VOLUME 14 FALL/WINTER 2000

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) and the Arctic Research Commission (ARC). Both the Interagency Committee and the Commission were 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 ARC and 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.

Cover

The USS L. Mendel Rivers *during the most recent deployment of an SSN-637 class submarine to the Arctic.*

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The Science Ice Exercise Program

History, Achievements, and Future of SCICEX

This report was prepared by George B. Newton, Chair, U.S. Arctic Research Commission

With the recent retirement of the USS *L. Mendel Rivers*, our nation bade farewell to the last of the Navy's "fully Arctic-capable" nuclear submarines—the SSN-637 Class. This event marks the passing of a significant platform capability, not only for the Navy, but for the Arctic research community as well.

It is appropriate therefore to pause and recall briefly the history of submarine data collection in the Arctic Ocean, note how the SCICEX Program emerged, identify some of the science achievements it enabled, and look at the prospects for the future operation of submarines for research in the Arctic.

Data collection by nuclear submarines operating under the Arctic Ocean sea ice started with the deployment of the USS *Nautilus* into the western Arctic Ocean in 1957. At that time, and for the next twenty or so years, all submarine deployments to the Arctic were classified. Information as to submarine location and time when deployed was rarely discussed outside Navy circles, let alone released to the general public. The Navy did collect some Arctic environmental data for its own use in understanding the Arctic and in fulfilling government/Navy research and development (R&D) data needs. Perhaps the most significant early data release was in 1976, when the USS *Gurnard* collected ice profile data north of Alaska to support the Arctic Ice Dynamics Joint Experiment (AIDJEX).

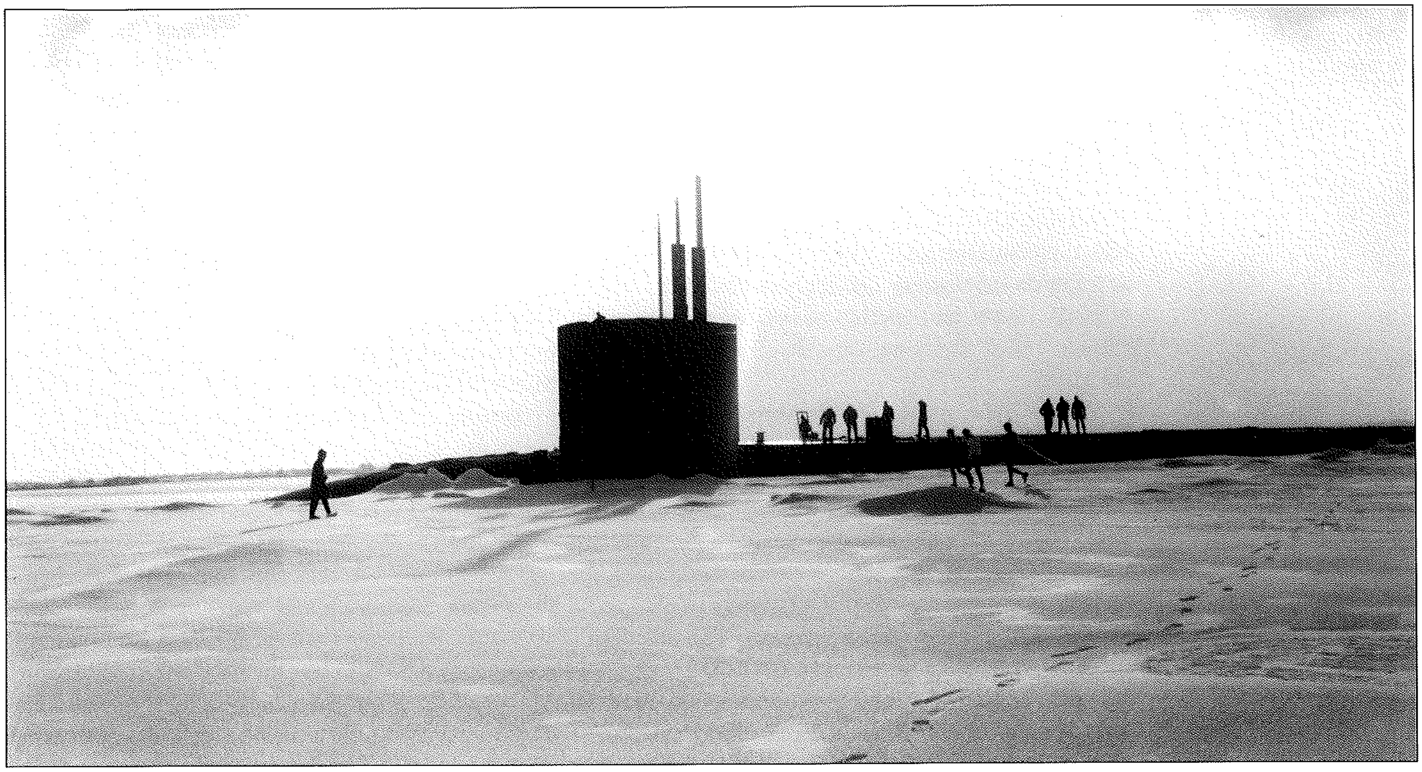
In the 1980s, stimulated by the Cold War, classified submarine deployments to the Arctic increased. Occasionally a researcher would be successful in gaining Navy approval for collecting data for a specific science need. Those data were usually declassified at some subsequent date.

