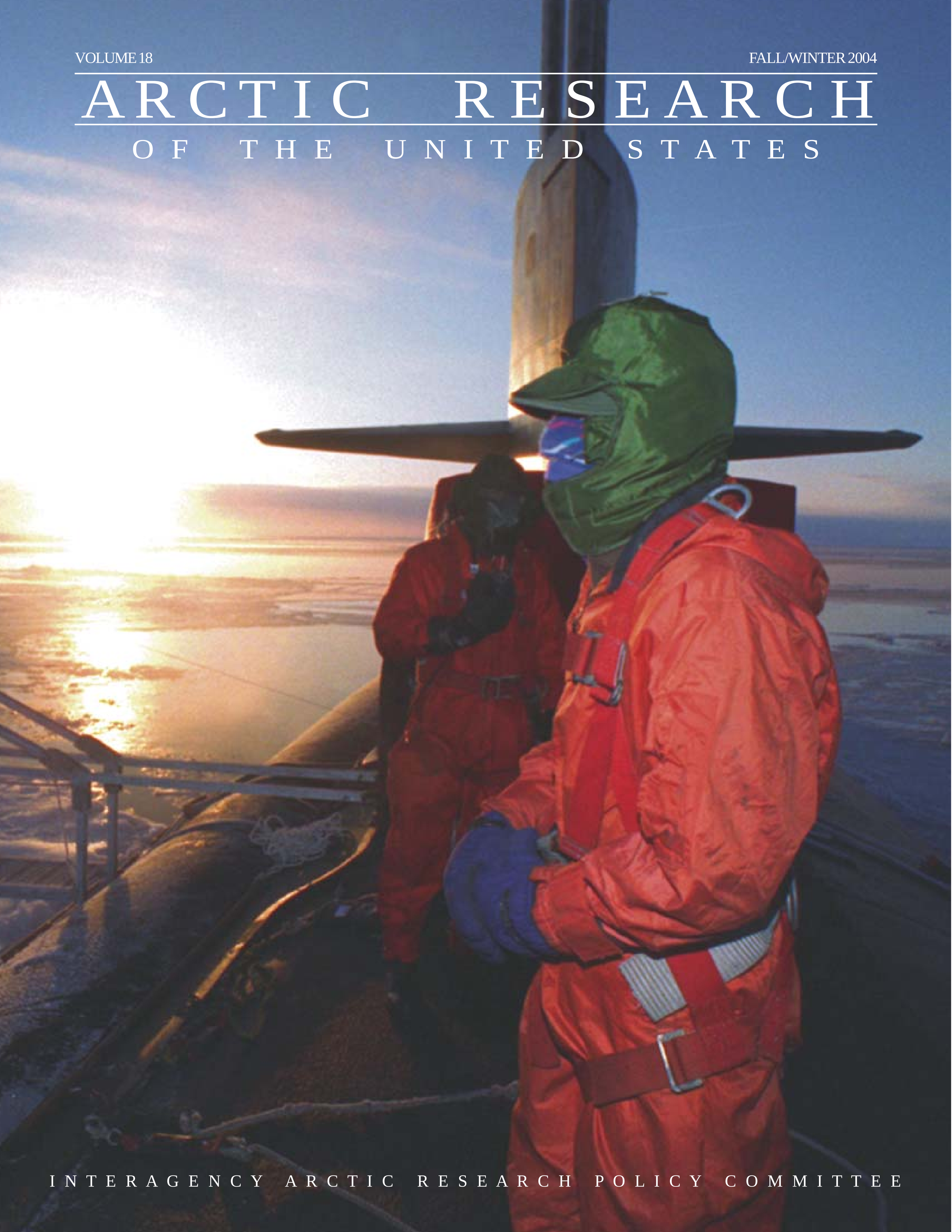
VOLUME 18 FALL/WINTER 2004

ARCTIC RESEARCH

OF THE UNITED STATES



INTERAGENCY ARCTIC RESEARCH POLICY COMMITTEE

About the Journal

The journal *Arctic Research of the United States* is for people and organizations interested in learning about U.S. Government-financed Arctic research activities. It is published semi-annually (spring and fall) by the National Science Foundation on behalf of the Interagency Arctic Research Policy Committee (IARPC). The Interagency Committee was authorized under the Arctic Research and Policy Act (ARPA) of 1984 (PL 98-373) and established by Executive Order 12501 (January 28, 1985). Publication of the journal has been approved by the Office of Management and Budget.

Arctic Research contains

- Reports on current and planned U.S. Government-sponsored research in the Arctic;
- Reports of IARPC meetings; and
- Summaries of other current and planned Arctic research, including that of the State of Alaska, local governments, the private sector, and other nations.

Arctic Research is aimed at national and international audiences of government officials, scientists, engineers, educators, private and public groups, and residents of the Arctic. The emphasis is on summary and survey articles covering U.S. Government-sponsored or -funded research rather than on technical reports, and the articles are intended to be comprehensible to a nontechnical audience. Although the articles go through the normal editorial process, manuscripts are not refereed for scientific content or merit since the journal is not intended as a means of reporting scientific research. Articles are generally invited and are reviewed by agency staffs and others as appropriate.

As indicated in the U.S. Arctic Research Plan, research is defined differently by different agencies. It may include basic and applied research, monitoring efforts, and other information-gathering activities. The definition of Arctic according to the ARPA is “all United States and foreign territory north of the Arctic Circle and all United States territory north and west of the boundary formed by the Porcupine, Yukon, and Kuskokwim Rivers; all contiguous seas, including the Arctic Ocean and the Beaufort, Bering, and Chukchi Seas; and the Aleutian chain.” Areas outside of the boundary are discussed in the journal when considered relevant to the broader scope of Arctic research.

Issues of the journal will report on Arctic topics and activities. Included will be reports of conferences and workshops, university-based research and activities of state and local governments and public, private and resident organizations. Unsolicited nontechnical reports on research and related activities are welcome.

Address correspondence to Editor, *Arctic Research*, Arctic Research and Policy Staff, Office of Polar Programs, National Science Foundation, 4201 Wilson Boulevard, Arlington, VA 22230.

Front Cover

During an Arctic sunrise on board the U.S. Navy’s attack submarine USS Pogy*, Navy Lieutenant Junior Grade Mark Cronley stands watch as a safety observer during a water collection procedure.The* Pogy *returned to Hawaii, on November 12, 2000, after a 45-day research mission to the North Pole. The second of five planned deployments through the year 2000,* Pogy *embarked with a team of researchers led by Ray Sambrotto of Columbia University. During the several-thousand-mile trek, the submarine collected data on the chemical, biological, and physical properties of the Arctic Ocean and conducted experiments in geophysics, ice mechanics, pollution detection, and other areas. For the purposes of this voyage, a portion of the submarine’s torpedo room was converted into laboratory space. However, at no time was the ship removed from front-line warship status.*

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The Office of Naval Research in the Arctic: History, People, Accomplishments, Legacy

The ONR High Latitude Dynamics Program

An Introduction

This article was prepared by Dennis M. Conlon, Office of Naval Research and Office of Polar Programs, National Science Foundation, and Thomas B. Curtin, Office of Naval Research.

The complete history of the Arctic Program lies in the scientific literature and in the numerous successful naval missions accomplished. Art Baggeroer, Andy Heiberg, Ken Hunkins, Leonard Johnson, Ned Ostenso, Norbert Untersteiner, and Willy Weeks contributed significantly to this article, which borrowed substantially from Thomas Curtin's 1998 article, "Historical Perspectives on the Arctic Program at the Office of Naval Research," published in Naval Research Reviews, *vol. L, no. 1.*

From a historical perspective, there have been three stages of the U.S. Navy's interest in the Arctic. The first stage was marked by exploration, driven by personalities like Robert Peary (first to reach the North Pole), Robert Byrd (first to fly over the Pole), Lincoln Ellsworth (with Roald Amundsen, first to fly over the Pole in a dirigible), and Elisha Kent Kane (multiple Arctic expeditions). The second stage was characterized by more focused investigations and classified operations, framed by the Cold War and the advent of the nuclear submarine. The Office of Naval Research (ONR) was established in 1946 at the beginning of this second stage, and it immediately began supporting research in the Arctic. The third and current stage, marked by waning military interest, began with the end of the Cold War.

At first, Arctic research at ONR was supported by the Environmental Biology Program, but after a few years it migrated to the Geography Programs before finally becoming an independent Arctic Science Program in 1954.* Singular among Federal research programs in any field, the ONR Arctic Program has been managed by just seven people spanning over fifty years. The tradition of proactive, involved managers was established early, as documented in one of the program's first publications:

> "The Office of Naval Research has many Arctic experts working on various phases of its Arctic research program. Several of these men have contributed to this pamphlet. Sir Hubert Wilkins has written a valuable introduction and Dr. Vilhjalmur Stefansson has compiled a useful bibliography on Arctic literature. The main article of the pamphlet was written by Dr. M.C. Shelesnyak, Head of the Environmental Physiology Branch, Office of Naval Research. Dr. Shelesnyak gathered material about the Arctic as United States Naval Observer with the Moving Forces, Canadian Army Winter Arctic Expedition, Operation Musk-Ox, in 1945. The expedition traveled by motorized, tracked vehicles 3100 miles across the Canadian Arctic prairies, Queen Maude Gulf, Coronation Gulf and southward from Coppermine to Port Radium, across Great Bear Lake and down through the bush country along the Alaskan–Canadian Highway to Edmonton. Dr. Shelesnyak's first-hand knowledge of the Arctic was further broadened by his experiences in traveling by dog sled from Coppermine N.W.T. to Cambridge Bay, Victoria Island, having left the Moving Forces to rejoin them later."†

A very early initiative of ONR was building the Arctic Research Laboratory (later named the Naval Arctic Research Laboratory) near Barrow, Alaska, in 1947. With the construction of the USS *Nautilus*, the first nuclear-powered submarine, and its later transit of the Arctic Ocean, the importance of Arctic research was recognized at the highest levels of the Navy and the government. The perception of a growing threat from the Soviet Union sharply increased interest. At first, the concern was with Soviet submarines transiting the Greenland–Iceland–Faroe Gap to take up stations in the western Atlantic Ocean; later, the impetus for Arctic research came with the construction of the Typhoon Class, which could surface through the Arctic ice pack loaded with ICBMs.

Program managers of the Arctic Program since its inception at the Office of Naval Research.

1947–1954	M.C. Shelesnyak
1954–1970	M.E. Britton
1970–1975	R. McGregor
1975–1984	G.L. Johnson
1984–1994	T.B. Curtin
1994–1996	M. Van Woert
1996–2003	D. Conlon

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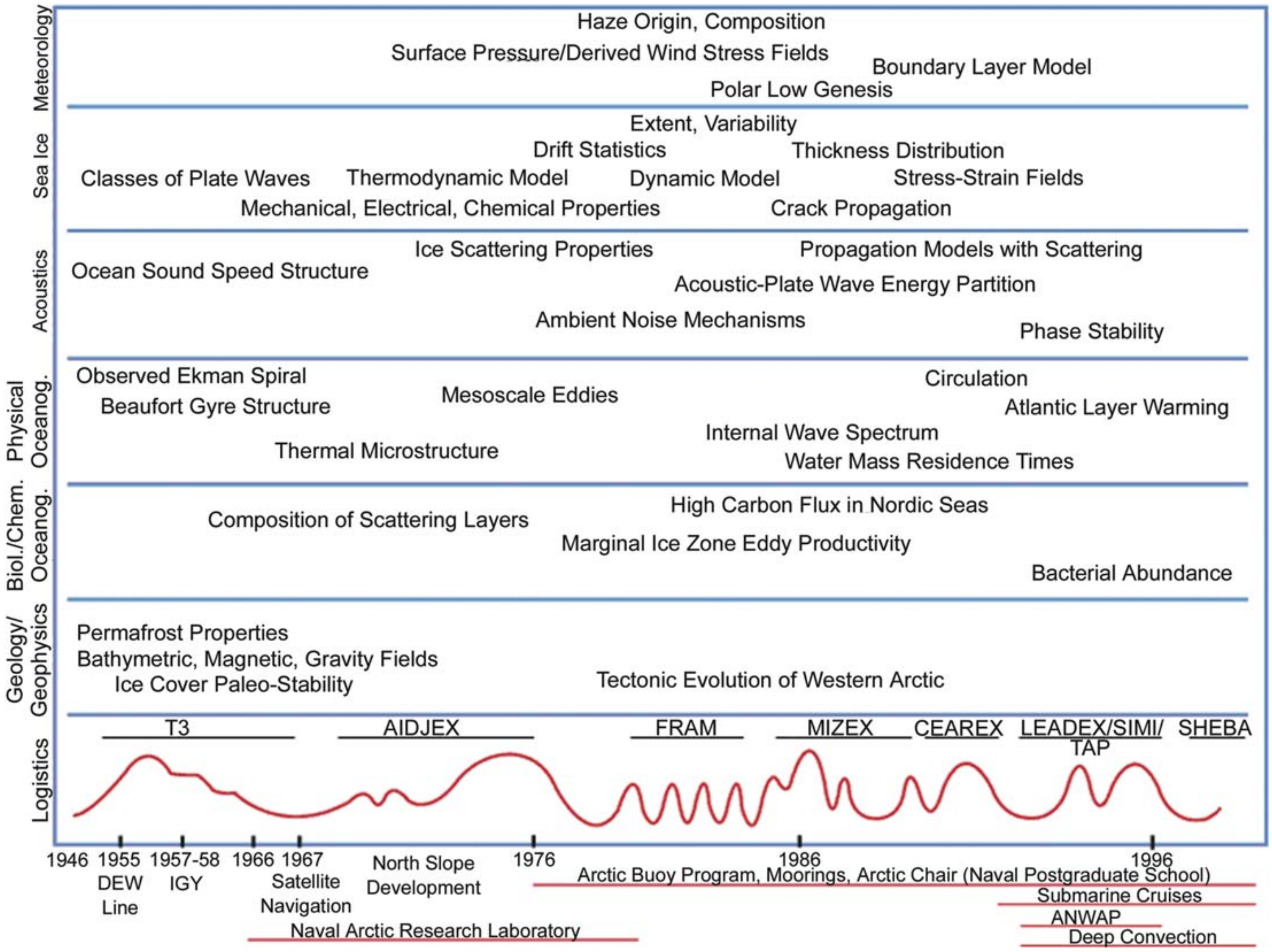
* See Maxwell Britton (2001) The role of the Office of Naval Research and the International Geophysical Year (1957-58) in the growth of the Naval Arctic Research Laboratory." In *Fifty More Years Below Zero*, Arctic Institute of North America.

† Shelesnyak, M.C., and V. Stefansson (1947) Across the top of the world, A discussion of the Arctic." Office of Naval Research, Navy Department, NAVEXOS P-489, Washington, D.C.



A few of the major insights by discipline achieved over the years of the Arctic Program at the Office of Naval Research. The curve at the bottom shows the relative activity of ice stations.

