is standing, and Bill Bosworth (Cold Regions Research and Engineering Laboratory) is at left. Lightweight synthetic materials and air-lift capabilities allow today's arctic researchers comfortable luxury compared to the heavy animal skins and dogsled transport of Nansen's day.



Telemetered seawater temperature and salinity data from 8 meters (lower dark-blue line), 43 meters (green), 75 meters (red), and 108 meters (black) were recorded in Honjo's lab and at JAMSTEC as the IOEB drifted toward Fram Strait. The rainbowlike density contours show cold, dense water (dark blue) "ventilating" through lighter, upper water.

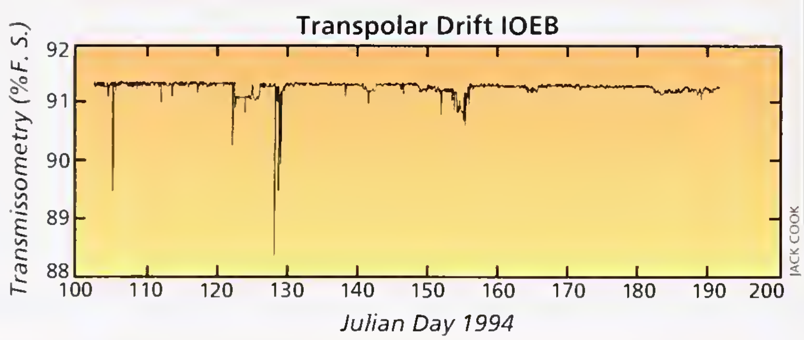
ceased during the next 35 to 40 days. After June 14, warmer surface waters induced melting at the bottom of the ice-floe to a maximum of approximately 8 millimeters per day while the ice-flow drifted southward.

The transmissometer recorded frequent turbidity anomalies at 108 meters throughout the southward journey of the Transpolar Drift IOEB. Turbidity variability showed a strong correlation to that of mean water density at 8 meters and, to a lesser extent, at 43 meters, except early in the experiment (April), when the IOEB was located farther north. For example, the mean water density increased significantly at the end of May 1994, to 26.6 at 8 meters and 27.2 at 43 meters. This event coincided with a period of significantly increased water turbidity at 108 meters. We interpret this as follows: A lead or wide crack in the ice cover exposes arctic surface water to cold air and sunlight. The cold air increases the water's density, so that it tends to sink. At the same time, the sunlight promotes primary production. As a result, the sinking water carries biogenic particles, which register on the 108-meter transmissometer as increased turbidity. If our interpretation is correct, this process may export to the Arctic Ocean interior a large amount of atmospheric carbon dioxide fixed by the organic particles. Documenting this process could be significant to understanding the Arctic's role in global cycling of the post-industrial-revolution increase in carbon dioxide and other biogeochemical elements.

Although sediment trap samples from these two IOEB experiments can only be evaluated after recovery of the instruments, telemetered signals from the Transpolar Drift IOEB indicate that some 10 lead-opening events have been recorded. We plan to recover the Transpolar Drift IOEB in late 1994. Because of its very remote location, recovery of the Beaufort Gyre IOEB is uncertain, so telemetered data may have to suffice. We expect the particles collected in the sediment traps and other data to verify the water density/turbidity events described above. These samples and data will provide critical information toward linking the variability of atmospheric, ice, and hydrographic conditions in the Arctic Basin with the Arctic Ocean's capability to fix and store fossil-fuel carbon dioxide in its interior.

This work was supported by the Office of Naval Research and the Japan Marine Science and Technology Center.

Sus Honjo carries a gene for always heading north. He was born and grew up in southern Japan but always wanted to go north. He graduated and received a Ph.D. degree from Hokkaido University, which is located in the northernmost island of Japan, and married there. Currently he is interested in the biogeochemical cycles of the Arctic Basin and its marginal seas, particularly the Sea of Okhotsk and the Bering Sea, and in comparing the oceanographic processes in northern oceans with those at low-latitude. He found himself to be almost unbelievably happy when he landed by airplane near the North Pole, but was also disappointed because there was not much room for him to go farther north!



Transmissometer data are strongly related to the density variability recorded in the figure above. Spikes in this graph correspond with dense water events in the 108-meter data above as the transmissometer records turbidity caused by descent of particles such as diatoms in the dense water.

A Glimpse Beneath the Ice

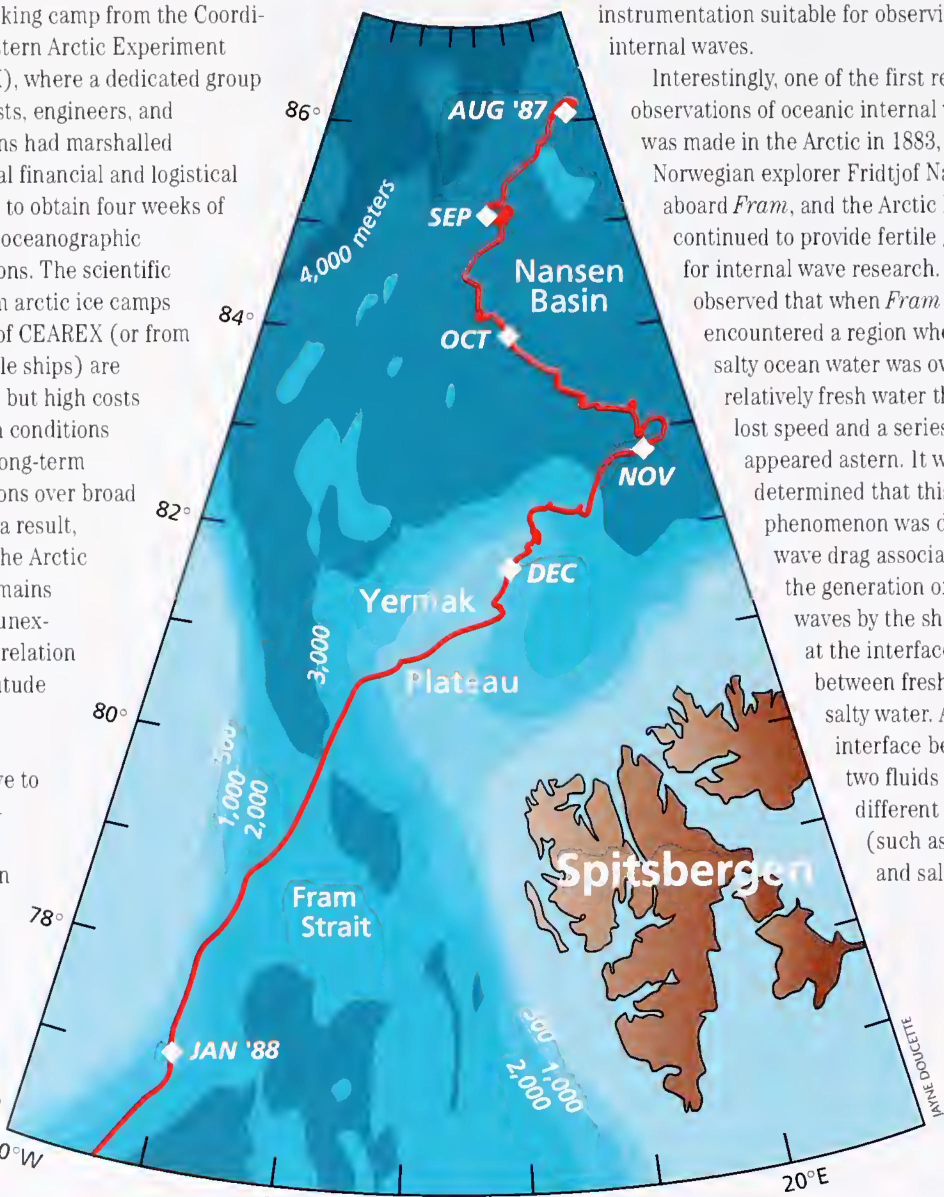
Internal Wave Observations from a Drifting Buoy in the Arctic Ocean