It was in 1988 that the U.S. Global Climate Change Program was established, which involved all agencies in the Federal Government having environmental interests. The program created a heightened public awareness of the need for environmental data. And in no area of the world was there a greater need for environmental data than in the Arctic.

Later in the decade of the 1980s, it became clear that the Cold War was ending. The Soviet Union was in serious and worsening financial condition, a situation that extended right through their military forces. This stimulated them to develop some unique fundraising ideas. They made offers to any and all that nuclear submarines could be available for science—at a price. During the period 1989–1993 there was much discussion about the "Victor Project," a concept that would make a Soviet Victor Class SSN available to the science community for data collection in the Arctic Ocean. This offer included the opportunity for civilian researchers to ride the submarine during each science deployment.

As interest in these events surged about the U.S. Arctic science community, the Arctic Research Commission (ARC), led by the author (who at that time was a Commission advisor), was attempting to stimulate the U.S. Navy to accept the concept of conducting civilian science from submarines. The Navy was cool to the concept. However, what the Navy did accept was the lessening of the Cold War and with that a concomitant decrease in the need (and funding) for Arctic R&D to enhance its Arctic (under-ice) warfare capability. Lacking a clear-cut military R&D requirement, the justification could be made for the performance of pure civilian science in the Arctic. With the submarine community facing reduced Cold War operational commitments, the Navy was able to support occasional deployments for the performance of pure civilian science in the Arctic.

It was early in 1989 that the Navy agreed to collect Arctic Ocean water samples for a civilian researcher during a spring deployment. The endeavor was intended to create a degree of accommo-



USS Cavalla *during SCICEX '95.*

dation among all those involved. Successful execution of this small-scale data collection was also intended to provide the Navy new information and understanding of Arctic Ocean currents that it would otherwise not acquire.

The collection of water samples during ICEX 1-89 went smoothly. A second collection was requested for a deployment in 1990. The Navy agreed to continue the effort. Concurrently the ARC and NSF continued to address the more comprehensive idea of dedicated Arctic Ocean science deployment(s) by an SSN. In 1990 the University National Oceanographic Laboratory System (UNOLS), which coordinates the U.S. academic community's research fleet, requested that the UNOLS Fleet Improvement Committee study the potential uses of a nuclear submarine for Arctic oceanographic research.

In early 1991 the ARC and NSF agreed that in order to accomplish the needed Arctic Ocean research, a dedicated cruise or series of cruises by a submarine would be required. The collection of data for science in small quantities, as was done with the water samples, was simply inadequate and impractical in the face of the emerging scientific interest in the Arctic Ocean and the gross lack of understanding of the area. Even if a scientist were to accompany every operational deployment the Navy made to the Arctic, such a program would never produce the integrated, interdisciplinary data sets needed by science. A dedicated science cruise fully committed to ocean data collection became the objective. Better yet, and clearly justifiable in the minds of the science community, would be a series of cruises.

Coincident with the development of the concept of dedicated cruise(s), the reduction of military forces began, as the Cold War abruptly ended.

In 1991 the ARC and NSF's Office of Polar Programs co-chaired a meeting with five prominent "Arctic" oceanographers and Navy representatives from the aviation, submarine, and "ice-camp" communities. The meeting was intended to start active discussions between science and the Navy concerning science's data needs and the Navy's ability to fulfill them.

In October the ARC prepared a point paper addressing the use of an SSN as an Arctic research vehicle, describing advantages to the Navy as well as to science.

In December 1991 the ARC met at the U.S. Naval Postgraduate School in Monterey, California. The theme of the meeting focused on the Navy's ability to support civilian Arctic Ocean research and data collection. The ARC responded positively to the presentations and embraced the concept as a major Commission activity.

In January 1992 the UNOLS report called *Scien-*

tific Opportunities Onboard a Nuclear Submarine (quickly dubbed the "SOONS" report) was published. The chair of UNOLS sent a copy to the Secretary of the Navy for comment and received a reply that the Navy was not interested in using an operational submarine for science. The response further stated that UNOLS should investigate the use of NR-1, an experimental, small, Navy-owned, nuclear research submarine. The reply neglected to note that NR-1 must be towed to its operations area by a surface vessel and is not capable of operating under ice.

By 1992 Navy interest in the project began to grow. At the same time the Navy defined the data collection area for science operations. To avoid diplomatic problems, the area was pointedly defined well clear of the established exclusive economic zones of all Arctic rim nations except the U.S.

In January 1993 the Navy was ready to plan an expanded (dedicated) science cruise. The planning for the first Science Ice Exercise (SCICEX) began with a committee of twelve prominent Arctic Ocean scientists and experts from the U.S. Navy's Arctic Submarine Laboratory (ASL), located in San Diego, California.

The first scientific cruise took place in September and October 1993 aboard the USS *Pargo* and proved to be a watershed event. On 21 November, drawing on the success of the *Pargo* cruise, the ARC convened a meeting of senior officials of the Navy and Federal science agencies to discuss where to go next. At this meeting were representatives of the Office of Naval Research (ONR), NSF, the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), the ARC, and the Chief of Naval Operations (CNO) staff. It was agreed to continue the program.