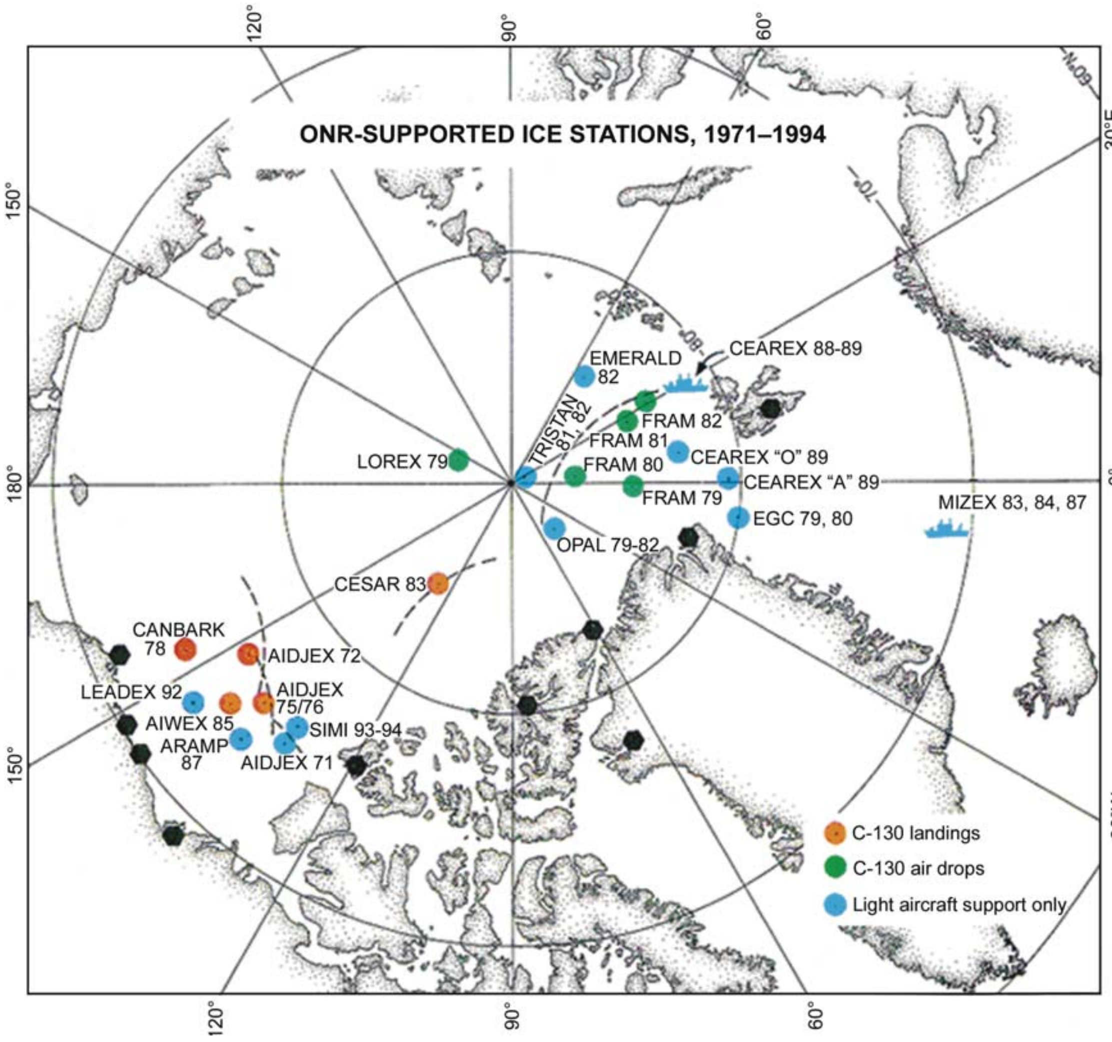
The Arctic Sciences Program became the leader in Arctic research in the Western world, paralleling the Soviet effort with its North Pole Stations and aircraft landings in the Arctic Seas, with the Arctic Ice Dynamics Joint Experiment (AIDJEX), a program largely stimulated by Dr. Norbert Untersteiner of the University of Washington. A veteran of the International Geophysical Year, Untersteiner convinced ONR to investigate how ice deforms in response to external stresses. The program began in 1970 with a pilot ice camp, and other efforts gradually built up to the peak effort in the summer of 1975, when four ice camps were built, surrounded by a constellation of data buoys that acquired data until the spring of 1976. During the following two decades, ONR initiated a series of large international field programs, including CANBAREX, FRAM I–IV (1979–1981), the Marginal Ice Zone Experiment (MIZEX, 1983-84, 1987), the Coordinated Eastern Arctic Experiment (CEAREX, 1987-88), the Leads Experiment (LEADEX, 1992), and the Sea Ice Mechanics Initiative (SIMI, 1993-94). Other major initiatives included Arctic Acoustics and Real-Time Environmental Arctic Monitoring (RTEAM).

The last major experimental effort supported by ONR was as a partner with the National Science Foundation in the Surface Heat Budget of the Arctic Experiment (SHEBA, 1997-98), in which the Canadian icebreaker *Des Grosselliers* was frozen into the pack ice and allowed to drift for 14 months. SHEBA focused on two feedback processes: ice–albedo feedback (increasing melt decreases albedo, further increasing melt) and cloud–albedo feedback (increasing melt increases clouds, increasing albedo and decreasing melt). Investigators were ferried on and off the SHEBA site, typically spending a few weeks performing research at one of several satellite structures surrounding the ship. Chief Scientists Richard Moritz and Don Perovich led an international team that developed a remarkable camaraderie during the year on the ice. According to Perovich, it was a common experience at mealtime to hear the words, "I saw the coolest thing today…."

Measures of the more than fifty years of research supported by the program are the associated cumulative scientific literature and the strategy and tactical procedures, both military and commercial, influenced by that knowledge. A comprehensive bibliography has not been compiled but would no doubt be impressive. These are a few of the major insights achieved over the years:

- Atmospheric circulation patterns and pollutant (haze) pathways are now well established.
- The mechanical, electrical, and chemical properties of sea ice, as well as its dynamics and thermodynamics over a hierarchy of scales, are known well enough to enable predictive models with some skill.
- The statistics of sea ice extent, variability, and drift, and to some degree its thickness, have been determined.
- The propagation of sound, at both low and high frequencies, including scattering and transformation into a rich class of plate waves, some of which were discovered initially in the Arctic, can now be modeled accurately.
- Ambient noise mechanisms have been established.
- The Ekman spiral, derived theoretically, was first observed in the Arctic, as was thermal microstructure.
- The ocean circulation, including water mass residence times and mesoscale eddy distributions, is now generally known.
- Unique aspects of the internal wave spectrum have been documented.
- The high primary productivity in the marginal ice zone has been quantified and its mechanisms elucidated.
- The Nordic Seas have been determined to be carbonate- (rather than silicate-) dominated, affecting global carbon sequestration.

Ice stations supported by the Office of Naval Research from 1971 through 1994.



- Near-surface bacterial abundance at high latitude is far greater than previously thought.
- The properties of permafrost are known and were used to great advantage in pipeline construction.
- Bathymetric, magnetic, and gravity fields have been mapped to useful resolution.

Understanding how much there is yet to be understood is always sobering. However, the contrast between the knowledge of the Arctic marine environment in 1945 and today gives an appreciation of how much has been accomplished.

Logistics has always been inextricable from science in the Arctic. Ice stations or camps have been central ways of doing business since Nansen pioneered the method with the *Fram*. During peak years, logistics costs typically ranged from $2 to 4 million, consuming 20–40% of the program budget. From the mid-sixties to the late seventies, many expeditions in the western Arctic were staged from the Naval Arctic Research Laboratory. Eastern Arctic stations were staged from Greenland or Norway. Since the Navy's divestiture of NARL to the North Slope Borough in the late seventies, there has been a slow but steady trend toward autonomous instrumentation. That trend is expected to accelerate in the coming years, with advances in microprocessor, navigation, and communication technology. Considering the number and diversity of people involved, the variability and extremes of nature, the remote and Spartan accommodations on the ice, and the invariably tight budgets, it is a notable tribute to the operations managers over the years that all have returned safely to analyze their data. One of the constants of experiments from AIDJEX on was the participation of Andy Heiberg of the Polar Science Center of the University of Washington; he has received awards from both ONR and NSF for his contribution to the logistics of Arctic research.

With the fall of the Soviet Union and the disappearance of an ICBM threat under the Arctic ice, support within the U.S. Navy for Arctic research began to decline, a process that accelerated in the late 1990s until the termination of the program in 2003. Ironically, it was the decline of a threat that also allowed the U.S. Navy to provide a nuclear attack submarine for Arctic research during the period 1993–2001, the SCICEX Program (described in detail in the article on p. 14, this issue).

Beginning in the mid-1990s, the decline in the program's funding was dramatic; in 1995 the Arctic Program funding was approximately $25 million (including a special $10 million appropriation for the Arctic Nuclear Waste Assessment Program, ANWAP), was managed by a staff of five program officers, and supported around 100 investigators. By 2003 the program was funded at less than $2 million, supported fewer than 30 investigators, and was managed by a single program officer. In fact, the impact on the field was far greater. In 1995 the average award of nearly $250 thousand paid for a significant fraction of the investigator's time and usually included a graduate student. Moreover, it was normal to be funding a major field effort every two or three years. By 2003 the average award of less than $70 thousand bought a month or two of the investigator's time, and field work was usually dependent on another agency's initiative.

Building on high-quality, multi-disciplinary investigations, key elements of the program, established at its inception and maintained for over a half century, were international collaboration, bold field experiments, development and use of innovative technology, and support of graduate students. The research community has lost a program to which they could come with innovative, risky ideas and pursue those ideas expeditiously in partnership with a fully engaged sponsor. In many ways, this engagement was the ONR paradigm envisioned by its founders.

What of the future for Navy interest in Arctic research? The simple answer is that the interest will be dictated by the need for missions in the Arctic, and future missions are difficult to predict. Dramatic environmental changes are clearly underway at polar latitudes, especially in the Arctic, and some projections predict economically useful openings of the Northern Sea Route and perhaps even the Northwest Passage. The need for enlightened leadership and a prescient investment strategy is acute.

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The ONR Chair in Arctic Marine Science at the Naval Postgraduate School

This article was prepared by Robert Bourke, Naval Postgraduate School.

The Naval Postgraduate School (NPS) Chair in Arctic Marine Science was initiated in 1976, largely through the efforts of Ron McGregor, then head of the Arctic Research Program at the Office of Naval Research, and Warren Denner, then of the NPS. The objectives of the Chair, throughout its existence, were to conduct polar research and assist in translating basic knowledge into operational products and to inculcate an interest in polar science in NPS students in order to provide the Navy with a cadre of officer and civilian polar experts.

Over the course of the Chair's existence, the Chairholders represented a broad spectrum of countries, universities, labs, and disciplines. Five came from other countries: Allen Milne from Canada, Peter Wadhams from England, Ola Johannessen and Arne Foldvik from Norway, and Ursula Schauer from Germany. Government laboratories were represented by Alan Beal of the Arctic Submarine Laboratory, Willy Weeks and Steve Ackley from the U.S. Army Cold Regions Research and Engineering Laboratory, and John Newton from the Navy Research and Development Activity. Private consultant and small business Chairs were Miles McPhee, Bob Pritchard, Jim Wilson, and Max Coon.

When categorized by scientific discipline, the largest preponderance, not surprisingly, were associated with sea ice; in this category, I have placed Warren Denner, Willy Weeks, Peter Wadhams, Steve Ackley, Bob Pritchard, Alan Thorndike, Bill Hibler, Martin Jeffries, Mark Johnson, and Max Coon. Their studies mainly dealt with the mechanics, properties, strength, thickness, and temporal and spatial distribution of ice. The study of the underlying ocean was the focus of work by Arne Foldvik, Joe Niebauer, Jamie Morison, Miles McPhee, Ursula Schauer, and, if we also associate the specialty of remote sensing, Ola Johanessen and Lawson Brigham. The lone Antarctic oceanographer was, of course, Arnold Gordon. The Navy has had a long and intense interest in acoustic propagation and noise generation in the polar seas, tied to its interest in submarine operations in ice-covered waters and the conduct of antisubmarine warfare (ASW). This group of scientists included John Newton, Jim Wilson, Allen Milne, Alan Beal, and Warren Denner. The lone biological oceanographer who occupied the Chair was Walker Smith, but he was well known for his interactions with physical oceanographers. Climate variability was the focus of John Walsh and Andrey Proshutinsky.

Some remarks are in order on the typical experience of a Chairholder. All enthusiastically enjoyed their tenure at the NPS in Monterey. Most found time to complete long-overdue manuscripts, to thoughtfully examine old and recent data sets, or to participate in planning future field projects. It was no coincidence that Chairholders played prominent roles in the early planning of the Marginal Ice Zone Experiment (MIZEX) and follow-on experiments such as the Coordinated Eastern Arctic Experiment (CEAREX) and the Leads Experiment (LEADEX). Many Chairs served as thesis advisors for Naval Officer students, and their expertise was highly sought after by both faculty and students.

I believe that the original goals of the Arctic Chair were consistently met. The U.S. Navy developed a pool of officers who had a strong appreciation for the impact of the Arctic environment on all aspects of naval operations, and many of these officers went on to occupy positions of technical and strategic importance at the National/Naval Ice Center, the Office of Naval Research, the Naval Research Laboratory, and other commands.

Occupants of the ONR Arctic Marine Science Chair

1976-77	**Warren W. Denner**	Naval Postgraduate School	(Ice Dynamics/Mechanics)
1977-78	**Alan M. Beal**	Arctic Submarine Laboratory	(Sea Floor Bathymetry)
1978-79	**Wilford (Willy) F. Weeks**	Cold Regions Research and Engineering Lab	(Ice Mechanics)
1979-80	**Allen R. Milne**	Institute of Ocean Sciences (Canada)	(Acoustics/Ambient Noise)
1980-81	**Peter Wadhams**	Scott Polar Research Institute (England)	(Ice-Wave Interaction)
1981-82	**Ola M. Johannessen**	University of Bergen (Norway)	(Marginal Ice Zone)
1982-83	**Miles G. McPhee**	Private Consultant	(Ice-Water Boundary Layer)
1983-84	**Walker O. Smith**	University of Tennessee	(Ice Edge Biology)
1984-85	**Joseph Niebauer**	University of Alaska	(Ice Dynamics)
1985-86	**Stephen A. Ackley**	Cold Regions Research and Engineering Lab	(Ice Mechanics)
1986-87	**John E. Walsh**	University of Illinois	(Sea Ice Variability)
1987-88	**Robert S. Pritchard**	Private Consultant	(Ice Dynamics)
1988-89	**Arne Foldvik**	University of Bergen (Norway)	(Ocean/Ice Shelf Interaction)
1989-90	**James H. Morison**	University of Washington	(Ice Boundary Layer Dynamics)
1990-91	**John L. Newton**	Private Consultant	(Arctic Antisubmarine Warfare)
1991-92	**Alan S. Thorndike**	University of Puget Sound	(Sea Ice Physics)
1992-94	**James H. Wilson**	Private Consultant	(Arctic Ambient Noise and Antisubmarine Warfare)
1994-95	**Arnold L. Gordon**	Lamont-Doherty Earth Observatory	(Antarctic Circulation)
1995-96	**Lawson W. Brigham**	CAPT, U.S. Coast Guard (Ret.)	(Ice Operations, Remote Sensing)
1996-97	**William D. Hibler, III**	Dartmouth College	(Sea Ice Modeling)
1997-98	**Martin O. Jeffries**	University of Alaska	(Sea Ice Processes)
1998-99	**Andrey Proshutinsky**	University of Alaska	(Arctic Climate Modeling)
1999-00	**Ursula Schauer**	Alfred Wegener Institut (Germany)	(Arctic-Subarctic Fluxes)
2000-01	**Mark Johnson**	University of Alaska	(Sea Ice Processes)
2001-02	**Max Coon**	Private Consultant	(Sea Ice Modeling)

Recent Evolution of Techniques for Studying the Physical Oceanography and Sea Ice of the Arctic Ocean

This article was prepared by Robin Muench of Earth and Space Research, Seattle, Washington.

Dramatic progress has been made over the past quarter century in our understanding of oceanographic and sea ice processes in the Arctic Ocean. The availability of new platforms, including highly capable icebreaking research vessels, remote instrumented buoys, and satellites, has allowed us to observe in detail those processes that dominate this climatologically crucial, and observationally difficult, part of the global ocean. Technological advances have allowed miniaturization of highly reliable components with low power usage, leading in turn to packaging of entire sensor and computer systems within autonomous instrument packages. Satellite-borne sensors now provide high-resolution information on ocean surface and sea ice conditions. These sensors are far more critical in the Arctic than elsewhere in the global ocean, as the logistical and environmental constraints of Arctic operations severely limit the means by which we gather information.

Physical oceanography encompasses studies of ocean circulation and mixing processes that allow us to understand the conditions that we observe in the ocean and to better predict changes in these conditions. The Arctic Ocean is one of several regions where dense water may form that impacts deep circulation and water characteristics in the global ocean. The upper layers receive a large amount of fresh water as both river runoff from the surrounding continents and as ice melt, and the distribution of this fresh water is believed to play a primary role in the formation of the deep waters and also in the maintenance of the permanent pack ice cover. These processes vary seasonally, interannually, and in response to longer-term climate change. A major internal warming event, with concurrent shifting in the distribution of fresh water in the upper ocean, started in the late 1980s and continues to the present. The pack ice cover has decreased in both thickness and geographical extent over recent decades. Understanding these processes in sufficient detail to predict likely future conditions requires a firm base in in situ observations of the conditions undergoing change.