Albert J. Plueddemann
Associate Scientist, Department of Physical Oceanography

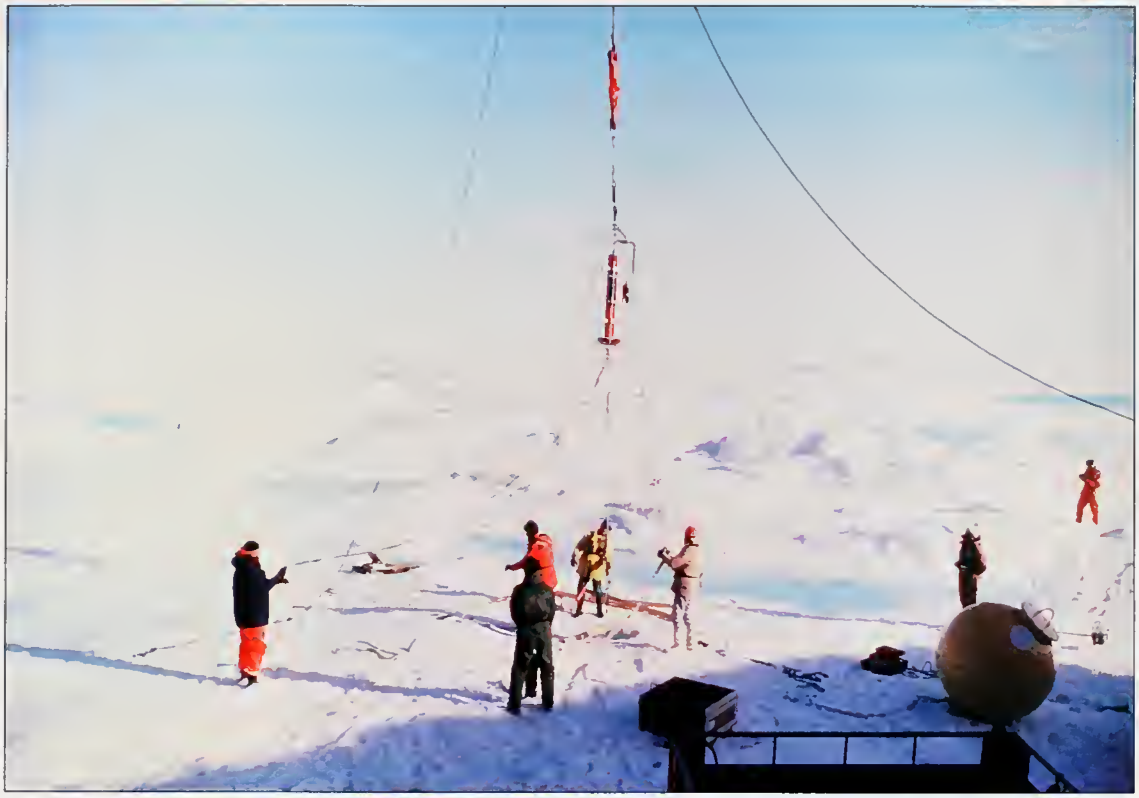
One of my most vivid memories of arctic field work is the numbness in my hands as I worked with a pocket knife in a swirling snowstorm to untie the knots, buried in ice, that attached our tent to its platform. We were breaking camp from the Coordinated Eastern Arctic Experiment (CEAREX), where a dedicated group of scientists, engineers, and technicians had marshalled substantial financial and logistical resources to obtain four weeks of intensive oceanographic observations. The scientific gains from arctic ice camps like that of CEAREX (or from ice-capable ships) are immense, but high costs and harsh conditions prohibit long-term observations over broad areas. As a result, much of the Arctic Ocean remains virtually unexplored in relation to midlatitude oceans.

An alternative to the hand-numbing work of an arctic ice camp is to use unattended, drifting buoys frozen in the pack ice to make oceanographic observations. The value of such observations has been recognized for some time, but only recently have arctic buoys been outfitted with subsurface instrumentation suitable for observing internal waves.

Interestingly, one of the first recorded observations of oceanic internal waves was made in the Arctic in 1883, by the Norwegian explorer Fridtjof Nansen aboard *Fram*, and the Arctic has continued to provide fertile ground for internal wave research. Nansen observed that when *Fram* encountered a region where the salty ocean water was overlain by relatively fresh water the ship lost speed and a series of slicks appeared astern. It was later determined that this phenomenon was due to wave drag associated with the generation of internal waves by the ship's keel at the interface between fresh and salty water. An interface between two fluids of different densities (such as fresh and salty water)



Track of the Arctic Environmental Drifting Buoy (AEDB). Note the Yermak Plateau, which rises steeply to about 700 meters from the 3000 meter deep Nansen Basin.