Early in 1994 the CNO's staff, ONR, and the ARC drafted a Memorandum of Agreement (MOA) to ensure continuation of the program over several years. NSF, NOAA, the USGS, and ONR, as participating science agencies, together with the Assistant Chief of Naval Operations and the Commanders of the Atlantic and Pacific Submarine Fleets, signed the agreement on August 17, 1994.

The first formal SCICEX cruise under the MOA departed from Pearl Harbor, Hawaii, aboard the USS *Cavalla* on March 8, 1995. It concluded with a port call near Victoria, British Columbia, on May 23, 1995. During the interim between the *Pargo* and *Cavalla* cruises, the Navy increased the unclassified operating depth of submarines from 400 to 800 feet and the unclassified speed from 20 to 25 knots. These unprecedented changes in Navy security restrictions were the first since World War II, and they allowed the submarine to collect unclassified data over the full extent of the surface mixed layer in the Arctic Ocean. At the same time the Navy declassified both the name of the vessel and the sailing date for the 1995 cruise well before the beginning of the exercise. This was another unprecedented action, which greatly benefited cruise planning. These steps were taken by the Navy to increase the value and utility of the SCICEX Program.

During the five years of the active SCICEX Program, the science community has benefited from an enormous infusion of data. Each submarine that was deployed was fitted with at least 8 and as many as 13 ocean data collection systems. On the last two cruises, the USS *Hawkbill* carried the Seafloor Characterization and Mapping Pods (SCAMP), the largest and most expensive civilian research system ever installed aboard a submarine.

The SCICEX submarines collectively spent 211 days in the data collection area and cruised over 95,000 km collecting data under sea ice. Not only was the data take huge (conservative estimates claim a doubling of the data available on the Arctic ocean in the seven-year period), there were notable and unique scientific achievements, most of which were only made possible from a submarine. They include (at this writing):

- Unequivocally superior access to the Arctic Ocean—in all seasons, in all weather, to all areas—on a platform that was quieter, more stable, and at least five times faster than any other Arctic Ocean data collection platform ever employed;
- Six synoptic views of the Arctic Ocean with co-registered data sets, achievements that no other platform had accomplished;
- Confirmation of significant warming of the core Atlantic water in the Arctic and abrupt movement of the Atlantic/Pacific front into the western Arctic Ocean basin;
- Determination that the Arctic sea ice pack has thinned by as much as 40% in this decade;
- Sub-bottom profiles heralded as the highest quality ever observed (because of the submarines' quietness);
- First-ever swath bathymetry surveys (in the 1998 and 1999 cruises) of critical areas of the Arctic ocean (Chukchi Cap, Northwind Rise, Lomonosov Ridge, and Gakkel Ridge), adding over 25 million soundings to the existing,

Dr. C. Peter McRay (right), of the University of Alaska Fairbanks, and Jeff Gossett, of the Arctic Submarine Laboratory, at the North Pole during the USS Pargo's 1993 SCICEX Demonstration Cruise.

USS Cavalla *surfaced for a science station during SCICEX '95. Note the warming hut at the left.*

all-source database of approximately 1 million, thus creating a new picture of the ocean bottom; and

- Irrefutable information, provided using SCAMP, about a massive Arctic ice sheet, the presence of huge icebergs, and sea floor volcanism, all of which will have great impact on the earth's geologic and climatic history.

Clearly SCICEX has motivated numerous revisions in what science had previously thought of the Arctic—and there remains much more data to be analyzed.

In addition to the at-sea science, other notable events have taken place during the past five years that are worth noting.

In October 1998 NSF and ONR jointly sponsored a workshop entitled SCICEX 2000. That meeting, attended by representatives of the government's science agencies, the academic community, and the Navy, attempted to define the future of SCICEX when all SSN 637 Class submarines have been retired in late 2000. The outcome was clearly mixed; a new understanding of the Arctic was described, but the prospects for continuing a regular series of dedicated cruises were stated as remote.

Then in May 1999 the U.S. Navy stepped forward and offered the USS *L. Mendel Rivers*, the last of the 637 Class, as a shared military–science community submarine for about 8 years (when her reactor core will be exhausted). Unfortunately sufficient resources were not available to pay for the science community's half of the project.

So where does science go next? The Navy is supportive of the need but also realistic about the availability of assets for any dedicated cruises. The Navy raised the prospect of a dedicated period of time for science, 2–3 years in the future. However, to ensure that such an event occurs, the Navy requested that the science community prepare a justification of its needs for data and dovetail the suggested science with Navy science needs. Regular dialogue between both parties in the months and years ahead was assured. Certainly this recent discussion is a good sign, given the alternatives.

At the same time, the science community, its appetite whetted by the new discoveries in the Arctic, seeks more information on the Arctic, sooner rather than later. Interest in data from the SCAMP system is considered of particular value. To that end Arctic scientists and science administrators met on March 28, 2000, to identify all possible data collection avenues to be examined and pursued in an effort to obtain a suitable platform. Six possible "roads ahead" were discussed, the last five being subordinate to the first.

The first option is obviously to continue a dialogue with the Navy for the use of a Navy nuclear submarine for dedicated cruises in the Arctic. At the SCICEX 2000 Workshop the Navy indicated that a dedicated cruise could be conducted if a satisfactory justification were submitted. The frequency and duration of such a dedicated cruise remains undefined.