Ocean Temperature and Salinity

Our ability to assess conditions and change in the ocean depends critically on our ability to measure the spatial distributions of various properties, such as temperature and salinity, as well as circulation. By the mid-1970s, instrumentation had developed to a state where it was possible to obtain reasonably accurate, continuous vertical profiles of oceanic temperature and salinity that could be used to derive the three-dimensional spatial distributions of these variables. These profiles revealed that older data, obtained using discrete sampling bottles spaced from 10 m to several hundred meters apart vertically, were missing a tremendous amount of information. Discretely sampled data failed to provide consistent or realistic values for maxima in properties such as temperature, and they were incapable of detecting smaller-scale vertical features that we now realize are related to ocean mixing and other important internal processes. Profilers have evolved further since the 1970s, with greatly increased measurement accuracy and with the ability to measure quantities such as dissolved oxygen and chlorophyll concentrations. We can now routinely observe vertical water column structures down to a resolution of 1 m or less, adequate for assessing the small-scale processes such as mixing that help control the ocean's response to external forcing.

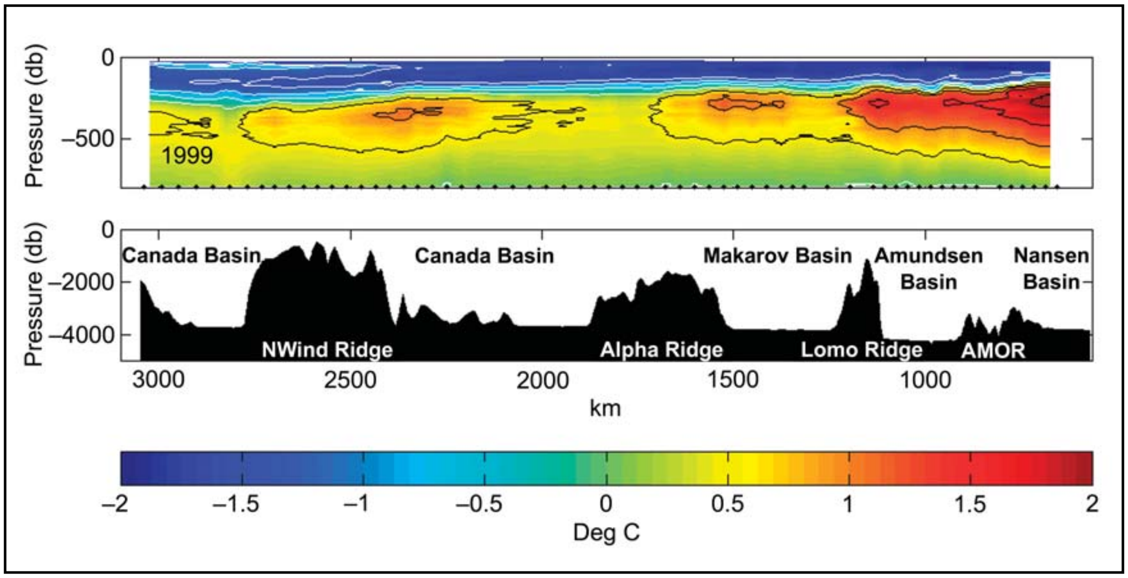
To measure vertical property profiles in the Arctic Ocean, we must use aircraft to reach the desired location and drill a hole in the ice through which to sample, or else we must reach the sampling location using an ice-breaking research vessel. Such operations are costly, time consuming, and potentially risky. Surface vessels and aircraft are still used and are generally crucial to research efforts. However, the development of autonomous profilers over the past few decades has lessened our reliance on such elaborate, costly, and potentially hazardous operations.

Bottom-moored, internally recording profilers are now available that can be left in place to record conditions continuously during the entire mooring period. Earlier versions of these devices were available in the early 1980s and profiled vertically by varying their own buoyancy while cycling upward and downward along a moored cable. Newer and more reliable versions cycle vertically on a moored cable by using a small electrically powered traction device. While the use of an icebreaking vessel is necessary to moor such instruments, the time series of vertical profiles can extend through the winter when the ice cover makes data acquisition using a surface vessel difficult or impossible. These bottom-moored instruments record data internally, allowing the data to be downloaded when the instrument is recovered by a surface vessel. Such profiling instruments also have the potential for deployment beneath surface buoys that are mounted on, and drift with, the pack ice.

Instruments mounted from surface buoys can transmit their data in near-real time through communications satellites. Satellites now available for this purpose have a much higher data transfer rate than older systems, making it feasible to transfer much larger amounts of data than was possible even a decade ago. Other profiling instruments cycle upward and downward while drifting freely in the open ocean, measuring vertical profiles of water properties as they cycle. Versions of these instruments are being modified for use beneath the Arctic ice. Such instruments might be deployed either through leads or in the marginal ice zone, then programmed to drift beneath the ice to obtain profiles there.

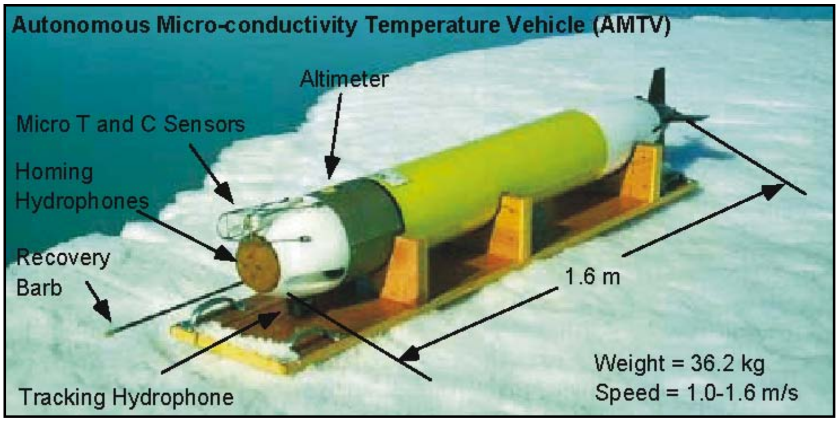
In the early 1990s, an agreement was reached among research funding agencies and the U.S. Navy enabling a program that allowed the use of U.S. fleet submarines for basic oceanographic research activities. This program, titled SCICEX (for SCientific ICe EXercise), carried out a broad suite of oceanographic observations from submarines that traversed the Arctic Basin underneath the pack ice. The first such deployment was in 1993, and subsequent traverses were made on nearly an annual basis through 1999. During this period, civilian scientists were able to participate in sampling aboard the submarines. The program of sampling by submarines along cross-Arctic transects continues to the present. Sampling is now being carried out by trained Navy personnel rather than by civilian scientists; however, the data are made available to the ocean research community. Sampling along a cross-Arctic transect by submarines has allowed us to monitor, over more than a decade to date, the internal warming event and associated changes that have been occurring in the Arctic Ocean since the late 1980s.

The 1990s warming was also measured with a new technique that utilized the transmission of a beam of sound waves across the Arctic Basin. This technique, called acoustic tomography, entails the transmission and receipt of acoustic signals in such a way that analyses of the data



Vertical distribution of temperature (ºC) in the upper Arctic Ocean (0–800 m deep) measured from a U.S. Navy submarine in the spring of 1999 under the auspices of the SCICEX program. The Bering Strait lies to the left (the Pacific Ocean side) and Fram Strait to the right (the Atlantic Ocean side). The core of warm water centered at 250–300 m deep originates from the Atlantic. Warm cores coincide with currents that flow along the flanks of mid-ocean ridges.

can provide information on water temperature along the pathway over which the acoustic signal is transmitted. Since sound velocity depends on water temperature, tomography provides a means for estimating water temperature along the pathway. Sound also reflects downward from an ice cover, and the resultant scattering during reflection can provide information on the roughness of the underside of the ice and, by implication, the ice thickness. In the late 1990s, a pilot experiment tested the feasibility of using a powerful acoustic source in the Russian Arctic to transmit sound across the entire Arctic Ocean to north of Alaska. This experiment was highly successful, demonstrating that sound transmission could in fact provide information on the internal temperature of the Arctic Ocean and on the roughness and thickness of the pack ice cover. Long-term deployment of such a tomographic system would allow multiyear monitoring of ocean conditions internal to the Arctic Ocean, as well as pack ice cover thickness. Combined with satellite imagery capable of defining the lateral extent of the ice cover, thickness information would contribute to the construction of a viable observational, multiyear pack ice budget.



An Autonomous Micro-conductivity Temperature Vehicle (AMTV) resting on pack ice at the SHEBA Ice Station in August 1998. The altimeter is used to determine the distance to the overlying pack ice when the instrument is operating beneath the ice.

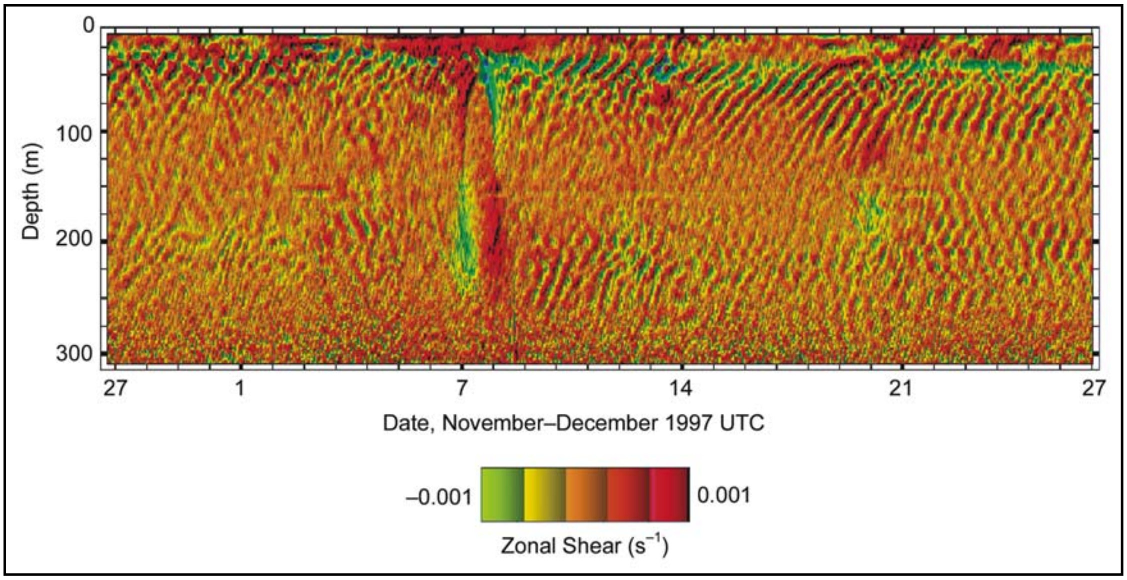
The methods summarized above have been useful for large-scale studies. However, many smaller-scale process studies have investigated properties unique to an ice-covered ocean. The pack ice can be viewed in many ways as beneficial, rather than as a hindrance, to small-scale studies because it provides a highly stable platform for carrying out measurements and allows rapid access to remote regions using aircraft equipped to land on the ice. Miniaturization has led to the development of much smaller and lighter versions of many instruments, such as profilers, that could previously only have been deployed from ships. The same advances that led to miniaturization have allowed the development of sophisticated velocity, temperature, and salinity sensors useful for measuring, for example, turbulent fluxes of heat and salt in the upper ocean beneath the ice cover.

Such sensors have been deployed from autonomous underwater vehicles (AUVs), which can sample horizontal as well as vertical profiles and can operate beneath the pack ice. These vehicles are especially well suited for studying small-scale features such as leads, which are believed to play significant roles in many Arctic Ocean processes. The highly discontinuous nature of processes in the upper Arctic Ocean produces spatial variability that is, in fact, difficult to impossible to sample without an AUV.

Ocean Currents

Prior to the 1980s, instrumentation for measuring ocean currents was limited to mechanical or electromagnetic current meters that were capable of measuring water motion only at the single point where the instrument was located. Vertical strings of many such instruments were required to obtain estimates of the vertical profile of horizontal currents needed to better understand the Arctic Ocean circulation. The development in the 1980s of acoustic Doppler current profilers (ADCPs) allowed, for the first time, the measurement of continuous vertical profiles of currents using a single instrument. These instruments use beams of transmitted sound, rather than mechanical or electromagnetic sensors, to measure current speed. Such instruments lend themselves to suspension beneath an ice cover, where they measure currents in the upper ocean beneath the ice. Mounted on vessel hulls, they have been used to map currents from ships both underway and stopped while sampling at measurement sites.

The development of ADCPs has continued to advance technologically. More recently developed systems allow the measurement of currents in greater detail and over greater ranges than ever before. The transport of materials from the shelves that surround the Arctic Ocean into the central basin depends in part on so-called mesoscale features such as eddies. The energy that drives internal mixing between waters having different sources is derived in part through the propagation of internal gravity waves through the ocean. Results from newly developed technology such as ADCPs are of critical importance in improving our understanding of processes internal to the ocean.



The zonal (east–west) component of vertical current shear measured in late 1997 from a drifting ice station in the central Beaufort Sea, well seaward of the continental shelf break, using an ADCP. The red areas correspond to an increase in eastward current speed with increasing depth. The complex patterns show the presence of internal gravity waves, generated in part by a storm on 5 December, that redistributed energy and led to mixing in the ocean. The vertical pattern on 7–8 December shows a large vortex or eddy over which the ice station drifted. Understanding these complex smaller features is crucial to our ability to predict ocean response to larger-scale, longer-period forcing.

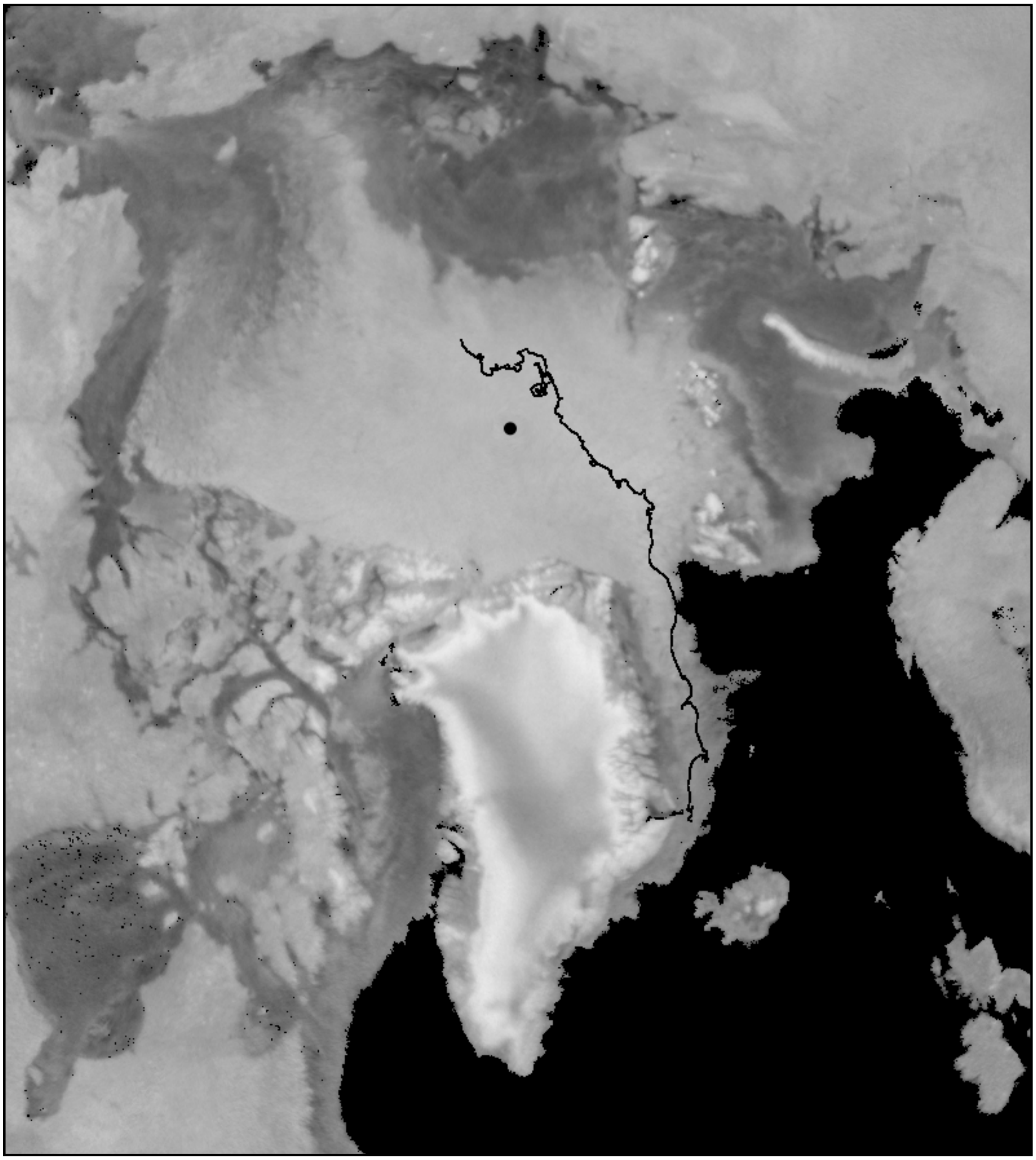
The Pack Ice Cover

The Arctic Ocean perennial pack ice cover comprises the ocean–atmosphere interface. It interacts closely with the underlying ocean through the transfer of wind energy, the provision or uptake of fresh water (depending on whether ice is freezing or melting), and effective thermal insulation of the upper ocean from the atmosphere. Large-scale movement of the pack ice internal to the Arctic Basin varies interannually in response to the Northern Hemisphere atmospheric pressure and wind fields. These variations exert a strong control over the ice budget, which is determined by freezing, melting, and export of ice from the Arctic Ocean, primarily southward through Fram Strait.