R/V POLARSTERN

Rick Krishfield (at center in orange jumpsuit) supervises deployment of the Acoustic Doppler Current Profiler through a 1-meter-diameter hole in the ice. It took over two hours to cut through the nearly 4-meter-thick ice with a hot-water melting ring. The yellow flotation sphere can be seen to the right.

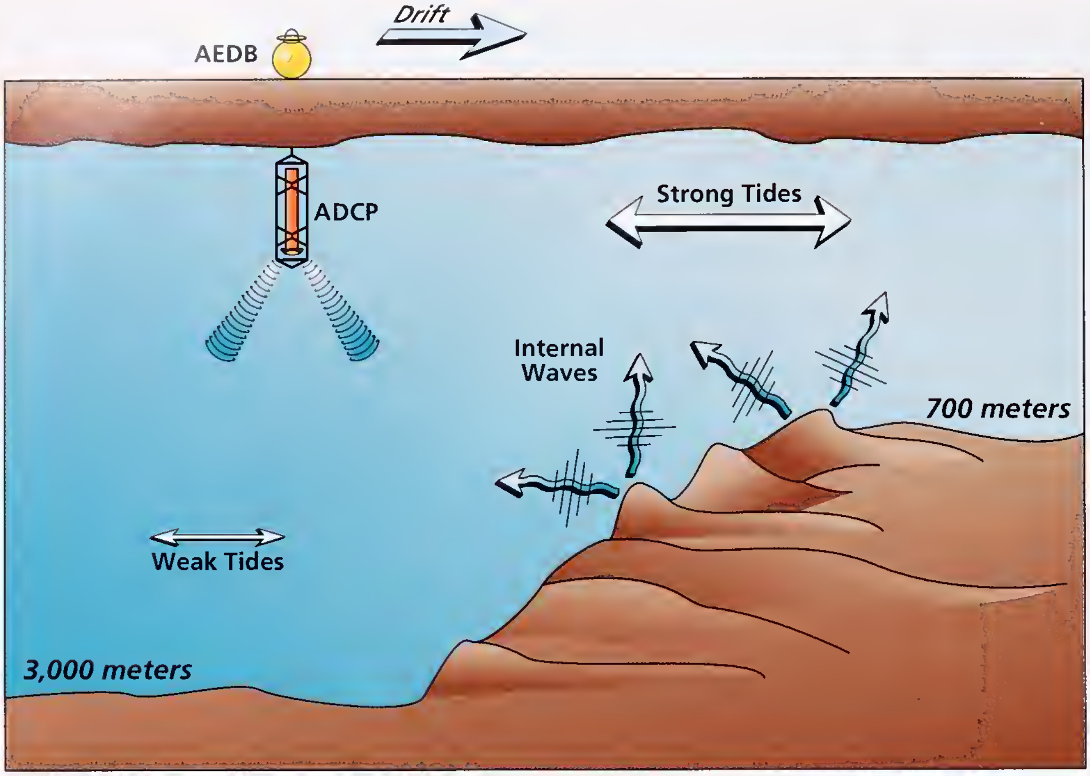
The surface flotation sphere of the AEDB after recovery by the Icelandic ship Arni Fridriksson. *Severe ice stresses crushed the lower half of the three-quarter-inch steel sphere. For later buoys, the shape of the surface flotation was redesigned to better accommodate the harsh arctic environment.*

can support gravity waves in a manner analogous to the more familiar waves characteristic of the interface between air and water.

An abrupt density interface is not necessary, however, for the existence of these waves; the continuously stratified ocean thermocline supports "internal waves." Since the density contrast is weaker than that between air and water, the restoring forces are weaker, and internal waves have much longer periods and wavelengths than surface waves. Like surface waves, internal waves are important in that they may transfer momentum without an associated transfer of mass. Unlike surface waves, which propagate only horizontally, internal waves may propagate both horizontally and vertically. Internal wave generation, propagation, and dissipation provide important links among atmospheric forcing, low-frequency oceanographic flows, and small-scale dissipation and mixing.

I was fortunate to have access to both the appropriate instrumentation and a capable platform to make one of the first long-term measurements of internal waves beneath the drifting pack ice. The instrument was an Acoustic Doppler Current Profiler, or ADCP, and the platform the Arctic Environmental Drifting Buoy, or AEDB, conceived by Susumo Honjo of WHOI (the AEDB was similar in design to the Ice-Ocean Environmental Buoy described in the previous article). The ADCP was attached at a depth of 16 meters below the AEDB flotation sphere, and profiled currents between about 50 and 250 meters with a vertical resolution of 15 meters. The buoy was deployed about 430 kilometers from the North Pole by the German icebreaker

R/V ARNI FRIDRIKSSON



internal wave energy over the plateau was coincident with an increase in the diurnal (daily) tidal amplitude. We hypothesized that the interaction of the strong tide (50 times more energetic than in the Nansen Basin) with the rough, shallow topography of the plateau was responsible for generating internal waves at the ocean bottom. A similar conclusion was reached independently by Eric D'Asaro and Jamie Morison (University of Washington) from the analysis of profiling velocity measurements made from *Polarstern* prior to and after

Schematic diagram of the bottom generation of internal waves by tides. Strong tidal currents oscillating back and forth over rough, shallow topography produce upward-propagating wave groups.

Polarstern on August 4, 1987. During the next 140 days the buoy drifted with the pack ice across the Nansen Basin and over the Yermak Plateau. At the southwestern edge of the plateau, as the pack ice began to break up and the buoy moved rapidly into the Greenland Sea, strain gauges registered impacts sufficient to deform the steel flotation sphere. It was assumed that the sphere, floating in open water by this time, was partially crushed by neighboring ice floes during a rapid deceleration of the surface current. Despite the impacts, the sphere retained sufficient buoyancy to remain on the surface for recovery.

Analysis of velocity data from the AEDB showed that the internal wave field had a very different character over the Yermak Plateau than in the Nansen Basin. The Nansen Basin observations were consistent with general features of the arctic internal wave field reported by previous investigators, in that internal wave energy levels were significantly less than those typically observed at mid-latitudes. This reduction of internal wave energy in the Arctic has been ascribed to the presence of ice cover, which serves to damp out internal wave motions and inhibits the effectiveness of atmospheric storms and surface gravity waves as energy sources. However, internal wave energy levels increased dramatically as the buoy passed over the Yermak Plateau, even though the surface remained ice covered. Much of the increased energy was found to reside in isolated, upward propagating wave groups. The magnitude of the upward energy fluxes associated with these wave groups was as large as the downward fluxes observed in ice-free oceans.