If it is not possible to continue the use of Navy submarines, the most satisfactory alternative may be the construction of a high-endurance autonomous underwater vehicle (AUV) for surveys under the Arctic sea ice. Such an AUV would be a major step upward in the capabilities of AUVs. An endurance on the order of 10,000 km for under-ice survey is required, and the vehicle would also have to support the power demands of SCAMP or a SCAMP-like system for bottom mapping. Battery power is insufficient for this task, and unmanned nuclear-powered systems are considered unacceptable. This leaves the kind of air independent propulsion (AIP) systems now under development or in operation by various European submarine manufacturers. In addition, the unattended, automated operation of SCAMP is far from reality, and a considerable development effort will be required for such a system. The time horizon for successful deployment is estimated to be 8–10 years. An AUV workshop will be conducted in Monterey.

The third alternative identified was the use of an AIP submarine from another nation. The Swedish Navy approached the Swedish science community about their interest in such a platform. Similarly Germany is working on the design of an AIP submarine system, and discussions will be initiated with the Alfred Wegener Institute in Bremerhaven, Germany. Either of these opportunities will require a major reorganization of the program to take into account the international implications.

Another alternative is the use of nuclear submarines from other nations. The possibility of using a Russian submarine has been discussed, but many concerns remain about utility and safety.

The fifth possibility is the development of a nuclear research submarine by the Japanese. The Japanese have communicated with U.S. scientists about their plans and have provided the concept design.

The sixth possibility is the development of NR2, a follow-on to the small nuclear research submarine NR-1 but possessing advanced capabilities. This is still in the planning stages, and several Arctic scientists have had input. This option is over a decade away.

Because the prospect of dedicated science cruises has diminished greatly, the Navy has offered to use portions of classified Arctic missions to collect high-priority scientific data. The mechanism for conducting these "accommodation" cruises was included as an element in the new MOA signed in May 2000. The first contribution to this effort was made by the USS *L. Mendel Rivers* late in 2000, with the data due to be released in January 2001.

In conclusion it is important to note that in the course of six SCICEX deployments, the total body of unclassified data available to science on the Arctic Ocean has been conservatively estimated to have more than doubled. Yet the advantages of employing an SSN for science have not yet been fully exploited. It remains critical that an ongoing dialogue be continued between the Navy and the science community. Significant challenges were overcome to create the SCICEX Program. A similar approach to the future of the concept of Arctic Ocean data collection remains the most logical approach.

Monitoring Sea Ice Thickness from Space

Background

Interactions between sea ice, the ocean, and the atmosphere in the polar regions strongly affect the earth's climate. Global climate models project that the largest greenhouse warming will be in the polar regions. This high-latitude sensitivity displayed by climate models has been attributed to positive feedback involving surface albedo, air temperature, and reduced sea ice extent and thickness.

The area covered by sea ice varies significantly. During the winter, sea ice covers approximately 7 million square kilometers of the Arctic Ocean. By the end of a typical summer, melt reduces that coverage to approximately 5 million square kilometers. The areal extent and thickness of the sea ice cover are sensitive to small changes in heat input or climatic warming because the ice is relatively thin—approximately three meters thick on average. Variations in sea ice extent, in turn, have the potential to amplify small changes in climate, in part because sea ice has a high albedo (that is, it reflects a relatively high proportion of the incoming solar radiation) and because it insulates the underlying ocean from the cold atmosphere.

Sea ice moves, largely in response to the wind, creating openings and closings of the ice cover and variability in ice thickness. In the winter, openings, called leads, expose the relatively warm ocean to the atmosphere. Through these openings, the heat flux to the atmosphere could be up to two orders of magnitude higher than over areas of thicker ice. Salt rejected by ice growth in these openings forms a cold dense brine, which sinks and affects the salt balance of the upper ocean. During closing events, sea ice is piled up or rafted to form ridges with deep keels. The thickness distribution of the ice cover is a record of the interplay between dynamical processes (lead formation, ridging, and advection) and thermal processes (ice growth and melt). The mechanical behavior of the ice cover also depends on the spatial variability of its thickness. Thus, thickness distribution of sea ice is an essential descriptor of the Arctic Ocean sea ice mass and heat balance.

This report was prepared by Ron Kwok, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