By the early 1980s, satellite-tracked buoys had become available and were being deployed on the pack ice to track large-scale ice movements under the auspices of the International Arctic Buoy Programme (IABP). (See the article on the IABP on p. 21.) Buoy location information, along with other data collected by attached sensors, is telemetered through Argos or other satellite systems. This program, with several satellite-tracked buoys deployed on the ice at any given time, has continued up to the present and has provided a priceless multi-year record of the ice movement and its interannual variability. Additional sensors provided on the ice buoys have allowed measurements of sea-level air temperature and pressure that have been used, in turn, to greatly improve predictions of the surface winds that drive the ice motion. The buoys can also support salinity, temperature, and depth observations at discrete intervals along a cable suspended beneath the buoy. In fact, instruments deployed from these buoys represented one of the earliest uses of conductivity cells, used to derive ocean salinity, in a moored or long-term drifting mode. Data from these and similar buoys have played an increasing role in operational observations, process studies, and long-term monitoring.

By the mid-1970s, satellite-borne remote sensing was becoming a useful tool for studying the Arctic pack ice. The sequence of NOAA satellites equipped with multi-band, very high resolution radiometers was underway, and analyses of the resulting imagery provided new information on ice extent and percent coverage and allowed estimation as to whether ice was first-year or multi-year. The radiometer data, which were passive and relied on the reception of energy radiated from the ocean surface, were limited, though, by a fairly coarse resolution of about 1 km and by their inability to penetrate cloud cover.

More-recent satellites carrying instruments that actively transmit multiband signals and then acquire the reflected signals for analyses have allowed us to derive far more information on sea ice cover. The transmitted signals fall in the radar, or microwave, frequency bands and allow us to determine, through the use of algorithms generated by comparing satellite data with ground truth data, ice characteristics such as overlying snow cover and roughness. These newer satellite-borne sensors also allow us to determine the geographical distribution of sea ice much more accurately (down to tens of meters) than the older passive radiometers. This better resolution has allowed more robust estimates of broad geographical



Ice drift trajectory (black line) derived from International Arctic Buoy Programme (IABP) data, superposed on a sea ice distribution derived from QuikScat/SeaWinds satellite data using the method reported in Haarpaintner et al. (2004). The land mass in the bottom center is Greenland, and the black dot is the North Pole.

variables, such as the percentage of open water as leads for a given season, than in the past. Automatic ice tracking can be performed on high-resolution SAR (synthetic aperture radar), as well as on low-resolution, Arctic-wide passive microwave and scatterometry, to assist in determining ice characteristics and drift.

Satellite-borne sensors designed for communications and for providing geographical locations have proven extremely useful for sea ice research. For the past two decades, geographical positions and recovery of data were possible using the ARGOS satellite system. These satellites returned geographical coordinates of buoys that were equipped with ARGOS receivers with an accuracy of approximately 100 m. They allowed for transmittal of data from the buoys at what is today considered a very slow rate, but, for years, they provided the only feasible means of data recovery from remotely deployed, non-recoverable instruments such as ice-mounted buoys. This system allowed us to recover not only the drift track of such a buoy, but also a time series of data such as surface temperature measured by sensors mounted on the buoy. This was the technology used for the Arctic Data Buoy System, which has been in use for several decades and has allowed a rigorous mapping of ice motion throughout the Arctic Ocean.

More-recent satellites provide considerably more-accurate positioning capabilities for remote instruments such as ice-mounted buoys. The GPS (global positioning system) satellites are in use everywhere and by virtually everyone from the military to mountain hikers. These satellites provide geographical locations to within a few meters. They are proving invaluable for studying ice motion because they can resolve the smaller-scale, shorter-period movements driven by tides and inertial oscillations that impact larger-scale properties such as ice strength and percentage of open water. The high accuracy of these satellites has also allowed some elegant studies of ice deformation in response to wind forcing over scales of a few kilometers. Such studies provide information on ice strength and response to forcing that is essential for our capability to numerically model and predict the distribution and motion of the pack ice, which has implications for the upper ocean freshwater balance and for climate change issues.

Newer-generation communications satellites such as Iridium provide us with much higher data transfer rates from remote instrumented platforms than were possible using the older ARGOS system. It's now feasible to design remote instruments capable of recording, and transmitting in real time, a broad range of environmental parameters. These parameters might include geographical position, surface air temperature and pressure, incoming solar radiation, and, from the underlying water, vertical profiles of temperature, salinity, and current velocity. Real-time transmittal of such data allows immediate inclusion into predictive models such as the U.S. Navy's PIPS (Polar Ice Prediction System).

Summary

The past few decades have witnessed tremendous advances in our ability to carry out both detailed, process-oriented studies and longer-term, monitoring-level observation programs in the Arctic Ocean. Most of these programs would not, in fact, have been possible prior to about 1980. The advances have paralleled much-larger-scale developments in instrumentation that have reduced the size and power requirements while improving reliability. Instrument development has been paralleled by greatly improved observational platforms, especially icebreaking research vessels and satellites. Serindipitously, these advances have coincided with, and have helped us understand, the many changes, dominated by both oceanic and atmospheric warming and the loss of the pack ice cover, now taking place in the Arctic.

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The SCICEX Program

Arctic Ocean Investigations from a U.S. Navy Nuclear-Powered Submarine

This article was prepared by Margo H. Edwards, Hawaii Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu; and Bernard J. Coakley, Geophysical Institute, University of Alaska Fairbanks. It is adapted from an article that originally appeared in Chemie der Erde/Geochemistry.

The SCience ICe EXercise (SCICEX), an unprecedented collaboration between the U.S. Navy and the marine research community, was designed to use nuclear-powered submarines to map and sample the ice canopy; the physical, chemical, and biological water properties; the seafloor topography; and the shallow subsurface of the Arctic Ocean. Data acquired during eight submarine cruises vastly improved our understanding of the Arctic Ocean and demonstrated the inextricable linkages between organisms, atmosphere, ice, water, and rock. This paper summarizes SCICEX results to demonstrate the important contribution of this program to Arctic science.

Brief History of the SCICEX Program

The SCICEX program began in January 1993, when the U.S. Navy announced that a nuclear-powered submarine would survey the Arctic Ocean that summer; the Navy invited the U.S. academic community to help plan the mission and participate in the cruise. In contrast to standard procedures, the Navy agreed to allow data collected during SCICEX-93 to be publicly disseminated. In August and September 1993 the USS *Pargo* carried out the joint naval and academic proof-of-concept field program. Based on the success of this program, the U.S. Navy and the National Science Foundation (NSF) signed a Memorandum of Agreement to undertake more joint submarine deployments to the Arctic Ocean. Five dedicated science programs took place annually from 1995 to 1999, with each including science-driven planning and civilian science riders. SCICEX-95 was a 43-day mission that took place during the spring of that year aboard the USS *Cavalla*. SCICEX-96 was a September–October program on the USS *Pogy* that lasted for 45 operational days. SCICEX-97 was a 30-day deployment aboard the USS *Archerfish* in the fall of 1997. The USS *Hawkbill* was the only Sturgeon-class submarine to repeat its participation in SCICEX, spending 31 operational days in the Arctic Ocean in August–September 1998 and another 42 days during April and May 1999 as part of the final dedicated-science SCICEX mission.

In October 1998 the U.S. Navy informed NSF that it would no longer be able to conduct dedicated Arctic Ocean science surveys, primarily because the nuclear submarine force was being reduced drastically. As an alternative to terminating the collaboration, the U.S. Navy and NSF agreed to “accommodation missions” that set aside time for acquiring unclassified data during otherwise classified submarine exercises. Results of two accommodation missions conducted in 2000 and 2001 are included in this paper.

SCICEX Results

SCICEX publications have contributed to most every field of science, providing novel observations, testable hypotheses for future work, and an increased understanding of both Arctic and global processes. SCICEX scientists were among the first to report on the pronounced changes in Arctic Ocean water temperature during the 1990s, to document the thinning of the Arctic ice canopy, to produce a detailed description of an oceanographic eddy in the Arctic Basin, to present evidence for a kilometer-thick ice shelf covering parts or the entirety of the Arctic Ocean during ice ages, and to show that recent volcanic eruptions have occurred along Gakkel Ridge. In some instances SCICEX data have supported widely held hypotheses, while in other cases SCICEX data demonstrate that existing models and theories need to be re-evaluated. In a 2003 paper, we presented a comprehensive overview of SCICEX accomplishments; this paper summarizes many of the major program results.

Preparations for surfacing of the U.S. Navy nuclear-powered submarine USS Hawkbill *at an ice camp 150 miles north of Barrow, Alaska, as part of the 1999 SCICEX program. The camp was named after the man who led the development of Arctic submarines, Dr. Waldo Lyon. An "X" shoveled across the ice pack at Ice Camp Lyon was visible on the upward-looking camera mounted on the sail of the USS* Hawkbill *and indicated to the sub's crew where they should surface. The arrow at one end of the "X" shows the suggested direction for the long axis of the submarine. A beacon and microphone were also lowered through the ice to communicate with the Hawkbill.*

Young Volcanoes in the Arctic Basin

Gakkel Ridge is part of the global Mid-Ocean Ridge (MOR), a long, linear volcanic chain where the earth's new crust is created. Gakkel Ridge extends 1800 km across the Arctic Basin, from the northeastern tip of Greenland to the continental margin of Siberia. It is categorized as an ultra-slow-spreading MOR, where new crustal material is created at a rate of less than 1.3 cm/yr. Because of the extremely slow crustal accretion, the contribution of volcanism to Gakkel Ridge topography remained controversial until the SCICEX surveys. SCICEX-98 and SCICEX-99 imaged two young volcanoes covering approximately 20% of a 3750-km^2 region on Gakkel Ridge (Edwards et al. 2001). One of these volcanoes is located near the locus of a 1999 earthquake swarm where 252 events were recorded over seven months (Müller and Jokat 2000, Tolstoy et al. 2001). Since this is the only earthquake swarm detected on Gakkel Ridge in about 100 years, Edwards et al. (2001) theorized that the SCICEX program imaged an eruption shortly after its occurrence. The subsequent discovery of hydrothermal venting along the ridge axis (Edmonds et al. 2003) in association with fresh-looking lava (Michael et al. 2003) confirm that Gakkel Ridge experienced a recent volcanic eruption.

Evidence for Thick Ice Shelves Extending into the Arctic Ocean

It has been hypothesized that during ice ages, glaciers extended from continents into the Arctic Ocean as thick ice shelves (Mercer 1970, Grosswald and Hughes 1999). This theory contrasts with a more conventional view that in the past the Arctic ice canopy was similar to its modern counterpart: a few-meters-thick layer of perennial sea ice with scattered icebergs (Clark 1982, Phillips and Grantz 1997, Spielhagen et al. 1997). SCICEX data resolved the debate by depicting a variety of glacigenic bedforms, including submarine flutes and moraines as well as iceberg-generated scour marks, in all shallow regions mapped. These bedforms extend to depths of more than 700 m on the Alaska margin and Chukchi Borderland, a topographic rise north of Bering Strait. On the central portion of Lomonosov Ridge, which extends from Siberia to Canada via the North Pole, there is evidence of thick ice to depths of almost 1000 m. Based on the SCICEX findings, Polyak et al. (2001) suggested that a vast ice shelf advanced from the Barents Sea shelf and eroded parts of the top of Lomonosov Ridge to depths of almost 1 km. Kristoffersen et al. (2004) presented an alternative model in which armadas of large icebergs entrained in sea ice modify the Arctic seabed. Although the form and extent of thick Arctic ice shelves remain controversial and the timing of their presence is not well constrained, the discovery of glacigenic bedforms in the central Arctic Ocean will lead to the revision of models describing the earth's major glaciations and related paleoclimate.

Thinning of the Present-Day Arctic Ice Canopy

Near the initiation of SCICEX, a number of studies reported that the Arctic ice canopy was thinning (McLaren 1989, Wadhams 1990, McLaren et al. 1994, Wadhams 1994). These studies were based on declassified ice draft data collected by nuclear-powered submarines beginning in 1958. Although thinning of the ice pack ice is consistent with the observed decrease in areal extent of the ice canopy (Maslanik et al. 1996, Parkinson et al. 1999), ambiguities introduced by the historical data sets, combined with the dynamic character of the moving, deforming ice pack, obfuscated the spatial and temporal scales of the effect. The SCICEX program improved on historical records by acquiring data for a larger cross section of the Arctic Ocean.

The initial analysis of the SCICEX data produced a disturbing result: between the 1970s and the 1990s the mean ice draft decreased by 1.3 m in the deep water regions of the Arctic Ocean (Rothrock et al. 1999). Suggested causes included enhanced export of ice through Fram Strait, a change in ice circulation and thus deformation within the Arctic, and more open water during the Arctic summer allowing increased absorption of solar radiation. Tucker et al. (2001) and Winsor (2001) countered that while some parts of the Arctic ice canopy were thinning rapidly, others (such as near the North Pole) were remaining essentially unchanged. To resolve the debate, Rothrock et al. (2003) limited their analysis to digitally recorded ice draft data collected between 1987 and 1997 and compared their findings with previously reported results for three regions: an angular swath between the Beaufort Sea and the North Pole, a region centered at the North Pole, and the entire SCICEX data set. They concluded that the general trend is an approximate decrease in ice draft of 0.1 m/yr except at the North Pole, where little change is observed.

Arctic Oceanography

The important contributions of SCICEX to volcanology, paleoclimatology, and climatology are mirrored in the field of oceanography. SCICEX

The USS Hawkbill *after it broke through the Arctic ice canopy in April 1999, greeted by distinguished visitors from the U.S. Cabinet and Congress, the U.S. Navy, and the National Science Foundation. Reporters from the National Geographic Society, CNN, PBS, and the Christian Science Monitor filmed and photographed scenes from the final year of the historic collaboration, documenting how the dedicated-science missions of nuclear-powered submarines significantly contributed to our understanding of the Arctic Ocean and global climate change.*

data provide new three-dimensional perspectives of the Arctic Ocean and, because of repeated surveys along the same tracks, yield time-series data that depict how the ocean is changing.

Warming Intermediate Water. During the first half of the 1990s, several Arctic field programs, including SCICEX, reported widespread changes in the Arctic Ocean's upper water column (Morison et al. 1998). The Atlantic Layer (AL; approximately 200–800 m deep) was observed to be extending farther from the Fram Strait into the Arctic Basin and becoming warmer; the front between the eastern AL (characterized by a temperature of 2–3°C) and the western AL (0.5°C) shifted from Lomonosov Ridge westward to Alpha-Mendeleev Ridge, which runs from Siberia to Canada on the Pacific side of Lomonosov Ridge. The AL also shoaled by approximately 40 m between 1991 and 1995 (Steele and Boyd 1998). To monitor changing water properties, various SCICEX submarines conducted repeated transects from the Alaska margin to the Barents Sea, collecting oceanographic data. Mean and maximum temperatures observed on the transects show that warming continued from 1995 until 1998, followed by a slight cooling during 1998-1999, with renewed warming between 1999 and 2000 (Gunn and Muench 2001, Mikhalevsky et al. 2001). Gunn and Muench (2001) showed that temperature changes as a function of location, leading them to propose that northward currents flowing along the flanks of the Arctic ridges move warm water from the continental margins into the central Arctic Ocean.