A candidate for the internal wave energy source was identified when we recognized that the increase in

deployment of the AEDB. It is likely that the bottom-generated internal waves observed over the Yermak Plateau are variable in space due to a close link with bottom topography and intermittent in time due to variability of the tidal forcing.

This glimpse of oceanic velocities beneath the arctic pack ice has shown dramatic variations in internal wave energy over relatively short distances and provided evidence that the ocean bottom may be an important source of internal waves where the presence of ice inhibits surface generation mechanisms. Thus, although the energy levels of the arctic internal wave field may be lower in general than those of ice-free oceans, these levels are not necessarily lower everywhere. In fact, these results suggest that internal wave "hot spots" might be predictable from knowledge of the tides and the bottom topography. This remains an issue for future research.

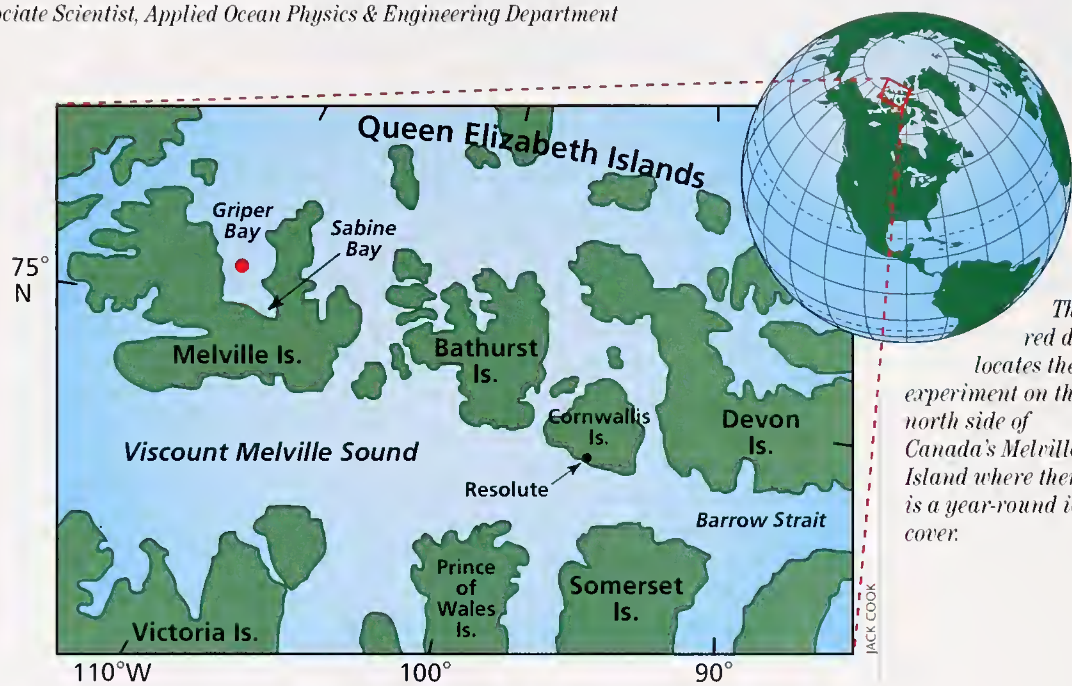
This work was funded by the Office of Naval Research. It was published in 1992 in an article entitled "Internal wave observations from the Arctic Environmental Drifting Buoy" (Journal of Geophysical Research, *Vol. 97, pages 12,619-12,638).*

Al Plueddemann was converted to an internal wave investigator and arctic oceanographer by the enthusiasm of his graduate advisor Rob Pinkel of the Scripps Institution of Oceanography. The dedication of Sus Honjo and Rick Krishfield to drifting buoy development has allowed Al to make his latest investigation of arctic internal waves via satellite telemetry. Having obtained a 23-month data set from a second-generation arctic buoy without ever leaving his office, he may have simultaneously set records for the longest internal wave time series in the arctic and the least arduous arctic expedition.

Acoustics Probe Sea-Ice Mechanics

Year-Long Tomography Experiment Measures Changes in Ice Properties

Subramaniam D. Rajan
Associate Scientist, Applied Ocean Physics & Engineering Department



The red dot locates the experiment on the north side of Canada's Melville Island where there is a year-round ice cover.

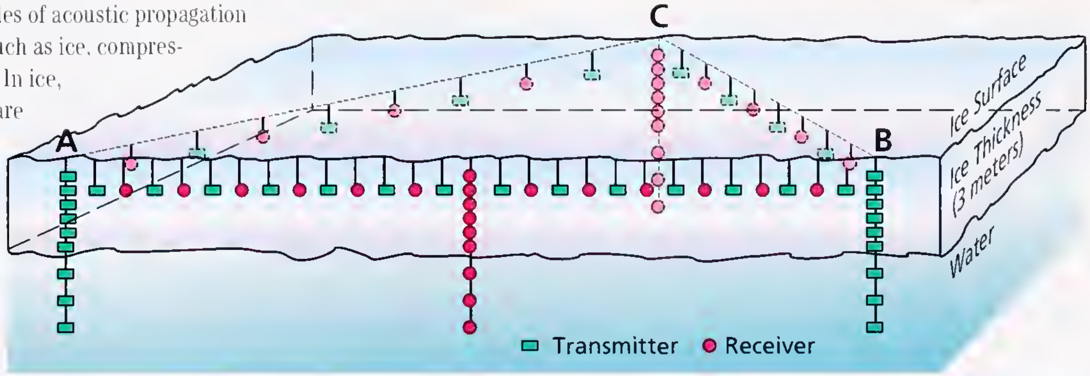
The nearly year-round Arctic Ocean ice cover controls heat exchange between the atmosphere and the ocean over a vast, important area of Earth's surface and thereby affects the planet's climate. In addition to climate considerations, there are also military and economic interests that motivate studies of the ice cover's mechanical properties, including seasonal growth and decay.

The traditional method for studying sea ice is examination of 3-inch-diameter cores taken from the ice cover. These ice-core studies show properties of sea ice to be functions of both space and time. While the spatial variability can be assessed by drilling a large number of cores, it is much more difficult to study the time variability, especially during the summer-melt phase. Use of acoustics can overcome this difficulty because the acoustical properties of sea ice are related to its mechanical properties, and high-resolution acoustic images provide insights into ice-strength characteristics. An acoustic system can be designed to operate unattended throughout the year in order to monitor the properties of a given volume of sea ice even during the summer melt period.