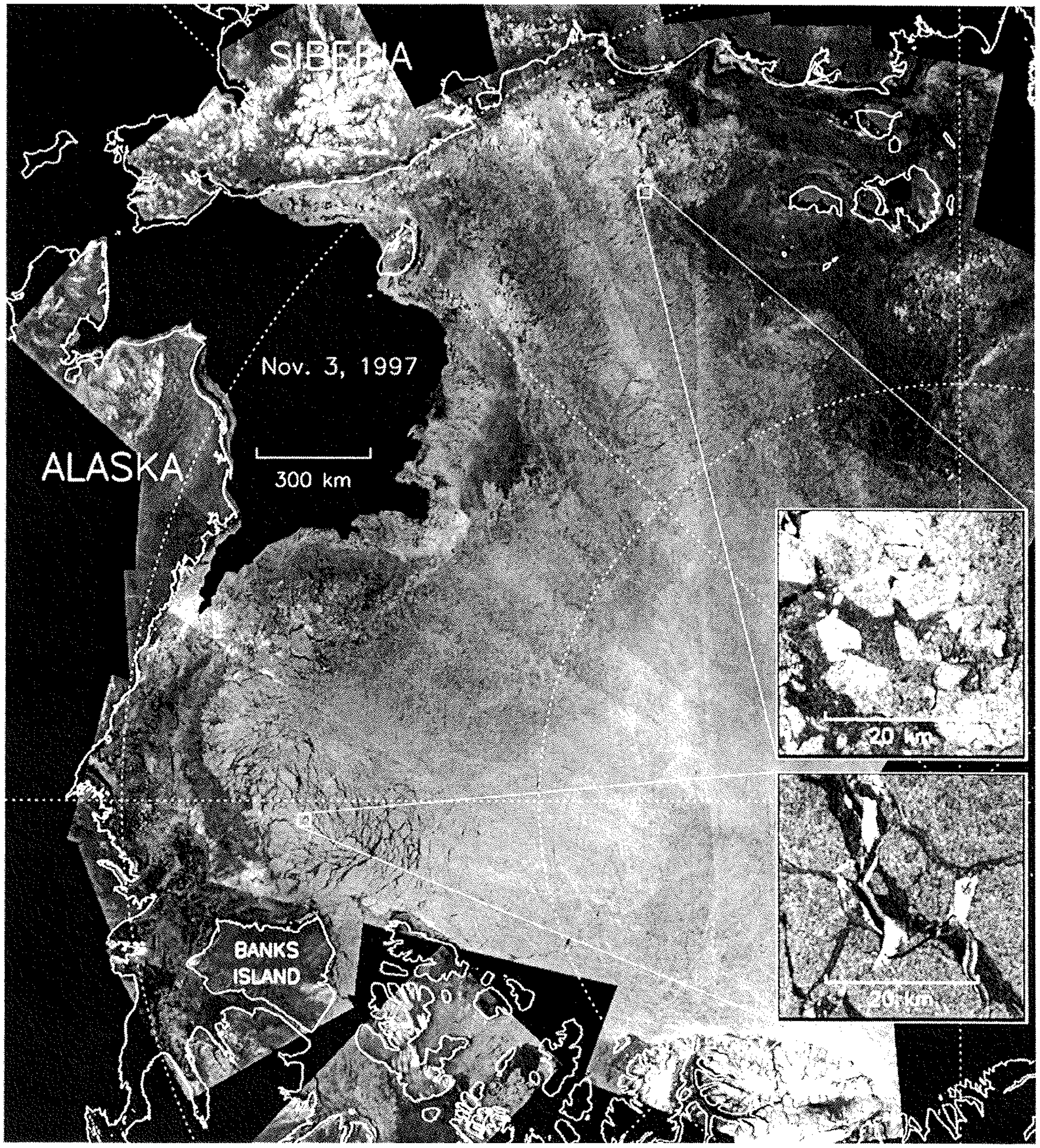
Our knowledge of the Arctic ice thickness distribution is derived largely from analyses of sonar data from submarine cruises. Preliminary evidence from analysis of ice draft data from submarine cruises shows that the ice cover has thinned by more than a meter over the past two to four decades. Moored upward-looking sonars have also been used to sample the thickness distribution at fixed locations. However, these observations do not provide a complete spatial picture or allow continuous monitoring of the thickness distribution.

This article describes a procedure for deriving the thickness of the seasonal ice created in the openings and closings of the ice cover using sea ice motion derived from sequential synthetic aperture radar (SAR) data. The procedure is now being used routinely to estimate the seasonal ice thickness over a large part of the Arctic Ocean. The results provide fine resolution of the seasonal end of the thickness distributions, which is the crucial range that produces the most ice growth, the most turbulent heat flux to the atmosphere, and the most salt flux to the ocean.