Cold Halocline Layer. The strong vertical stratification of the Arctic Ocean is largely responsible for the existence of the ice canopy that covers the ocean. The halocline, where salinity changes rapidly, suppresses vertical mixing, isolating the upper ocean and ice cover from the underlying warm Atlantic water (Aagaard et al. 1981, Rudels et al. 1996). The central Arctic Ocean exhibits a cold halocline layer (CHL), characterized by an approximately constant, near-freezing temperature and strong vertical stratification in salinity. Decreases in the extent of the CHL have the potential to cause a corresponding decrease in the extent of the ice canopy and a subsequent increase in global temperatures.

Using SCICEX data, Steele and Boyd (1998) showed that the extent of the CHL decreased during the early 1990s. They inferred that between Barents Shelf and Lomonosov Ridge, much of the upper mixed layer was in direct contact with the AL, yielding higher heat fluxes and reduced ice formation during the winter. Boyd et al. (2002) used SCICEX to demonstrate that the CHL began to recover in 1998, with the recovery continuing into 2000. Was the CHL sufficiently weakened to account for the observed reduction in sea ice during the 1990s (Rothrock et al. 1999, 2003)? Estimating upward heat flux, Boyd et al. (2002) concluded that the weakened CHL did not unilaterally cause the decrease in sea ice thickness. Björk et al. (2002) suggested that the recent return of the CHL could increase the mass balance of sea ice; their model predicts increased winter sea ice growth of 0.25 m when the CHL is present versus when it is absent.

Water Circulation in the Central Arctic Ocean. Understanding Arctic Ocean circulation is necessary to understanding global climate. A number of Arctic expeditions, including SCICEX, systematically sampled the Arctic water column to this end, lowering bottles from the ice canopy to depths reaching 1600 m. SCICEX water samples were analyzed for temperature, salinity, oxygen, nutrients, and chemical tracers. Smethie et al. (2000) used these data to develop a time scale describing the transport of intermediate water into the Arctic Basin. Their results show that, in contrast with the prevailing model of Arctic circulation (Rudels et al. 1994), intermediate water moves rapidly into the interior of the Canada Basin near Chukchi Rise. Smethie et al. (2000) found the oldest intermediate water near Lomonosov Ridge and suggested that its location is the result of either a small gyre isolating this part of the ocean or the observed influx of AL water into the Arctic Ocean. Using radionuclides in SCICEX samples, Smith et al. (1999) estimated that it takes 6.5–7 years (±0.5 years) for the transport of upper AL water from the Norwegian Coastal Current to the Siberian continental slope, with transport into the interior Arctic Basin having a lower limit of eight years. Transit times for the halocline at water depths of 59 and 134 m are, on average, 0.5 years lower than those for AL water at 240 m deep (Smith et al. 1999).

Guay et al. (1999) analyzed SCICEX samples collected along the Beaufort, Chukchi, East Siberian, and Laptev shelves to identify where river waters cross the shelves and join the circulation of the upper Arctic Ocean water column. Their data sets include temperature, salinity, chlorophyll, barium (Ba), total organic carbon (TOC), and dissolved organic carbon (DOC). Regions where river waters cross the shelves and enter the interior Arctic Ocean are identified by the coincidence of salinity minima with maxima in Ba, DOC and TOC. Guay et al. (1999) found three major regimes along the shelf transect: the Canada Basin and Chukchi Cap regime that is dominated by mixing between Pacific inflow, discharge from the Mackenzie River, and ice melting; a transition zone centered over the Siberian end of Alpha-Mendeleev Ridge that corresponds to the front between Pacific and Atlantic waters; and a Makarov and Amundsen Basin regime that is dominated by discharge from Eurasian Arctic rivers and Atlantic water.

Detailed Mapping of an Arctic Eddy. Eddies were first documented in the Arctic Ocean in the 1970s (Newton et al. 1974). These nearly ubiquitous features of the western Arctic Ocean provide important roles in ocean circulation and mixing and can persist for years. During SCICEX-97, embarked researchers seized an unprecedented opportunity to map a cold core eddy both horizontally and vertically. Muench et al. (2000) detailed the shape of the eddy and used chemical tracers to examine its age and source region. The eddy they encountered was approximately 20 km in diameter, extending from 40 to 400 m deep. Core temperatures in the eddy were cooler than in the surrounding water, with the greatest difference occurring at approximately 230 m deep. The eddy core contained less salt than the surrounding water from the top of the eddy to depths of about 185 m; deeper than that, the salinity was less than ambient values. The maximum current speeds recorded in the eddy were 20 cm/s. Muench et al. (2000) suggested that the likely source of the eddy was a polynya along the Alaskan Chukchi coast; chemical tracers placed an upper limit of two years on the age of the eddy core. Muench et al. (2000) estimated that if the eddy formed along the Alaskan Chukchi coast during the winter prior to its encounter, it migrated northward at a rate of approximately 1 cm/s, transporting 2000 m^3 of shelf water per second. If eddies are the sole mechanism for venting water from the shelves into the deep Arctic Ocean, volume considerations imply that approximately 250 eddies form and migrate annually.

Steve Okkonen and Dean Stockwell from the University of Alaska Fairbanks store water samples in copper tubing for post-cruise analysis by oceanographers at Lamont-Doherty Earth Observatory.

Biogeography of Bacterioplankton. The Arctic Ocean receives organic matter from several sources, including riverine inflow from continents, phytoplankton production, and ice-algal production (Ferrari and Hollibaugh 1999). SCICEX water samples presented an unprecedented opportunity for biologists to study organic matter on a basin-wide scale and in different parts of the water column. Bano and Hollibaugh (2000) examined the distribution of ammonia-oxidizing bacteria in the Arctic Ocean and found that these oxidizers are more prevalent in halocline waters than in shallower and deeper waters. They suggested that this is the result of organic matter accumulating at the boundary layer (where water density changes rapidly) and decomposing to release ammonium. Bano and Hollibaugh (2002) also addressed the fundamental questions of whether bacterial communities that evolved in perennially cold oceans have diverged from communities in temperate and tropical waters and whether the polar oceans exhibit similarities or differences in their species. They found that the diversity of the Arctic assemblage is comparable to temperate oceans and that the Arctic community is composed of a mixture of uniquely polar and cosmopolitan types.

The Future of SCICEX

Because of the expanding availability and utility of SCICEX data and results, the enthusiasm engendered by the program continues to flourish, even though the dedicated science missions have been discontinued. While the international science community would welcome further dedicated cruises, the decommissioning of Sturgeon-class submarines has limited the ability of the U.S. Navy to support scientific missions. Alternative approaches for SCICEX-like investigations involve using autonomous underwater vehicles or nuclear-powered submarines from other nations; however, these programs are unlikely to achieve the scope of the SCICEX program within the next decade. The political process could potentially allocate resources and direct deployment of submarines in service of U.S. national needs. The results summarized in this paper present compelling scientific reasons to accomplish this goal.

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The International Arctic Buoy Programme–Monitoring the Arctic Ocean for Forecasting and Research

This report was prepared by Ignatius G. Rigor and Mark Ortmeyer, both of the Polar Science Center, Applied Physics Laboratory, University of Washington.

Changes in the Arctic have long been considered a harbinger of global climate change. Simulations with global climate models predict that if the concentration of CO_2 in the atmosphere doubles, the Arctic would warm by more than 5°C, compared to a warming of 2°C for subpolar regions. This "polar amplification" of the global warming signal is attributed to changes in sea ice, which has a higher albedo (reflectivity) than the darker ocean, and hence its presence reduces the amount of sunlight absorbed by the ice-covered ocean. If temperatures warmed, this may decrease the area of sea ice and increase the exposed area of the darker ocean, increasing the amount of sunlight absorbed, thus warming the ocean, melting more sea ice, and amplifying the initial perturbations. (This process is called ice–albedo positive feedback.) And, indeed, studies of the observational records show polar amplification of the warming trends.

These temperature trends are accompanied by decreases in sea level pressure over the Arctic Ocean, changes in the circulation of sea ice and the surface ocean currents such that the Beaufort Gyre is reduced in size and speed, and decreases in sea ice thickness. During the last three summers (2002–2004) we have observed near-record minima in summer sea ice extent in the Arctic.

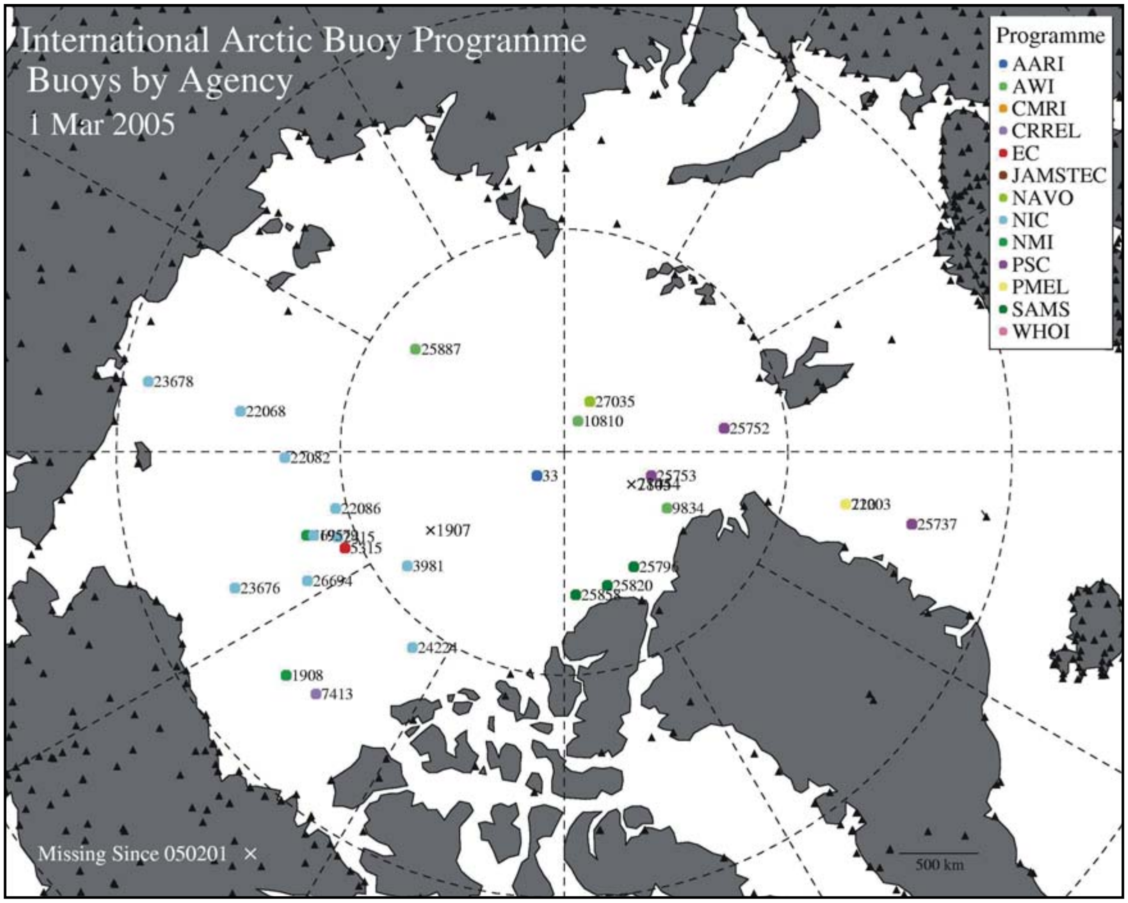
These changes have a profound impact on wildlife and people. Many species and cultures depend on the sea ice for habitat and subsistence. The lack of sea ice in an area along the coast may allow ocean waves to fetch up higher, producing stronger storm surges that may threaten low-elevation coastal towns. And from an economic viewpoint, the extent of Arctic sea ice affects navigation from the Atlantic to the Pacific through the Arctic along the Northern Sea Route and Northwest Passage, which are as much as 60% shorter than the conventional routes from Europe to the west coast of the U.S. or Japan. Thus, monitoring the Arctic Ocean is crucial not only for our ability to detect climate change, but also to improve our understanding of the Arctic and global climate system, and for forecasting weather and sea ice conditions.

IABP History

A network of automatic data buoys for monitoring synoptic-scale fields of sea level pressure (SLP), surface air temperature (SAT), and ice motion throughout the Arctic Ocean was recommended by the U.S. National Academy of Sciences in 1974. Based on that recommendation, the Arctic Ocean Buoy Program was established by the Polar Science Center (PSC), Applied Physics Laboratory (APL), University of Washington (UW), in 1978 to support the Global Weather Experiment. Operations began in early 1979, and the program continued through 1990 under funding from various agencies. In 1991 the International Arctic Buoy Programme (IABP) succeeded the Arctic Ocean Buoy Program, but the basic objective remains: to maintain a network of drifting buoys on the Arctic Ocean to provide meteorological and oceanographic data for real-time operational requirements and research purposes, including support to the World Climate Research Programme and the World Weather Watch Programme.

The IABP currently has 33 buoys deployed on the Arctic Ocean. Most of the buoys measure SLP and SAT, but many buoys are enhanced to measure other geophysical variables, such as sea ice thickness, ocean temperature, and salinity.

This observational array is maintained by 21 participants from 10 countries. These participants support the program through contributions of buoys, deployment logistics, and other services. The U.S. contributions to the IABP are coordinated by the U.S. Interagency Arctic Buoy Program (USIABP), which is managed by the National Ice Center. Of the 33 IABP buoys currently reporting, 13 buoys were purchased by the USIABP, and 18



Positions of the IABP buoys on March 1, 2005. The colors correspond to the various participants of the IABP. (See below for a list of acronyms.)

IABP Participants

1. Alfred Wegener Institute (AWI), Germany
2. Arctic and Antarctic Research Institute (AARI), Russia
3. Chinese Arctic and Antarctic Administration (CAAA), China
4. Christian Michelsen Research Institute (CMRI), Norway
5. Collecte Localisation Satellites and Service Argos, France and USA
6. Cold Regions Research and Engineering Laboratory (CRREL), USA
7. Environment Canada (EC), Canada
8. Institute of Ocean Sciences, Canada
9. International Arctic Research Center (IARC), University of Alaska Fairbanks, USA, and Japan
10. Japan Agency for Marine–Earth Science and Technology (JAMSTEC), Japan
11. Marine Environmental Data Service (MEDS), Canada
12. Metocean Data Systems, Canada
13. Nansen Environmental and Remote Sensing Center (NERSC), Norway
14. National/Naval Ice Center (NIC), USA
15. Naval Oceanographic Office (NAVO), USA
16. Norwegian Polar Institute (NPI), Norway
17. Norwegian Meteorological Institute (NMI), Norway
18. Pacific Marine and Environmental Laboratory (PMEL), USA
19. Polar Science Center (PSC), Applied Physics Laboratory, University of Washington, USA
20. Scottish Association for Marine Science (SAMS), Scotland
21. Woods Hole Oceanographic Institute (WHOI), USA
22. World Climate Research Programme (WCRP), Switzerland

USIABP Contributors

1. International Arctic Research Center, University of Alaska Fairbanks
2. National Aeronautics and Space Administration
3. National Oceanic and Atmospheric Administration (NOAA), Arctic Research Office
4. NOAA, National Environmental Satellite, Data and Information Service
5. NOAA, Office of Global Programs
6. Naval Oceanographic Office
7. Naval Research Laboratory
8. National Science Foundation
9. Office of Naval Research
10. U.S. Coast Guard

buoys were deployed using logistics coordinated by the USIABP. The USIABP also funds the coordination and data management of the IABP by the PSC. The observations from the IABP are posted on the Global Telecommunications System for operational use; they are also archived at the World Data Center for Glaciology at the National Snow and Ice Data Center (http://nsidc.org) and can be obtained from the IABP web server for research (http://iabp.apl.washington.edu).