There are two primary modes of acoustic propagation through any elastic medium such as ice, compressional waves and shear waves. In ice, their speed and rate of decay are controlled by salinity, temperature, and density structures. From knowledge of these structures, we can make inferences about mechanical properties that are key to understanding the stability and failure modes of sea ice, and directly affect the design of and expectations for offshore structures and ships operating in the arctic environment.

Applying techniques developed for the water column in ice for the first time, we employed cross-hole tomography, which is in principle similar to CAT scans used in medical imaging. Holes were drilled in the ice to accommodate two vertical arrays of acoustic transmitters and two arrays of receivers in the triangular configuration shown below. Additional transmitters and receivers were placed along the paths between the vertical arrays. Then the time required for an acoustic pulse to travel from a transmitter to a receiver was experimentally determined. The travel time depends on wave speed along the

A triangular array of acoustic transmitters and receivers was placed in the ice for the year-long tomography experiment.



SUBRAMANIAM RAJAN

During a break in blizzardlike conditions, researchers prepare the ice for deployment of the array.

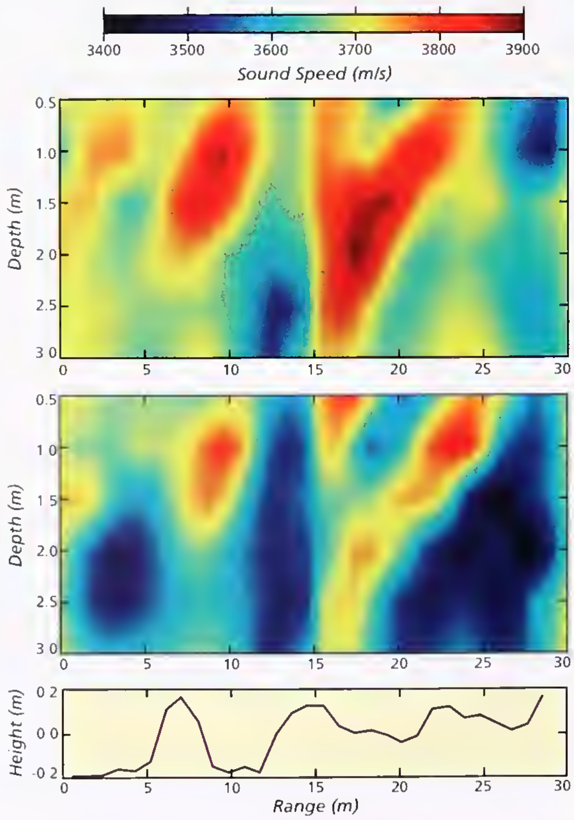
acoustic ray path, so assembly of travel-time information for all transmitter/receiver pairs provides images of the wave speeds in the ice, as well as information on surface topography and the structure of the water just beneath the ice cover. By repeating this experiment at different time periods, we obtained information on how the wave speeds—and the salinity, temperature, and density structure of the ice—change over time.

We conducted a multi-season, cross-hole tomography experiment in the Sabine Bay area of the Canadian Archipelago in 1992. Two considerations went into the selection of this site. The protected nature of the bay gave us a relatively flat stretch of ice free from pressure ridges and rubble fields, but more important, ice in this region remains intact even through the summer melt season, increasing the probability of monitoring summer changes in sea ice. The aim of the experiment was to obtain images of the wave speeds in sea ice in a three-dimensional volume and to monitor their changes over time. One of the obvious problems with conducting experiments in the Arctic is the adverse environment—during experiment set up, we encountered blizzardlike conditions for five consecutive days, with temperatures below -30°C and wind speeds over 40 knots (a wind chill factor of -110°C!).

The system commenced operation on April 1, 1992. It was designed to operate unattended, repeating a tomographic experiment at intervals of three days. Our home laboratory satellite monitor indicated that it stopped working on April 15. We scrambled a return to the site and reconnected wires that a polar bear had apparently pulled loose. When we recovered the arrays on April 1, 1993, we found that the system had collected data during the entire year except for the six-week "polar bear interval," from April 15 to May 31, 1992. Analysis of the data is still in progress, but some preliminary results are available.

The compressional wave speed structure in a vertical slice along the line corresponding to the base of the experimental triangle (A to B in the figure on page 27) is charted in the figure below with data for April 1, 1992, above and for June 18, 1992, below. Differences in wave speeds between the two plots largely reflect changes in temperature structure. Note the triangular region of high velocity at ranges between 15 and 20 meters. Coring carried out in this region indicated the presence of an inclined ice layer at this depth, probably the result of an ice fracture. The line graph below the color plots shows the variation in mean ice-surface height along the same line. Note here that depressions on the top surface correspond to the regions of higher wave speeds in the color plots, which reflect a salinity structure caused by melt water finding its way to the bottom of the ice to form under-ice melt ponds where it overlies the colder and denser seawater. Our experiment also allowed us to investigate melt-pond structure and its effect on the ice cover.

Further analysis of our data set will provide first-time, three-dimensional, field-data images of wave speeds and attenuation in sea ice as well as their time variability.



Contour plots show compressional wave speed on April 1, 1992 (top) and June 18, 1992 (bottom).

This work is funded by the Office of Naval Research.

Subramaniam Rajan writes: "I was born in the sunny city of Madras, India, where the three seasons are described as hot, hotter, and hottest. After an education in engineering, I worked for over two decades in a naval dockyard. As years went by, the desire to do research grew stronger, and I finally took the plunge in my late forties and traveled to the United States, where I entered the MIT/WHOI Joint Program and acquired a Ph.D. in oceanographic engineering. Since then I have been at the Woods Hole Oceanographic Institution, where one of my research areas is arctic acoustics. This interest has led me to spend time in very cold regions, and my folks back in India are amazed how one can live in sub-zero temperatures in a tent. But, then, they do not know the compensations!"