Viewing the Arctic Ocean with Synthetic Aperture Radar

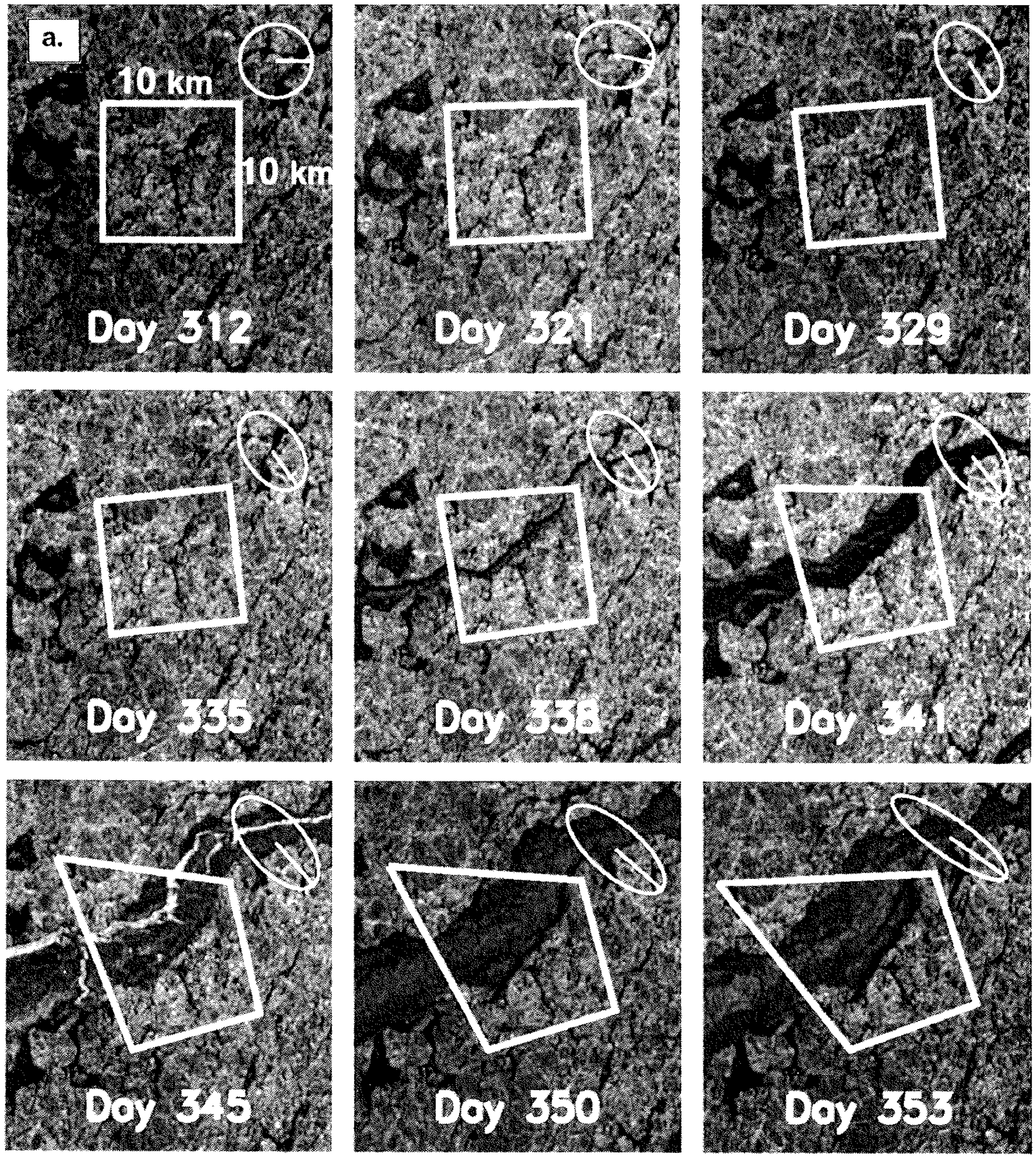
Spaceborne SAR provides high-resolution imagery of the earth's surface. It does not depend on solar illumination, so it provides day and night coverage of the Arctic Ocean, and the data are relatively free from contamination by atmospheric effects. The image on the next page is a mosaic of a large part of the Arctic Ocean, constructed using Radarsat SAR imagery. The satellite was launched in November 1995 into a 24-day repeat cycle, an orbit configuration that provides near-repeat coverage of the high latitudes at three-day intervals. The C-band radar (with a wavelength of approximately 5 cm) has an imaging mode that illuminates a wide swath (460 km) and is well suited to large-scale mapping of the earth's surface.

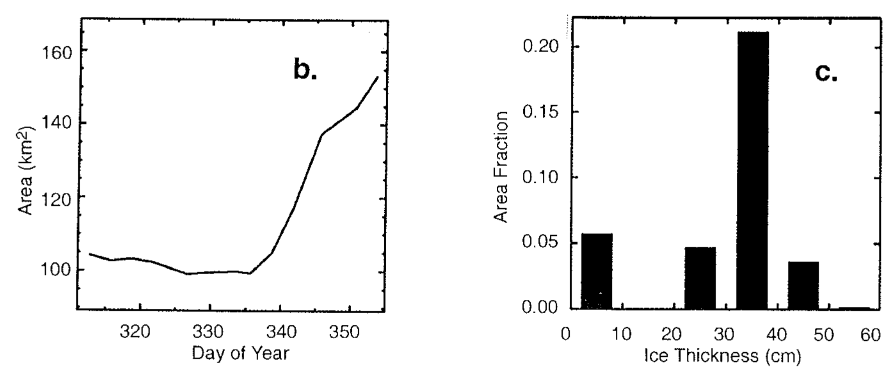
SAR provides an amazingly detailed look at



Mosaic of the western Arctic Ocean constructed from Radarsat imagery. The images were processed at the Alaska SAR Facility, University of Alaska Fairbanks. Each pixel covers an area of 100 × 100 m. At this resolution it takes almost a billion samples to cover the entire Arctic Ocean ice cover. Other spaceborne remote sensing instruments that provide regular coverage of the Arctic Ocean have resolutions more than ten times poorer than that of the SAR. Insets show the details of the actual data. (Imagery copyright CSA 1997.)

sea ice cover, but the level of detail is so great that it is not at first apparent how to utilize the data for improving sea ice data sets and models. Sea ice motion is readily observable in SAR imagery and is derived by tracking common features in time-sequential image frames. In the Northern Hemisphere, drifting buoys have provided a substantial base of knowledge of large-scale (over 300 km) ice motion in the central Arctic Ocean, but gaps need to be filled, particularly in regions that have been sparsely sampled by buoys. High-resolution SAR ice motion reveals deformation of the ice cover at the kilometer scale. When the ice cover deforms, the material yields along cracks that are then filled with open water or ridged ice. Typically, these thin cracks (usually a few kilometers wide) are long linear features that could extend for hundreds of kilometers. Dense spatial sampling is