Uses of IABP Data

The observations from the IABP have been particularly important for:

- Forecasting weather. The IABP buoys are essential for analyzing and forecasting weather features in the Arctic.
- Detecting Arctic and global climate change. One of the first indicators of Arctic climate change was found by Walsh and colleagues using the buoy data. They showed that sea level pressure over the Arctic Ocean decreased by over 4 hPa from 1979 to 1994. Data from the IABP have also been assimilated into the global temperature data sets, and the IABP surface air temperature analysis shows that the increased air temperatures noted over land extend out over the Arctic Ocean. Specifically, Rigor and colleagues found warming trends in surface air temperature (SAT) over the Arctic Ocean during winter and spring, with values as high as 2°C per decade in the eastern Arctic during spring.
- Forcing, assimilating, and validating global weather and climate models. For example, the buoy data have been used to validate the Polar Ice Prediction System model developed at the Naval Research Laboratory and are assimilated into the National Center for Environmental Prediction–National Center for Atmospheric Research re-analysis data sets.
- Predicting sea ice conditions. Our ability to accurately forecast sea ice conditions depends on observations of surface air temperature and sea ice motion over the Arctic Ocean. For example, during the summers of 2002 and 2003, lower-than-normal air temperatures were observed over the Alaskan coast, and yet record minima in sea ice extent were observed. To explain this paradox, Rigor and Wallace hypothesized that these recent minima may be due to changes in the thick-

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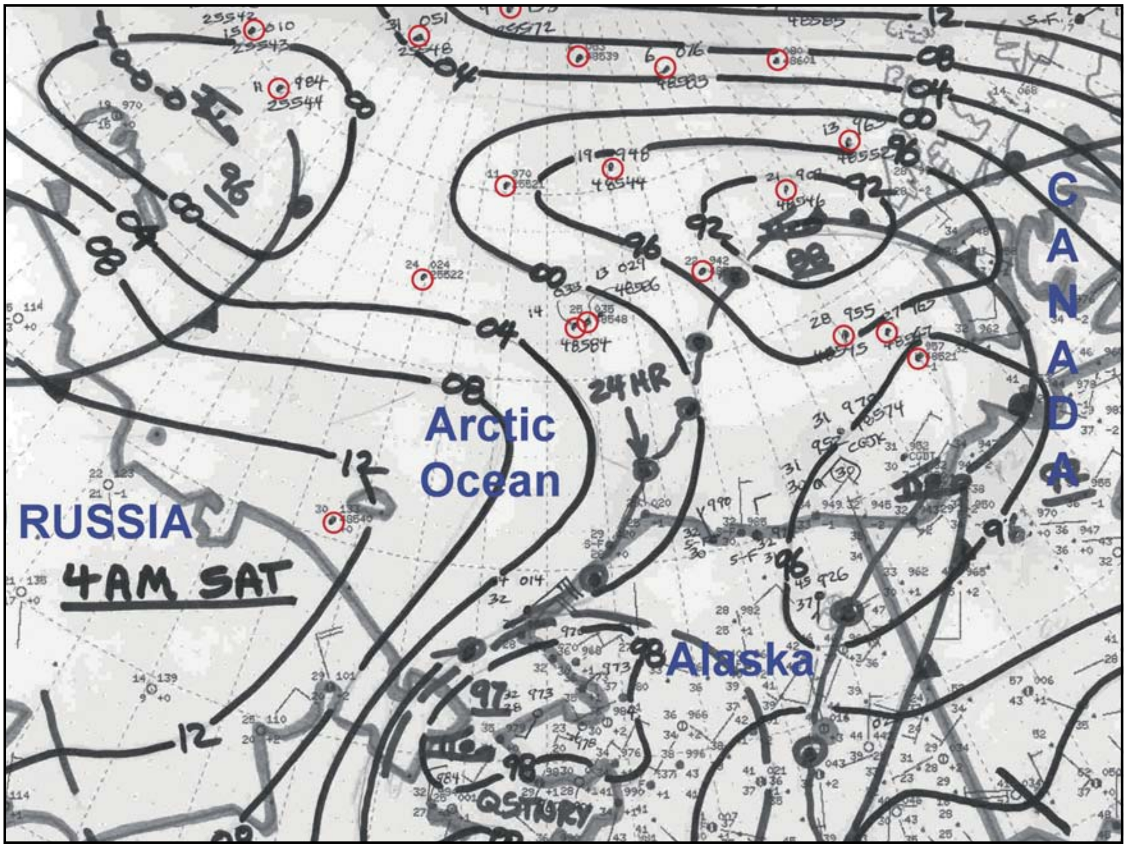
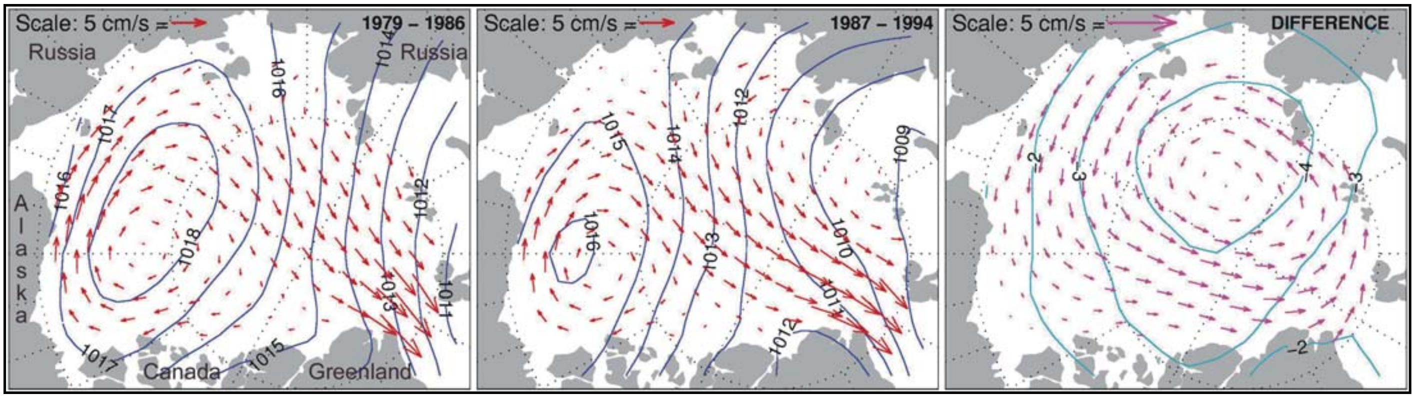


Weather map showing a cyclone approaching Alaska from the Arctic Ocean. The red dots show the positions of the IABP buoys. The strength and trajectory of this storm would have been difficult to predict without observations from the buoys.



Change in sea level pressure over the Arctic Ocean. Using IABP data, Walsh and colleagues showed that SLP decreased by over 4 hPa (right), when they took the difference between IABP SLPs from 1979 to 1986 (left) and 1987 to 1994 (center). These changes in SLP (winds) drive a cyclonic anomaly in ice motion (vectors).

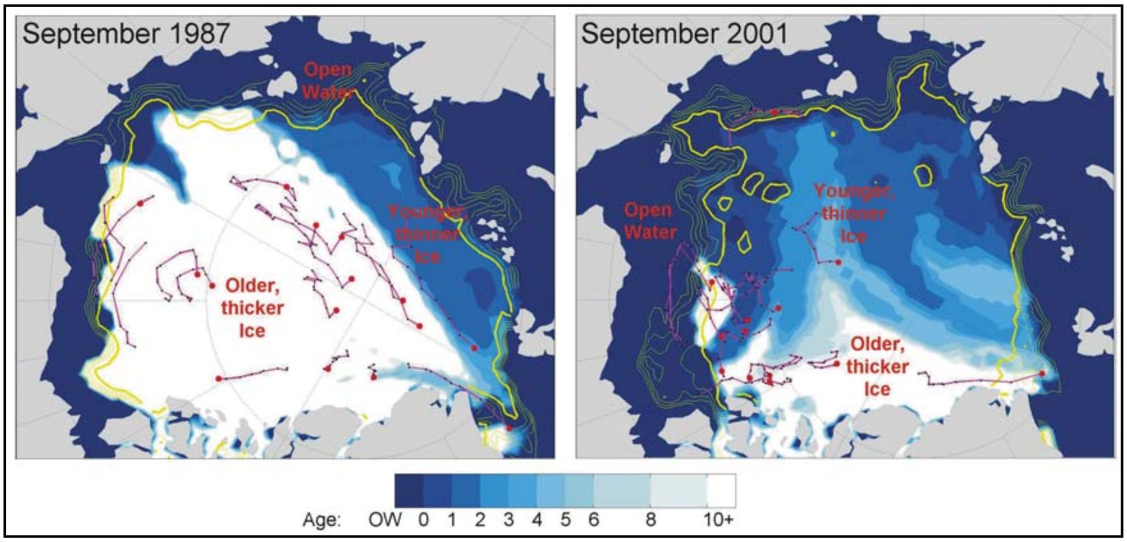
ness of sea ice blown towards the Alaskan coast by the surface winds. To show this, they used a simple model to estimate the age of sea ice based on the observed drift (residence time) of the sea ice provided by the buoys. They showed that the age (and thickness) of sea ice has decreased dramatically in the 1990s, and this younger, thinner sea ice was observed to drift towards the Alaskan coast during the last few years. They argued that although temperatures may have been lower, the air was still warmer than the melting temperature of sea ice, and it simply takes less heat to melt younger, thinner sea ice, thus explaining the recent record minima in sea ice extent.

As of 2004, over 500 papers have been written using the observations collected by the IABP.

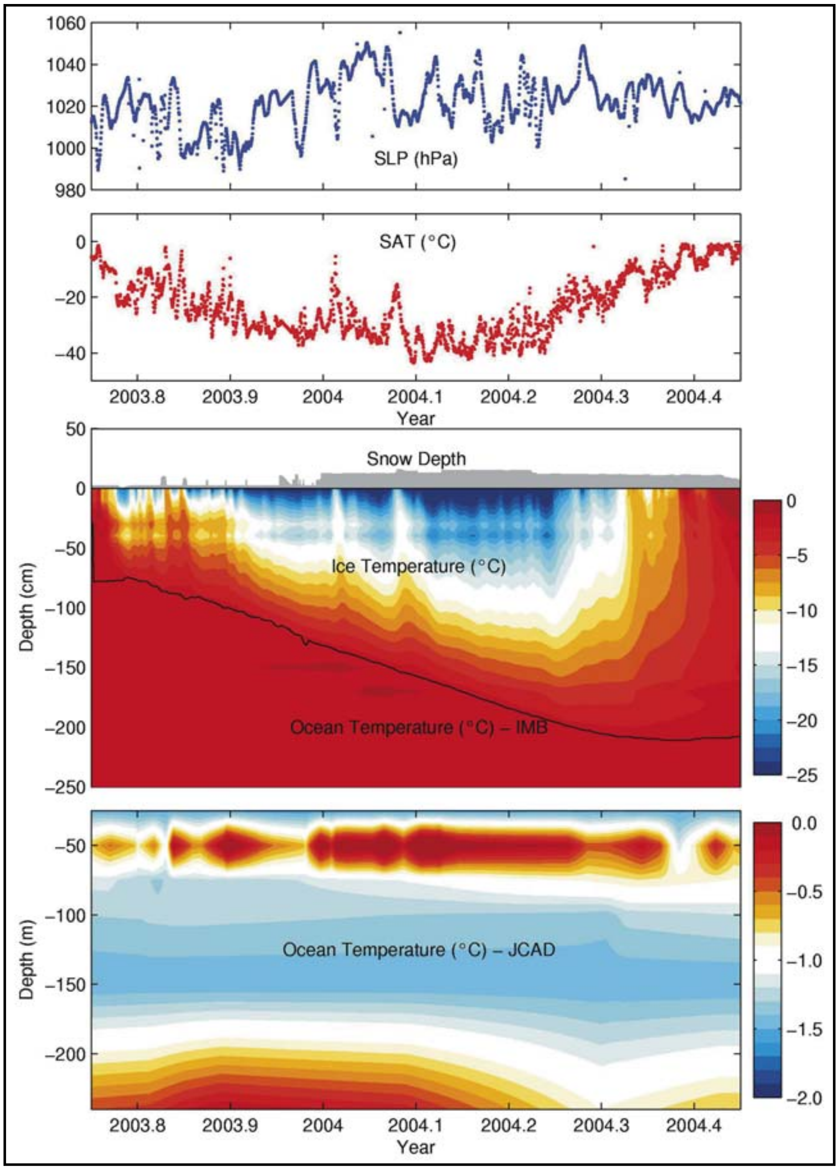
IABP in the Future

The observations from IABP have been one of the cornerstones for environmental forecasting and studies of climate and climate change. Many of the changes in Arctic climate were first observed or explained using data from the IABP.

The IABP is also evolving to better support the operational and research requirements of the community. For example, some of the participants of the IABP have been deploying buoys that measure not only SLP and SAT, but also ocean currents, temperatures, and salinity. Other buoys have been enhanced to measure the ice mass balance using thermistor strings and pingers aimed at the top and bottom of the sea ice. The data provide a myriad of concurrent time series at a few points across the Arctic Ocean. From these data we can also estimate time variations in other geophysical variables, such as oceanic heat storage and heat flux. These stations provide critical atmospheric, ice, and upper ocean hydrographic measurements that cannot be obtained by other means. These data can be used for validating satellites; for forcing, validation, and assimilation into global climate models; and for forecasting weather and ice conditions.



Changes in the age (thickness) of sea ice from September 1987 to September 2001. The larger area of younger, thinner ice (right) is less likely to survive the summer melt. For details, see "Variations in the age of sea ice and summer sea ice extent," by I.G. Rigor and J.M. Wallace, Geophysical Research Letters, *Vol. 31, 2004, which can be obtained from http://iabp.apl.washington.edu/IceAge&Extent/).*



Monitoring the Arctic using enhanced IABP buoys. The top two panels show sea level pressure and surface air temperature measured by the Japan Agency for Marine–Earth Science and Technology (JAMSTEC) Compact Arctic Drifter (JCAD) and an ice mass balance (IMB) buoy that are collocated in the Arctic Ocean. The third panel shows snow depth, ice temperature, ice thickness, and ocean temperature measured by the IMB. The bottom panel shows ocean temperatures from the JCAD.

The Arctic and global climate system is changing. These changes threaten our Native cultures and ecosystems, but they may also provide economic and social opportunities. To understand and respond to these changes, we need to sustain our current observational systems, and for the Arctic, the IABP provides the longest continuing record of observations.

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A Personal View of the ONR High Latitude Upper Ocean Physics Programs

This article was prepared by Miles G. McPhee, McPhee Research Company, Naches, Washington.

Introduction

In the post WWII era, the Office of Naval Research High Latitude Dynamics (formerly the Arctic Code) program sponsored a wide variety of upper ocean research as part of a continuing series of ice station experiments. By using drifting ice as a rotating laboratory (the Coriolis force is important) without the complicating effect of surface gravity waves, our research community investigated how rotation impacts the turbulent boundary layer and upper pycnocline. In this article, I use four examples to illustrate how ice station experiments substantially advanced knowledge of Ekman dynamics, turbulent (Reynolds) stress behavior, fluxes of scalar properties in the ocean boundary layer, and Rossby adjustment.

My introduction to polar regions came with the first nighttime C130 Hercules landing on sea ice at the Arctic Ice Dynamics Joint Experiment (AIDJEX) Pilot Study station in March, 1972. I was standing on the flight deck (FAA restrictions were less stringent in those days) as we came down onto a frozen-lead runway lit with smudge pots, and it is the only time I have ever experienced a landing where I could not tell when the wheels actually touched down. My memory of the remainder of that first night is the roar of the C130 turbines as flight after flight landed,* and we were rousted out to lend a hand offloading. Still, despite the sleep deprivation and aching muscles of the first few days (a common feature of some twenty-odd camps since), I had a chance to observe a completely new environment, where the air was so cold it stopped your nostrils, sunlight so intense it made your eyes ache, and the "terrain" of pressure ridges and sastrugi ice dunes made it easy to imagine you had seven-league boots. Aside from the airplane loads of stuff we brought with us, the color spectrum consisted only of gradations from white to blue. I was hooked.