Arctic Infrastructure

The Need for Dedicated Arctic Research Support

Oceanographers Dream of Continuous Access North of the Arctic Circle

Richard F. Pittenger
Associate Director for Marine Operations

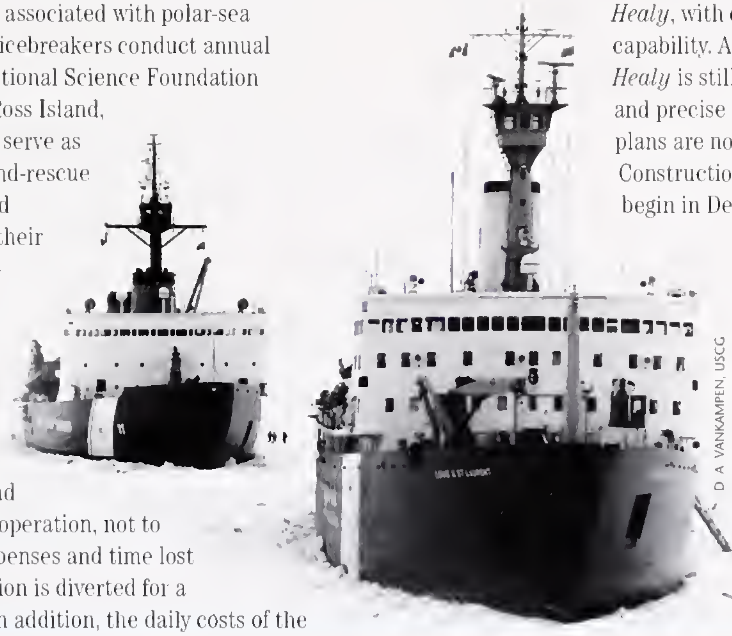
> *"Because the Arctic Ocean and its environs are remote, inhospitable, and sparsely populated, effective scientific research in this region is particularly dependent on the availability of research platforms such as icebreakers, ice-strengthened ships, and aircraft, and on other elements of research infrastructure including satellites, remote sensors, and specialized equipment."*
>
> —From *Icebreaker Arctic Research Vessels*, the report of a 1990 workshop on Arctic Ocean-Atmosphere-Ice Interactions (OAII)

The arctic workshop report quoted at right repeated a long-standing desire of the US ocean science community for a dedicated arctic research vessel. While American scientists have enjoyed use of US Coast Guard ice breakers and the excellent arctic research vessels of Germany, Sweden, and the USSR, the availability of both types of vessel for this community's work is always uncertain.

The disadvantages for science of the two arctic-capable Coast Guard icebreakers, *Polar Sea* and *Polar Star*, are generally rooted in the military nature of the Coast Guard, especially personnel turnover and conflicting mission priorities. Military units routinely experience very high turnover rates (one-third per year is the norm), which does not mesh well with the arctic science need for continuity when dealing with the steep learning curve associated with polar-sea operations. The two icebreakers conduct annual "break-ins" to the National Science Foundation research station at Ross Island, Antarctica, and they serve as emergency search-and-rescue vessels in ice-covered regions. As a result, their schedules are uncertain and often interrupted, which can be catastrophic for a scientist who has devoted a great deal of time to funding and planning a research operation, not to mention logistics expenses and time lost when a science mission is diverted for a military operation. In addition, the daily costs of the icebreakers are based on large crews (by research-ship standards) mandated by their military duties.

The Coast Guard has made a recent effort to improve its response to science needs. *Polar Star*, along with the Canadian icebreaker *Louis St. Laurent*, has just completed a mission to the North Pole (see inside back cover). *Polar Star* carried 81 officers and crew, and there were 33 in the scientific party. The wide-ranging science program included studies of Arctic Ocean biology and meteorology, sea-ice physics and chemistry, ice-borne sediment transport, and the geological and tectonic framework of the Amerasia Basin, as well as a ship technology program. In addition to upgrading science facilities on the polar-class ships to some degree, the Coast Guard has a contract to build a very large but moderately powered icebreaker, USCGC *Healy*, with considerable science capability. As of this writing *Healy* is still in the design phase and precise scientific outfitting plans are not yet complete. Construction was scheduled to begin in December 1994 with delivery planned for mid 1997.

As the Polar Class icebreakers approach the end of their expected service lives, the science community, led by the Fleet Improvement Committee of UNOLS —the Univer-



D A VANKAMPEN, USCG

The US Coast Guard's Polar Sea *(left) and Canadian Coast Guard's* Louis S. St. Laurent *were photographed near the North Pole during the Arctic Ocean Section '94 expedition.*

Construction of a new US Coast Guard icebreaker, Healy, *with considerable science capacity, was scheduled to begin in December 1994. The ship is expected to be in service in 1997.*

sity National Oceanographic Laboratories System—has expended considerable effort on a preliminary design concept for a dedicated (nonmilitary) Arctic Research Vessel (ARV). Its characteristics are shown opposite. The ARV will carry 34 to 36 scientists with a crew of 27 and have over 4,000 square feet of laboratory space and a complete suite of science winches, wires, and other instrumentation.

Arctic Research Submarines

Another intriguing, long-discussed approach to arctic research is use of a nuclear-powered submarine. Recognition of the unique match between the submarine's capabilities and the harsh arctic ocean conditions dates at least to the early 17th century, well before the invention of a practical submarine, when John Wilkes, a member of the British Royal Society wrote of a submarine: "Tis safe…from the ice and great frosts, which do much endanger passages toward the Poles. If may be unspeakable benefit for…experiments and discoveries." In the 1870 novel *Twenty Thousand Leagues Under the Sea*, the science fiction visionary Jules Verne not only recognized that the Arctic Ocean offered a unique transit route by having his submarine *Nautilus* cross the North Pole from the Atlantic to the Pacific, but also correctly foresaw that it would take an entirely new form of propulsion to make this feasible. The pioneer Norwegian polar scientist Fridtjof Nansen concluded in 1907 that while submarines "…would give excellent opportunity…" for polar research, the state of development was insufficient "…at least for the present."