Time series observations of one Lagrangian element (initially enclosed by a 10- × 10-km square) in Radarsat imagery. a) The deformation of a cell over a period of 41 days beginning on November 8, 1996. The area of the cell stays fairly constant until Day 338, when a lead opens. The same lead continued to open between Days 341 and 345, contributing new ice area and ice categories to the cell. At the end of the 41-day period, the area of the thin ice occupies more that 50% of the total cell area; b) The history of the area of the cell; c) The thin-ice categories occupying the new areas created since Day 312. The largest thin-ice category was created between Days 341 and 345.

therefore important for understanding small-scale processes because the motion field is spatially discontinuous. With the repeat coverage from the Radarsat satellite, we now have the ability to derive ice motion over the entire Arctic Ocean. In addition to the measurement of ice motion, we have devised a novel approach for estimating the seasonal ice thickness distribution using the small-scale deformation described by the ice motion from high-resolution radar.

The computational procedures for extracting ice motion and estimating ice thickness are implemented in a system called the Radarsat Geophysical Processor System (RGPS). It uses over 100 wide-swath radar images of the Arctic Ocean every three days and produces estimates of ice motion, deformation, and thin-ice thickness distribution (0–2 m). We have acquired repeat coverage of the Arctic Ocean since November 1996. Over a 24-day repeat cycle of the satellite, we have close to eight observations of the western Arctic Ocean within the ASF reception mask in Fairbanks, Alaska. The repeat coverage of the Eurasian Basin is less frequent, only six days. We expect to continue this acquisition process over the life of the Radarsat mission. The goal is to build a data set that could support large-scale studies of the geophysical processes of the Arctic Ocean, and eventually a data set with a time span that is long enough for climate research.

Deriving Seasonal Ice Thickness

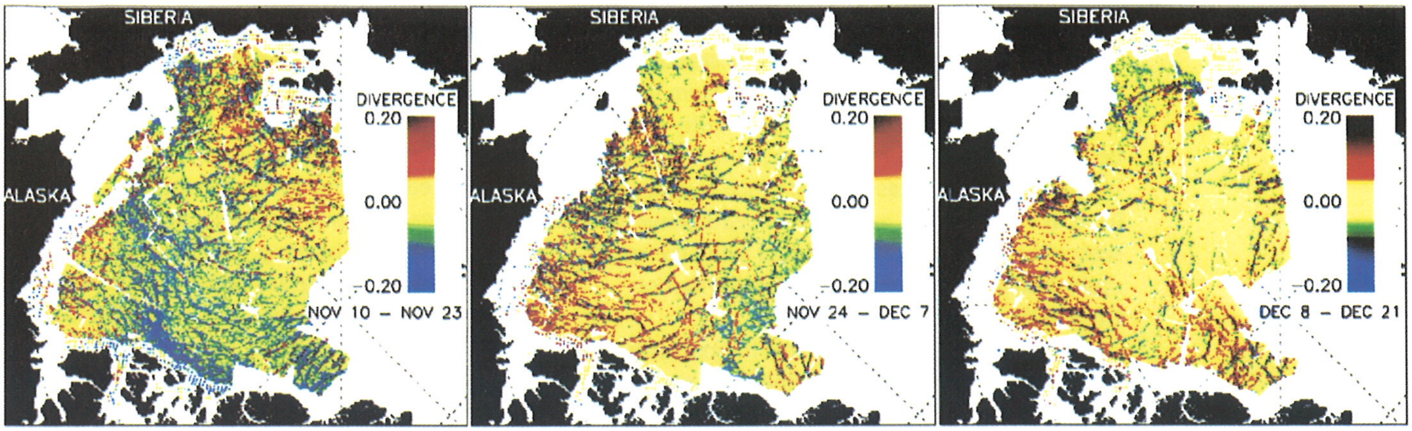
The approach to estimating ice thickness depends on repeated observations of material elements or cells of sea ice in sequential SAR imagery. The figure to the left shows the time series of observations of one 10- × 10-km cell within a matrix of such cells, strain ellipses describing the deformation, graphs of the history of the cell area, and the thin-ice coverage within that cell at the end of a 41-day period. Line segments connecting the four vertices of a cell define its boundaries. The drift and deformation of a cell over time are obtained by tracking the displacement of its vertices in sequential SAR imagery. The underlying deformation of the cell evolved from a circle through a series of increasingly eccentric ellipses showing the directions of maximum stretch and compression as a lead opens. Note the steady evolution of the ellipse. This sequence of observations demonstrates that lead ice controls the mechanical behavior of the ice cover through its orientation and yield strength. This orientation of the weakest ice (the thin ice in leads) gives the ice cover a marked anisotropic character, or directional dependence in its mechanical behavior.