As a neophyte graduate student under Prof. J. Dungan Smith, I learned a lot in the following weeks. Smith was an exacting but inspiring advisor, who fortunately paid little attention to the conventional wisdom that it was impossible to directly measure turbulent fluxes in the ocean. As few had before, he understood the potential of the drifting ice platform as a superb laboratory for studying rotating turbulent boundary layers (where the Coriolis force is important), and he designed a remarkable experiment that was probably the first and most complete study of its kind. It became the focus of my thesis, and in retrospect I was indeed fortunate to have been associated with such a project.

For me, Smith's approach to science fit well with an attitude that many scientists, at least in the Arctic community, identified with the Office of Naval Research. It seemed that, more so than the other agencies, ONR was willing to stretch to accommodate a researcher with novel, often untried ideas, if the program managers had faith that something useful might come of it. Smith's 1972 AIDJEX project was a good example: in the face of a community skeptical to begin with that turbulent flux could ever be measured in the ocean, he proposed an audacious ocean boundary layer experiment with 75 optically sensed current meters suspended in triads on inverted masts at various depths up to 54 m below the ice, all sampled 20 times per second and interfaced to one of the first commercially available minicomputers (in fact, the first ever to appear at an ice camp). These arrays would for the first time provide simultaneous measurements of turbulent (Reynolds) stress and velocity spectra through an entire planetary boundary layer.

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* By modern standards, the AIDJEX Pilot Study drift station was huge. Conceived and organized under the leadership of N. Untersteiner as a pilot for the year-long 1975–1976 AIDJEX study, it was supplied by 18 C130 and numerous smaller aircraft flights. Its peak occupancy exceeded 80 scientists and support personnel (Heiberg and Bjornert 1972).

The author and Prof. J. D. Smith (red vest) deploying a Smith-rotor current meter triad in a large hydrohole during the AIDJEX 1972 Pilot Study north of Barrow, Alaska. The triads measured three-dimensional currents (u, v, w) at numerous levels to 54 m depth and provided the first simultaneous measurements of Reynolds stress at multiple levels through an entire planetary boundary layer.

Mountaineers and climbers put great store by *first ascents*, i.e., the first documented climb of a particular peak or climbing route. Science has a similar ethic. In my opinion, a disproportionate number of "firsts" in the subdiscipline of upper ocean physics can be traced to farsighted support from ONR High Latitude Dynamics (including its Arctic Code predecessors). In what follows, I have chosen four examples where understanding of outstanding problems in upper ocean (boundary layer) physics has been advanced by ice station experiments sponsored or cosponsored by ONR-High Latitude Dynamics. This list is by no means exhaustive and is meant much more as a personal reminiscence than as a complete survey. I have taken the liberty of injecting some personal anecdotes and descriptions in hopes of capturing at least a hint of the unique flavor of polar research. In my experience, ice camps are very much collaborative ventures, where the scientists expect (and are expected) to help clear runways, build shelters, drill holes, mine for fresh water, etc. Thus, the names on the title page of any particular scientific article usually represent a much larger pyramid of both scientific and logistic support.

Upper Ocean Physics from Ice Camps

Ekman Spirals and Eddy Viscosity

At the risk of overworking a hackneyed phrase, the holy grail of planetary boundary layer physics in the first half of the 20th century was documentation of Ekman's spiral. In a remarkable paper published in 1905, V.W. Ekman, inspired by Nansen's observations during the Arctic drift of the *Fram* in 1893–1896, had predicted that ocean currents forced by wind at the surface would trace an elegantly simple spiral with increasing depth, with the somewhat startling result that at some level in the boundary layer (the Ekman depth) the velocity would be in the opposite direction from the surface wind stress, and that the integrated velocity (volume transport) would be at right angles to the surface stress. He showed that for this to happen over a reasonable depth (tens of meters), there must be an "eddy viscosity" that behaved like kinematic molecular viscosity but several orders of magnitude greater.

Over time, there was much inferential evidence that Ekman dynamics held for both the atmosphere and the ocean, yet an unequivocal example of an Ekman spiral in the ocean did not appear until Ken Hunkins (1966) published data from Ice Station Charley. Hunkins made use of the concept of a *surface layer*, which accounted for much of the shear in the upper meter or two of the water column, without much diminishing the stress.* In other words, the Ekman layer, through which eddy viscosity was relatively constant with depth, began a short distance into the boundary layer, not right at the interface. Ekman (1905) suggested with remarkable insight that eddy viscosity should vary as the

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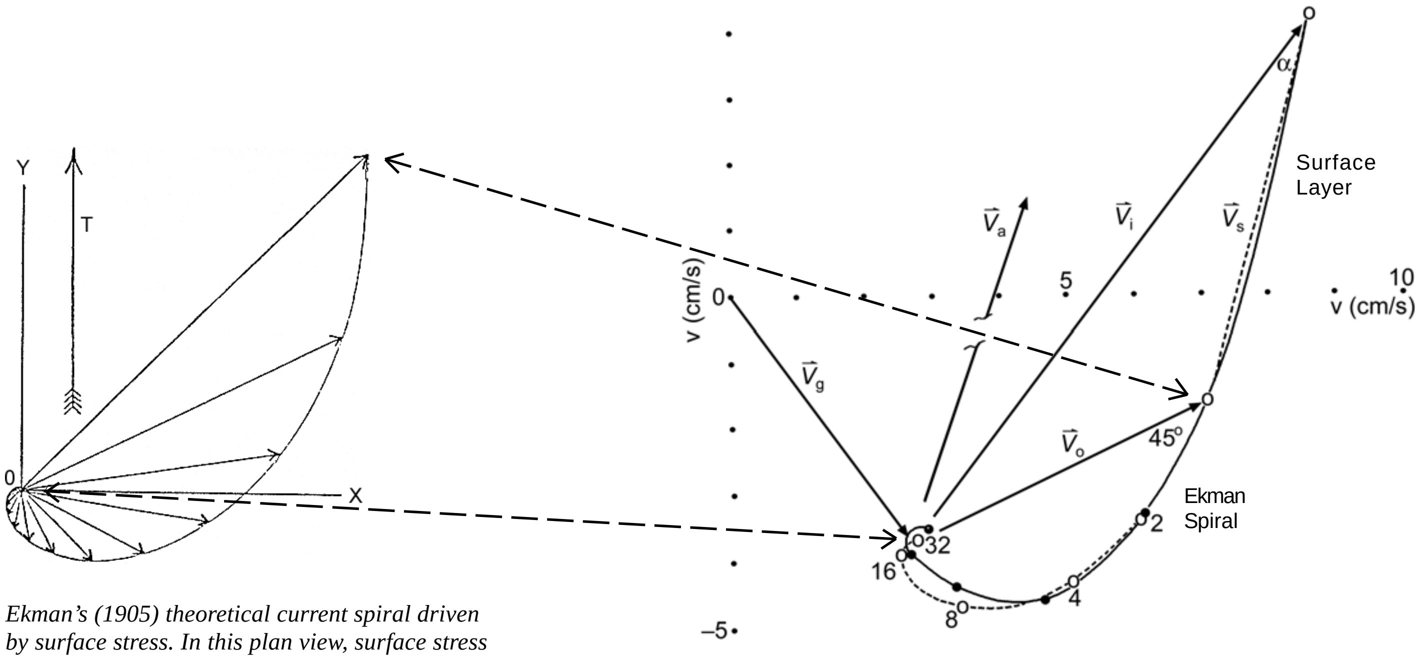
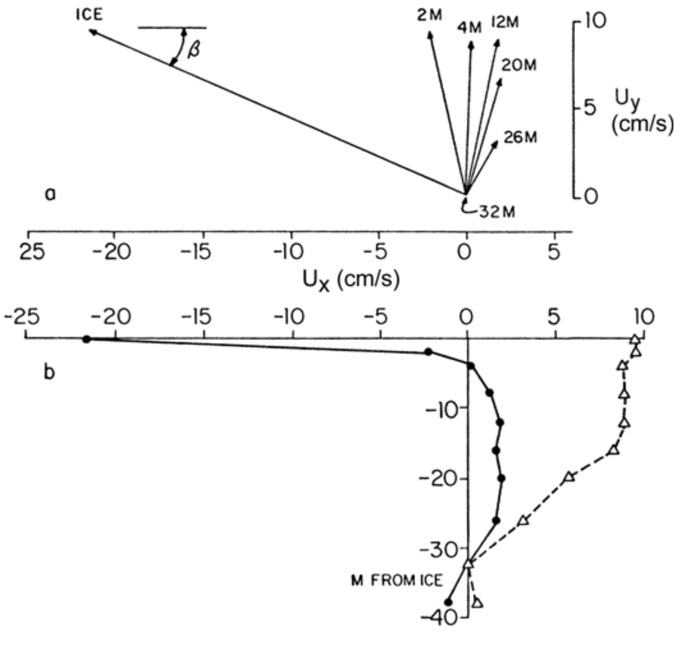
* In the neutral surface layer, eddy viscosity varies as distance from the surface. For the atmosphere, the surface layer is typically 50–100 m thick, but it is smaller in the ocean by a factor of about 30, approximately the square root of the density ratio of water to air.



Ekman's (1905) theoretical current spiral driven by surface stress. In this plan view, surface stress is indicated by the "T" arrow and current velocities by the connected arrows, which spiral downward with increasing depth from the surface. The surface (largest) vector is 45° to the right of surface stress.

Hunkins's (1966) vector average of nine current profiles (indicated at several depths by filled circles) taken over a two-month period at Drift Station Alpha during the IGY compared with a theoretical Ekman spiral for eddy viscosity equal to 23.8 cm^2/s (open circles). Note that a region of high shear (V_s) separates the ice from the upper limit of the spiral in Hunkins's construction, with the assumption that turbulent stress varies little over this distance. The whole boundary layer is advected with respect to the ocean floor with velocity V_g. V_a is wind velocity, V_i is ice velocity relative to V_g, and V_o is Ekman surface velocity relative to V_g.



square of the wind speed, i.e., that it was depth independent but would change substantially with time depending on stress at the surface. Despite this, Hunkins's relatively small value for eddy viscosity based on rather weak mean currents became the de facto standard for oceanographers for some time, apparently for lack of other information. We now know that eddy viscosity (and scalar eddy diffusivity) routinely exceeds Hunkins's value by an order of magnitude in the well-mixed ocean boundary layer and that in essence Ekman was right in his assessment of its dependence on surface stress (McPhee and Morison 2001).

A facet of Ekman's theory of particular importance to ocean modelers and theoreticians is that,

Plan view and profile rendition of an approximate Ekman spiral (plus surface layer) in 5-hour average currents measured on 12 April 1972 at the AIDJEX Pilot Study camp. Velocities are shown relative to the measured velocity at 32 m, where the U_x component (solid circles) is aligned with the negative direction of stress at the interface and the U_y (triangles) component is 90° clockwise. Adapted from McPhee (1986).

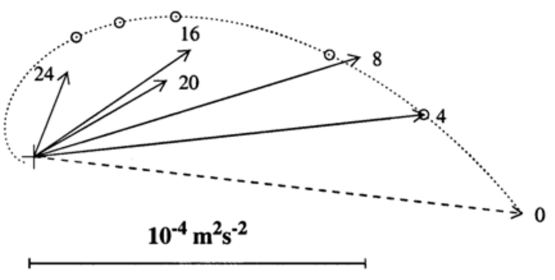
regardless of the vertical structure or magnitude of eddy viscosity, the steady-state volume transport in the boundary layer is at right angles to surface stress and proportional to its magnitude. This was illustrated convincingly by measurements made with Smith's apparatus during a storm at the AIDJEX Pilot Study in 1972. Despite the large U_x component at the surface, its integral from the surface to the base of the mixed layer is nearly zero, corroborating the current reversal predicted by Ekman.

Reynolds Stress

Surface gravity waves make measuring turbulent stress in the open ocean notoriously difficult, because orbital velocities and measurement platform motion must be separated from the relatively small fluctuations that contribute to the covariance among the various velocity components that make up the Reynolds stress tensor (from which both the horizontal shear stress and the turbulent kinetic energy are derived). Consequently, the most successful approach for studying open ocean turbulence is to measure turbulence at the smallest scales (microstructure), then in essence work backwards by a series of assumptions through the turbulent kinetic energy cascade to get at the turbulent kinetic energy (TKE), Reynolds stress, and eddy viscosity that characterize the large-scale flow (Gregg 1987, Shay and Gregg 1986).

A sea ice cover effectively quells short-period waves, and in most situations the ice provides a very stable platform moving at the maximum velocity in the boundary layer. Once the logistic hurdle of operating in polar regions is overcome, drifting ice thus represents an almost ideal laboratory for studying ocean boundary layer physics in the absence of surface waves.

By analogy with atmospheric surface layer methods, Untersteiner and Badgley (1965) used mean profiles of current velocity measured under Ice Station ARLIS II to estimate stress at the ice/ocean interface and the hydraulic roughness of the ice underside. A different method based on integrating the velocity component perpendicular to stress was adapted by Hunkins (1975) for estimating stress from mean currents.



Spiral-like structure in Reynolds stress observed at five depths at Ice Station Weddell (1992) during a storm. The numbers refer to the depth in meters from the ice undersurface. The dashed curve is a simple complex exponential, following the similarity model described by McPhee and Martinson (1994). Rotation is counterclockwise in the southern hemisphere.

The first direct evaluation of the Reynolds stress tensor through the entire ocean boundary layer awaited development of Smith's small ducted rotor current meter arrays and their capability of measuring three-dimensional currents. The results showed striking similarity between ocean boundary layer measurements under pack ice and numerical results from the rapidly developing field of atmospheric PBL modeling (McPhee and Smith 1976), suggesting that atmospheric models had direct applicability to the ocean boundary layer, provided scaling was done properly.

Numerous ice station experiments since Smith's pioneering work during AIDJEX have confirmed the basic behavior of turbulent stress in the under-ice ocean boundary layer. A sometimes overlooked aspect of Ekman's theory is that it predicts a spiral in turbulent stress as well as velocity.

Turbulent Scalar Fluxes in the Ocean

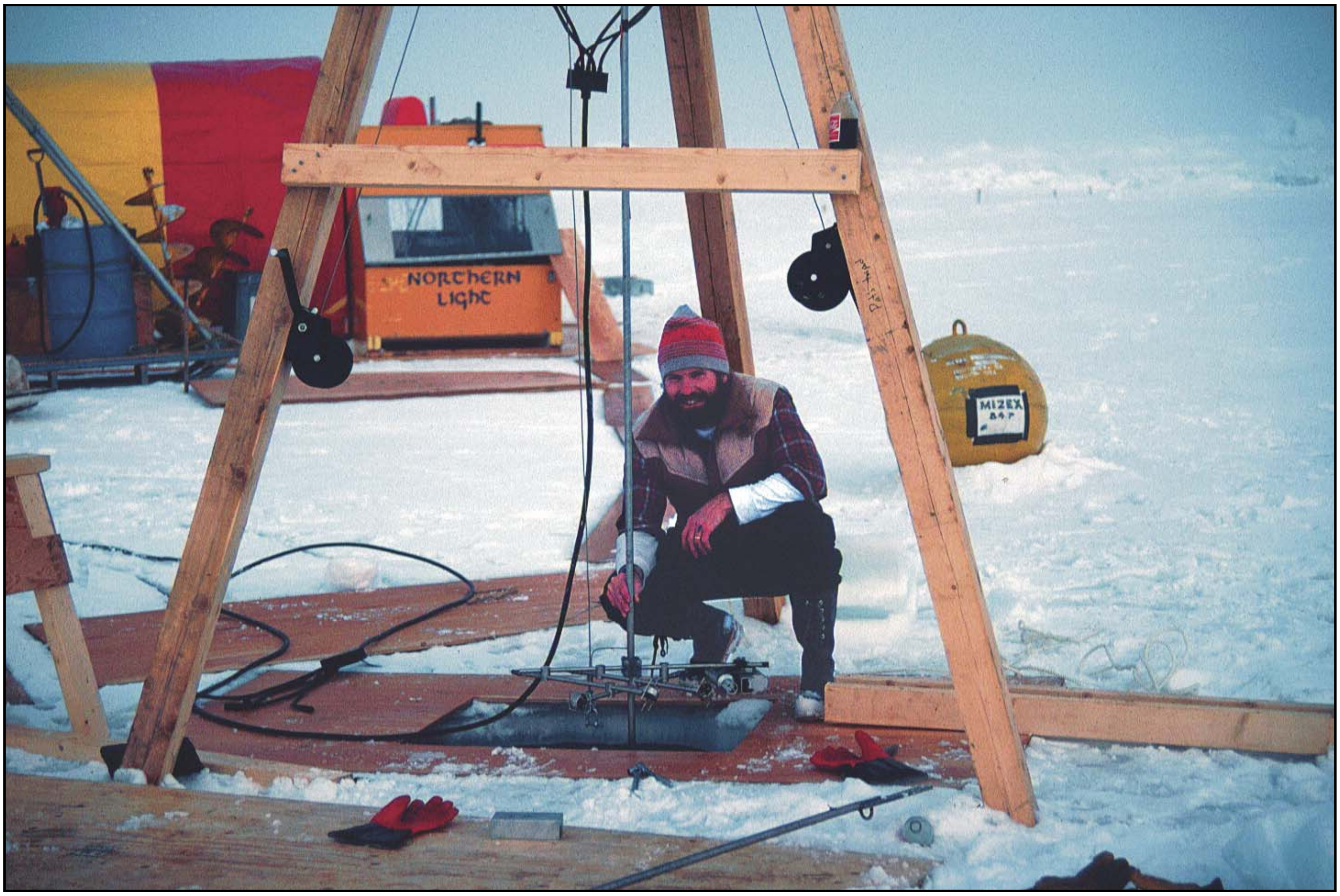
Although Smith's AIDJEX Pilot Study project had demonstrated the feasibility of measuring the covariance of three-dimensional current components in the under-ice ocean boundary layer, the system was not yet capable of addressing directly the important issue of turbulent heat and salt flux. Combined, the scalar fluxes determine buoyancy flux, an important element in the turbulent kinetic energy balance whenever vertical density gradients are encountered in the ocean boundary layer. It is the interplay between buoyancy flux and stress that determines, for example, how deep relatively fresh water from basal melting will penetrate, or how fast heat and salt will be entrained into the mixed layer from the underlying pycnocline. It provides an important constraint on the ice energy balance.