An attempt was mounted in 1931 to use an excess World War I submarine, renamed *Nautilus*, in an expedition with noted oceanographer H.U. Sverdrup as science leader. This work was sponsored by the fledgling Woods Hole Oceanographic Institution, and published as five papers in a collection of monographs entitled *Papers in Physical Oceanography and Meteorology* (WHOI contribution numbers 1 through

U.S. Coast Guard Icebreaker *Healy*

Length (Overall)	*420 feet*
Beam (Extreme)	*82 feet*
Draft (Full Load)	*28 feet*
Displacement (Full Load)	*15,332 long tons*
Propulsion:	
Diesel Electric AC/AC Cycloconverter	
Shaft Horsepower/Screws	*30,000/2*
Sustained Speed	*12.5 knots*
Endurance	*16,000 nautical miles at 12.5 knots*
Icebreaking	*4.5 ft. at 3 knots*
Mission Profile:	
Ice Free Transit	*15 days*
Full Power Icebreaking	*12 days*
Half Power Icebreaking	*18 days*
Hove To/At Anchor	*20 days*

5). The project failed because the submarine design was not up to the rigors of arctic operations and because the Navy and the submarine crew had no expertise in this region. (There is a story that a crew member, apparently fearing for his life, actually sabotaged the submarine.) True arctic capability only emerged with the Cold War and the advent of nuclear power, special ice-hardening designs, and practical experience of frequent US Navy arctic operations.

In attempts to explain the role that a nuclear-powered submarine might play in arctic basin exploration, the word unique is inevitably used. Compared with other potential research platforms and methods, such as ice camps, aircraft, spacecraft, icebreakers, and remote sensing, the submarine uniquely can go anywhere, any time more or less independent of season, ice cover, and weather. The submarine uniquely could conduct detailed, systematic geological and geophysical surveys (bathymetry, gravity, magnetic, and seismic) of this hitherto virtually unsurveyed ocean basin. Uniquely, too, the submarine could measure ice characteristics and undertake water and bottom sampling programs.

There has been some progress toward using submarines for arctic research. In 1993, for the first time, a science party of five was embarked in a US nuclear submarine, USS *Pargo,* for unclassified, dedicated science. This very successful pilot program was followed by promises of more research programs, and a memorandum of agreement among several government agencies has recently been signed to "facilitate the use of US Navy submarines for science in the Arctic." The signatories believe that submarines are "invaluable (arctic) research platforms." Plans call for one cruise per year over a five-year period beginning in 1995.

A much more ambitious program, is being discussed for a "White Submarine"—a Navy-crewed ship, with no military mission, dedicated to oceanic scientific investigations and technology developments for the national and international communities. This concept would take advantage of a rapidly closing window of opportunity to utilize these assets before age and Navy budget pressures close the window, perhaps forever: All of the submarines that might be used for this purpose will come up for decommissioning over the next few years. Many questions remain to be answered, most involving financial issues, but the prospect of employing a nuclear submarine to support ocean research is very exciting.

Arctic/Antarctic Infrastructure Imbalance

As the articles in this issue of *Oceanus* attest, more than seagoing capability is required for significant arctic research. Though it can hardly be argued that arctic science is less important than antarctic science, there is a vast difference in facilities for extreme northern and southern research efforts. National Science Foundation (NSF) support for US antarctic science includes:

• Three permanent, year-round bases that include logistic facilities such as aircraft runways and services, ground transportation, housing, roads, and science laboratories at McMurdo/Ross Island, on the Antarctic Peninsula, and at the South Pole, plus numerous small, seasonal encampments for specific scientific programs. *(There are no permanent camps or bases in the Arctic Ocean.)*

• Seven LC130 ski-equipped Hercules aircraft and six helicopters flown by specially trained Navy crews. In addition, NSF annually arranges personnel and supply transport by larger US Air Force C-140s and occasionally C-5s, and for New Zealand aircraft to make logistics flights from Christ Church. *(The Arctic has no permanently assigned aircraft, though commercial transportation is available on land.).*

• A full suite of long-haul, short-haul, and satellite communications connects all of the science posts and aircraft. Polar orbiting satellites provide science data and weather. *(The Arctic has no dedicated communications facilities for science.)*

These facilities are in addition to two dedicated research vessels, *Polar Duke* and *Nathaniel Palmer,* that are leased for antarctic research, annual Coast Guard icebreaking at McMurdo, and arrangements for bulk cargo ships that carry food, fuel, and supplies.

Funding

What about funding all these expensive science programs and their logistics? There is no question that the conduct of research, especially oceanography, in arctic environs is very expensive and that expense is driven by the cost of the logistics infrastructure required for safe and effective research. There is also no question that the level of funding presently available is inadequate and would certainly be inadequate if not attended by concomitant increases. To illustrate this point, in 1993 the National Science Foundation funded a grand total of $6,434,292 for Arctic Marine Sciences, of which $726,483 was for facilities. An adequate Arctic Research Vessel alone

Arctic Research Vessel

Length Overall	*343 feet*
Design Load Waterline (DWL)	*309 feet*
Beam:	
Maximum, main deck at reamer	*90 feet*
Amidships, main deck	*84 feet*
Depth	*38 feet*
Draft:	
At DWL	*28 feet*
Maximum Endurance	*30 feet*
Displacement:	
At DWL	*10,500 LTSW*
Maximum Endurance	*11,840 LTSW*
Class	*ABS Ice Class A3*
Propulsion Horsepower	*16,000 BHP*

UNOLS, an association of operators and users of the US academic fleet, has assembled a preliminary design concept for an Arctic Research Vessel.

will cost at least $7 million per year to operate and $150 million to build.

More funding will be needed if any of the changes in infrastructure discussed above are to occur. As it is, NSF chronically underfunds non-Arctic US research fleet ship time by about 10 percent ($4 to $5 million of a proposed $55 million annual budget). Facilities funding is dominated by large-ship costs that run $4 to $4.5 million per year. A truly capable Arctic Research Vessel will cost two or three times more to operate than conventional large research ships. Since the ARV would replace the intermediate-size R/V *Alpha Helix* (operated by the University of Alaska at an annual cost of about $1.5 million), there would be a net increase in NSF ship costs of at least two large-ship equivalents.

Recommendations

Given the many cogent statements of arctic research priorities and needs, the US should implement a National Arctic Research Plan that bounds the problem, sets goals and priorities, and establishes funding mechanisms for infrastructure acquisition and operation as well as for science. In the process, we must decide whether we intend to continue doing Arctic research in the present mode—or do it right.

A National Science Logistics and Infrastructure Plan based on the National Arctic Research Plan, would include research vessels capable of safe and effective operations in the high arctic as well as in the marginal seas and ice zones. Both modern-design surface ships and excess Cold War submarines should be considered. Since these facilities are very expensive to procure and operate, some very serious decisions are needed, based on need, affordability, and opportunity costs. The nation must deal with the three US Coast Guard icebreakers (*Polar Sea*, *Polar Star*, and the new *Healy*) and decide which, if any, are to be used for science and at what cost to science. These three ships are facts. Then comes the fancy—the academic community's dream Arctic Research Vessel. Is it needed? Is it affordable? Do we need it now or could it wait? And finally, we must not let slip away the opportunity to capitalize a potential major post-cold-war dividend, a nuclear submarine. Whereas building such a vessel is far beyond reach, the cost of converting and operating one is not.