At the time of the AIDJEX experiments in the 1970s, high-resolution profiling conductivity-temperature-depth (CTD) instruments were still in their infancy. Interestingly enough, the genesis of the modern standard for CTD instruments, manufactured by Sea-Bird Electronics, Inc. (SBE), owes much to projects sponsored by ONR-High Latitude Dynamics. According to its founder Art Pederson, the first SBE CTD was built in 1982 for Jamie Morison, who had been a fellow graduate student with me under J.D. Smith. The new instrument implemented a novel period-counting scheme to the Wien-bridge circuitry and unique ducted conductivity cell that Pederson had developed earlier in working with the SPURV vehicle at the University of Washington Applied Physics Laboratory. Morison incorporated the new CTD into a profiling instrument that included velocity measurements (again based on a Smith-rotor triad) that he used during several High Latitude Dynamics projects during the 1980s.

For me Pederson's timing was impeccable. I spent the 1982-83 academic year in the High Latitude Dynamics-sponsored Arctic Chair at the Naval Postgraduate School in Monterey, during which I was immersed in planning for the upcoming series of Marginal Ice Zone Experiment (MIZEX) projects in the Greenland Sea as deputy to chief scientist Ola Johannessen, whom I succeeded in the Arctic Chair. I realized that if Smith's current measuring system could be combined with the SBE sensors, we would be able to measure a critical aspect of ice/ocean interaction in the MIZ, namely turbulent heat flux in the ocean, something that had not been done before anywhere. With encouragement from G. Leonard Johnson, High Latitude Dynamics program manager at the time, I approached Art Pederson with the concept of incorporating output data from Smith's current meters (which by that time had switched from an optical pickup to a Hall-effect magnetic sensor) into the SBE period-counting scheme. Not one to back down from an electronic challenge, Art devised a special version of the SBE CTD he dubbed the SBE 1135, which handled a total of seven instrument clusters, each with five channels: three low-frequency velocity signals plus higher-frequency temperature and conductivity data, with the cables from each cluster plugged directly into the backplane of the 1135 deck unit. The instrument was assembled in Art's garage on Mercer Island, and it worked flawlessly the first time I plugged it in. Some years later Art and Ken Lawson adapted the scheme to a system with a somewhat more conventional combination of pressure case connected by sea cable to a standard deck unit. This allowed a mast with several clusters to be lowered as a unit deep into the upper ocean.

The capability for measuring ocean heat flux during MIZEX did in fact turn out to be quite

A five-component turbulence instrument cluster (u, v, w, *temperature, and conductivity) ready for deployment during the 1984 MIZEX project in the Greenland Sea. The cable connects directly to the backplane of the SBE 1135 special CTD deck unit. In the background is Morison's Northern Light enclosure housing the winch for his SBE-based profiling system.*



LeadEx just-on-time delivery to the temporary camp deployed at the edge of a lead.

important for understanding ice–ocean interaction. By measuring both turbulent heat flux and Reynolds stress as well as the elevation of temperature above its freezing point (a function of salinity), we were able to establish a functional relationship for heat flux in terms of relatively easily measured variables that has withstood the test of time remarkably well.

The MIZEX heat flux measurements demonstrated for the first time that scalar fluxes of heat and salt at the ice–ocean interface were controlled by molecular processes in thin layers near the interface. While at the Naval Postgraduate School, I had begun a collaboration with George Mellor, who was visiting from Princeton at the time and from whom I learned much about boundary layer modeling. We had worked on details of the boundary condition at the ice–ocean interface, including a modification in which the effective “roughness lengths” for heat and salt were much smaller than the momentum roughness length, thus slowing the melt rate considerably from what had been previously thought (Mellor et al. 1986). Even so, during the last week of the MIZEX drift of the M/V *Polar Queen*, our multiyear floe unexpectedly survived with relatively modest basal ablation in water more than a degree above freezing, when according to our model it should have melted clean away. By incorporating laboratory results on heat and mass transfer over rough surfaces that explicitly included the laminar sublayers (Yaglom and Kader 1974), we were able to greatly improve the scalar boundary condition representation in numerical sea ice/upper ocean models (McPhee et al. 1987, McPhee 1987, Mellor and Kantha 1989).

When ice melts rapidly, fresh water introduced at the surface has a strongly stabilizing effect on ocean boundary layer turbulence. The new technology applied during MIZEX substantially increased our observational understanding of this process, confirming both second-moment turbulence model parameterizations (Mellor and Yamada 1982) and a relatively simple similarity approach to scaling turbulence in statically stable, or neutrally stable, planetary boundary layers (McPhee 1981). The other remaining important case— when rapid freezing created statically unstable conditions— provided much of the scientific rationale for the 1992 Lead Experiment. In this truly ambitious undertaking, a complete ice station was transported by helicopters to the edges of newly opened leads, with instruments deployed in just a few hours. Seeing my helo hut lift off for the first time, carrying nearly all of the essential (and expensive) equipment, gave me a decidedly “Wizard-of-Oz” feeling, with new meaning to one of Roger Andersen’s pet ice-camp pronouncements: “We’re not in Kansas anymore.” In keeping with Mother Nature’s proclivity for playing games with scientists, LeadEx was plagued by a shortage of leads near the main staging station (following ice camps like AIDJEX Big Bear, where unwanted leads had forced data interruptions and hasty relocations or abandonment); yet when she did relent and open Lead 3 about 20 km south of the main station, the conditions were almost perfect: a steady north breeze blew our station located on the north edge of a 1-km-wide lead south, so that we were seeing the full fetch of open water and thin ice in our oceanographic measurements.

LeadEx provided a critical test for one further improvement to the turbulence instrument cluster (TIC) concept: the addition of a fast-response microstructure conductivity instrument. The standard Sea-Bird conductivity instrument uses a ducted design to increase accuracy, but the restriction impacts to some extent the response to turbulent fluctuations. As far as I know, LeadEx was the first time the total buoyancy flux was measured directly in the ocean boundary layer. The results confirmed the importance of buoyancy production in the TKE balance for the statically

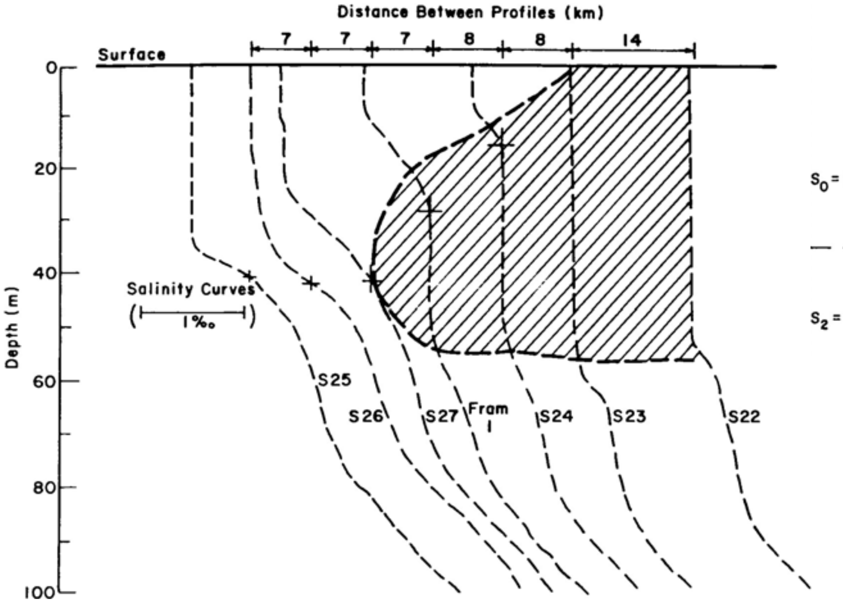
Temporary LeadEx camp deployed at the north edge of Lead 3, about 20 km south of the main station. The newly opened lead was about 1 km wide, with the ice pack drifting south (toward the left) in response to a northerly breeze.

unstable case with rapid freezing, in addition to providing concrete data on turbulence scales in forced and free convective boundary layers, which were roughly ten times as large as for a neutrally buoyant ocean boundary layer with similar surface stress (McPhee and Stanton 1996). There was an unexpectedly strong diurnal signal in turbulent heat flux, with as much as 12% of the total incoming solar energy being mixed downward by turbulence at midday, despite rapid freezing in the lead and a 5- to 10-cm-thick ice cover. There was close correspondence between heat flux measured by the thermal dissipation technique from Tim Stanton's microstructure profiler and the direct TIC flux measurements, as well as comparable measures of TKE dissipation by the two instrument systems. Such comparisons in the ocean are rare, limited mainly to the under-ice boundary layer.

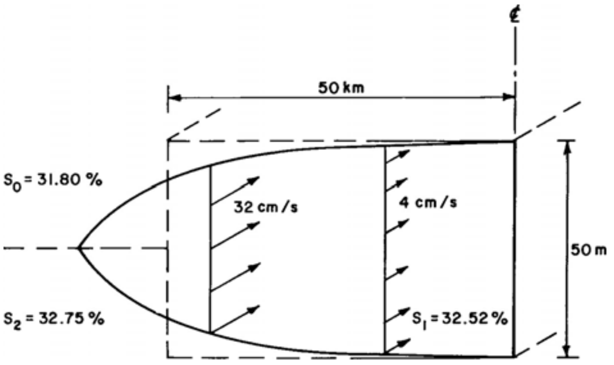
Another unique aspect of LeadEx was using an autonomous conductivity temperature vehicle (ACTV) developed at University of Washington Applied Physics Laboratory by Jamie Morison to observe the horizontal variability associated with fetch across (and distance from) convecting leads. The ACTV was nearly neutrally buoyant and relatively small, so Morison was able to show that it provided a good estimate of vertical velocity, hence independent estimates of the turbulent heat and salinity flux. Comparisons with the fixed-mast TIC measurements at the edge of the lead provided important calibration and tie-point data (Morison and McPhee 1998). Similar instrumentation and analysis of data from the SHEBA summer investigated the complementary stably stratified lead situation (Hayes and Morison 2002, Hayes 2003).

Geostrophic Adjustment

One of the great rewards of polar research for me has been the opportunity to work with many extraordinary people. A fine example is Alan Gill, whom I first encountered during the AIDJEX years when he was working as a science technician and all-around Arctic expert for Lamont-Doherty Geological Observatory (LDGO). With a real dedication to his scientific work, he was a legendary figure to a lot of us young Arctic researchers, having



Salinity profiles centered at ice station FRAM I showing an intrusive layer of water with a salinity of 32.5 psu (shaded). Pluses mark a salinity of 32.52 psu. Samples were made by helicopter in a line perpendicular to a current jet observed in a layer 20–50 m deep at the manned station.



Beginning (dashed) and end (solid) structure in the idealized collapse of a lens of intermediate-density fluid with an initial thickness of 50 m and a halfwidth of 50 km, between layers in a rotating, inviscid fluid. Instead of continuing to spread between the upper and lower layers, the intermediate density layer reaches an equilibrium with a jet as shown and a nose about two Rossby radii in extent. Salinity values were chosen to match the observations, yielding an internal Rossby radius of 12 km.

been a member of the three-man British Transarctic Expedition that trekked by dog sled across the Pole from Barrow to Svalbard in 1968-1969 (thankfully, we did not have to address him as Sir Alan, as Wally Hebert gained the only knighthood from that adventure). Alan and I worked together at Fram I (1979) on a collaborative project with LDGO (K. Hunkins) to gather CTD data by helicopter (we helped time pass in the –35° temperatures at the edges of steaming leads by carrying on intense level-wind competitions on our portable winch). I figured out early on that if I wanted to get along in the polar environment, I should copy just about everything Alan did, including, on Fram I, literally following in his footsteps over questionable ice during our helo CTD surveys. Nevertheless, I went through to my armpits twice, exactly where he had walked.

I can attest to at least one occasion when Alan's dedication paid off in a big way. Fram I was a particularly hardworking camp with a very international flavor, where we often gathered in the mess hall late at night for conversation and socializing. In the wee hours of one morning, Alan glanced at his watch and started to excuse himself from the gathering to do the standard profiling current meter run. Despite some suggestion that it might not hurt to miss one station, he persevered, and a while later he asked me to look at the profile he had just taken. It showed an anomalous current jet in the upper part of the pycnocline unlike anything we had seen before. We arranged to commandeer the helicopter for the next day, then used it to run a densely spaced CTD survey centered on the station, perpendicular to the direction of the isolated jet Alan had noticed in the profile. Upon later analysis, the results showed that Fram I had drifted across a very nice example of Rossby adjustment in the ocean. The classic problem of how a layer of intermediate density adjusts in a

Alan Gill going for the perfect level wind on the portable winch used for helicopter CTD surveying during Fram I in the eastern Arctic in 1979. He made it on at least one occasion.

rotating environment (Rossby 1938) is a staple in nearly every geophysical fluid dynamics textbook (e.g., Stern 1972). The measured current was considerably smaller than the idealized potential vorticity end state, but this would be expected since the fluid was not really inviscid and the feature, which extended north-south for as far as we could measure by helicopter, appeared to be migrating slowly westward.*

Closing Comments

I owe much to ONR High Latitude Dynamics. A whole succession of program managers (Ron MacGregor, Leonard Johnson, Tom Curtin, Mike van Woert, Dennis Conlon) nurtured my career as a scientist early on and then provided me with the support, both financial and moral, to pursue what I thought were interesting and important problems that could be tackled from drifting sea ice. In effect, they provided me and my colleagues with a superb ocean laboratory. I believe that collectively we have built both observational and theoretical bases for understanding ocean boundary layers that have advanced the field substantively. It seems to me that much of the success our nation experienced in fostering the explosive growth in scientific understanding in the postwar period came from a fundamental commitment to basic research: "Go find out how things work; we'll worry about applications later." ONR High Latitude embodied that attitude very well and, in my estimation, has much to show for it.

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* The front also drove home the need for caution in interpreting large changes in upper ocean properties. Mixed layer salinity changed by about 0.7 psu (31.8 to 32.5 psu) across a frontal zone about 25 km across measured on one day. This is roughly equivalent to the entire seasonal change in mixed layer salinity measured during summer at the AIDJEX stations in 1975.

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Back Cover

USCG icebreaker *Healy* in the Arctic, September 17, 2003.