The community's surface ship needs could be met in the near-term by US Coast Guard vessels and expansion of the Coast Guard's recent efforts to satisfy its science customers. The Coast Guard should consider civilianizing its icebreakers to overcome the significant turn-over problem, and the cost of operation should be subsidized so that science only pays reasonable science-related costs.

Unless an infusion of significant amounts of "new" Arctic research funding are guaranteed, procurement of the Arctic Research Vessel should be deferred for a decade. In that decade, a "de-fanged," arctic-capable, US Navy-operated, converted nuclear submarine could fulfill science needs and conduct a detailed mapping survey (bathymetry, magnetics, gravity) as well as ice, water, and bottom studies. Unless we seize this opportunity, the submarines will be scrapped and the opportunity lost. The Navy, US Geological Survey, National Oceanic Atmospheric Administration, Minerals Management Service, and National Science Foundation could cooperatively support this effort, which should be comparable to the avoided cost of the ARV. An absolutely firm Navy commitment must precede this recommended course of action.

The arctic regime requires a different set of air logistics assets than those servicing Antarctic science; therefore, balancing the air services between poles is not a simple matter of using the same aircraft seasonally in both the north and south polar regions. There should be careful assessment of replacement of the hodgepodge of military and private US and foreign aircraft currently providing arctic air logistics. These assets should provide heavy-lift to forward-staging sites and then onward-lift to science sites such as ice camps and ice-science sensor platforms.

Arctic communications and data telemetry are both spotty to regionally nonexistent at present. Decent remote sensing is dependent upon telemetry data links, and safe and effective remote-area science and logistic support requires much better connectivity than is currently available in the arctic region.

Dick Pittenger served in the US Navy for 37 years, counting enlisted reserve, Naval Academy, and commissioned service. As a surface ship officer, he specialized in applied oceanography, also known as antisubmarine warfare (ASW). Rear Admiral Pittenger's polar-related endeavors included planning the largest-ever marginal ice zone, multiplatform ASW exercise; sponsoring several classified arctic research programs; and, as Oceanographer of the Navy, conducting the most extensive post-World War II study of Navy requirements for icebreakers and acting as executive agent for the Navy's logistic support to National Science Foundation in Antarctica (Operation Deep Freeze). After retirement from the Navy, he joined WHOI as Arctic Research Coordinator and later became Associate Director for Marine Operations.

STEVE WHEELER

WHOI Engineer Elizabeth Osborne stands on the Arctic ice during the final leg of the historic North Pole crossing voyage.

Icebreakers Transit Arctic For Global Climate Studies

An historic North Pole crossing was accomplished August 22, 1994, by US and Canadian Coast Guard icebreakers during a voyage for an environmental arctic research program. Arctic Ocean Section '94 was the culmination of four years of joint planning by US and Canadian agencies, and researchers from more than 20 institutions participated in the study. Their objective was to make shipborne observations in the world's least studied ocean toward understanding the processes that drive global climate change.

Research programs ranged from atmospheric measurements for studies of how the world's heat budget is affected by arctic freezing and melting to collection of seafloor sediments for historical studies of arctic climate over the past 2.6 million years.

WHOI Engineer Elizabeth Osborne from the laboratory of Associate Scientist Glenn Jones participated in the cruise to collect sediment samples for analysis at WHOI's National Ocean Sciences Accelerator Mass Spectrometer Facility. This work will help to reconstruct arctic environmental conditions over the last 50,000 years.

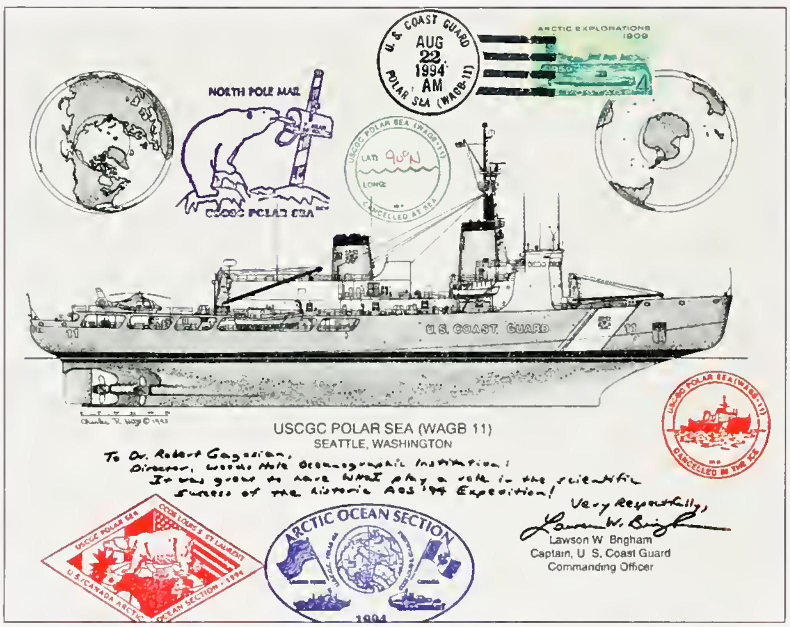
Captain Lawson W. Brigham, Commanding Officer of the US icebreaker *Polar Sea*, has had a long association with WHOI. He was in residence as a Research Fellow at the Marine Policy Center in 1989 and 1990 when his arctic studies included the Soviet maritime Arctic and the northern sea route.

BONNIE MACE

Polar Sea *Commanding Officer Lawson Brigham and Elizabeth Osborne congratulate one another upon their arrival at the North Pole*

ELIZABETH ORSBORNE

Elizabeth Orsborne used a box corer to collect sediment samples during the historic 1994 crossing of the North Pole. The 1-to 2-meter-thick ice packed around the Polar Sea's *hull made deployment and recovery of the instrument particularly difficult.*



A certificate of appreciation for WHOI participation in the polar crossing was sent to WHOI Director Robert Gagosian by Polar Sea *Captain Lawson Brigham. It bears a likeness of* Polar Sea *and various ship, expedition, and US postage stamps.*

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