Ice thickness distributions during the winter are produced from intermediate estimates of ice age. The age histogram of the ice within a cell is computed from the temporal record of area changes. An age histogram of sea ice specifies the fractional area covered by ice of different chronological ages. Every time the area defined by a cell is imaged by the radar, if the area increases compared to an earlier observation, we interpret it as the creation of an area of open water. New ice is assumed to grow over this area immediately after opening. The uncertainty of the ice age occupying this area depends on the time interval between observations. This age range is recorded as a new age category in the histogram. At the same time a new category is introduced, existing age categories are "aged" by the same time interval. In the figure this procedure created five ice age categories from the sequence of positive area changes (divergence) since Day 335. A decrease in area (convergence) is assumed to have ridged the youngest ice in the cell, reducing its area. The assumption here is that once ridging starts, the deformation tends to be localized in the recently formed thinner and weaker ice in leads. This area of ridged ice is tracked as a separate category in the age histogram. Ice age is converted to ice thickness using an empirical air-temperature-dependent ice growth formula, with the temperature taken from fields derived from surface measurements. Volume is conserved when ice is ridged. We assume that all ridged ice is five times its original thickness and occupies a quarter of the area.

Complete coverage of the Arctic takes approximately 70,000 cells. The thickness distribution of an individual cell evolves independently based on its deformation history and the near-surface air temperature. The thickness distribution keeps track of all the seasonal ice created by the deformation of the cells over the entire winter. The ice thickness distribution of the ice cover at the beginning of the season is not known.

Ice Motion, Deformation, and Thickness, Winter 1996–97

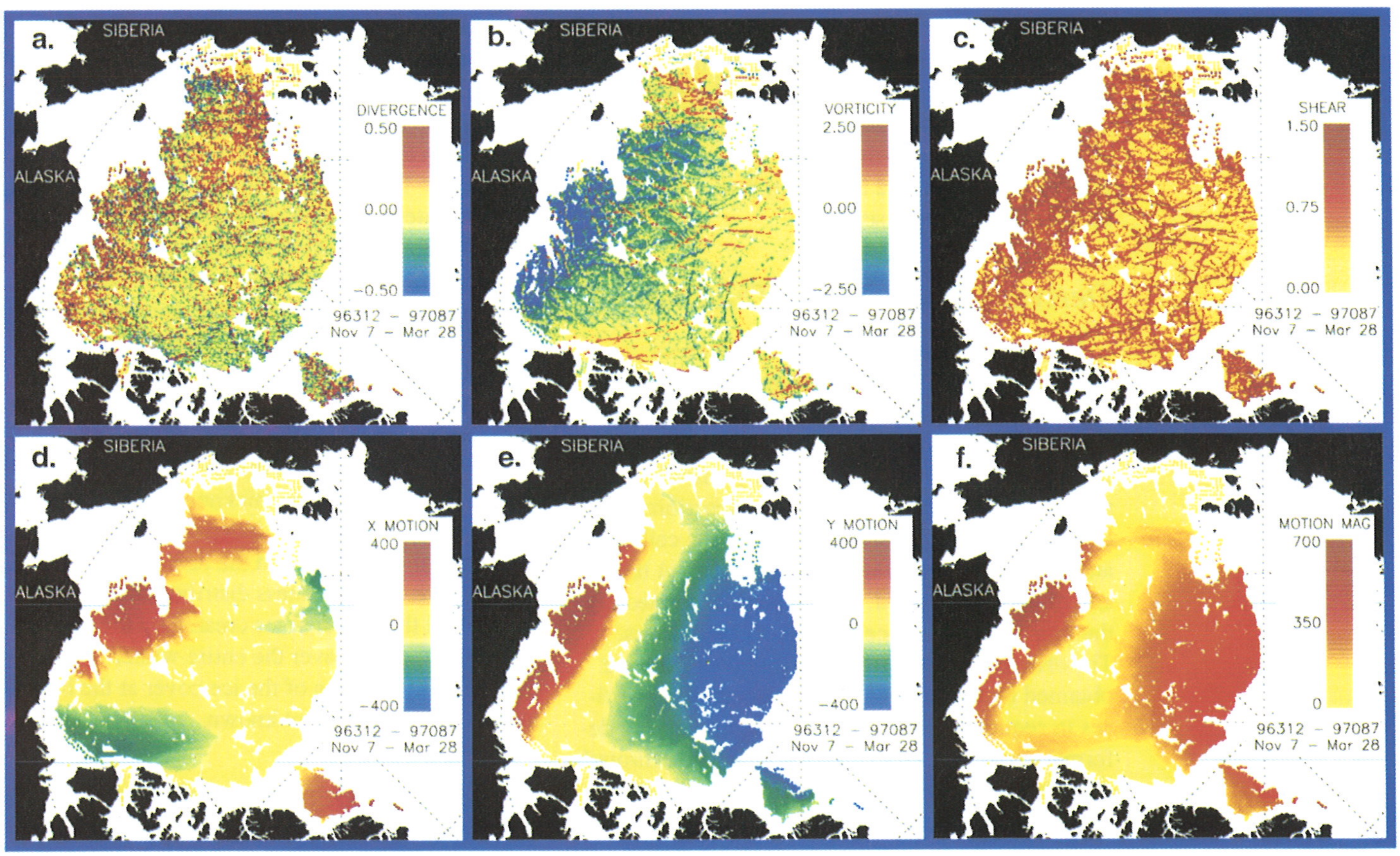
Over an ice growth season, the products from the RGPS system provide temporal records of the following properties of each 10- × 10-km cell: its



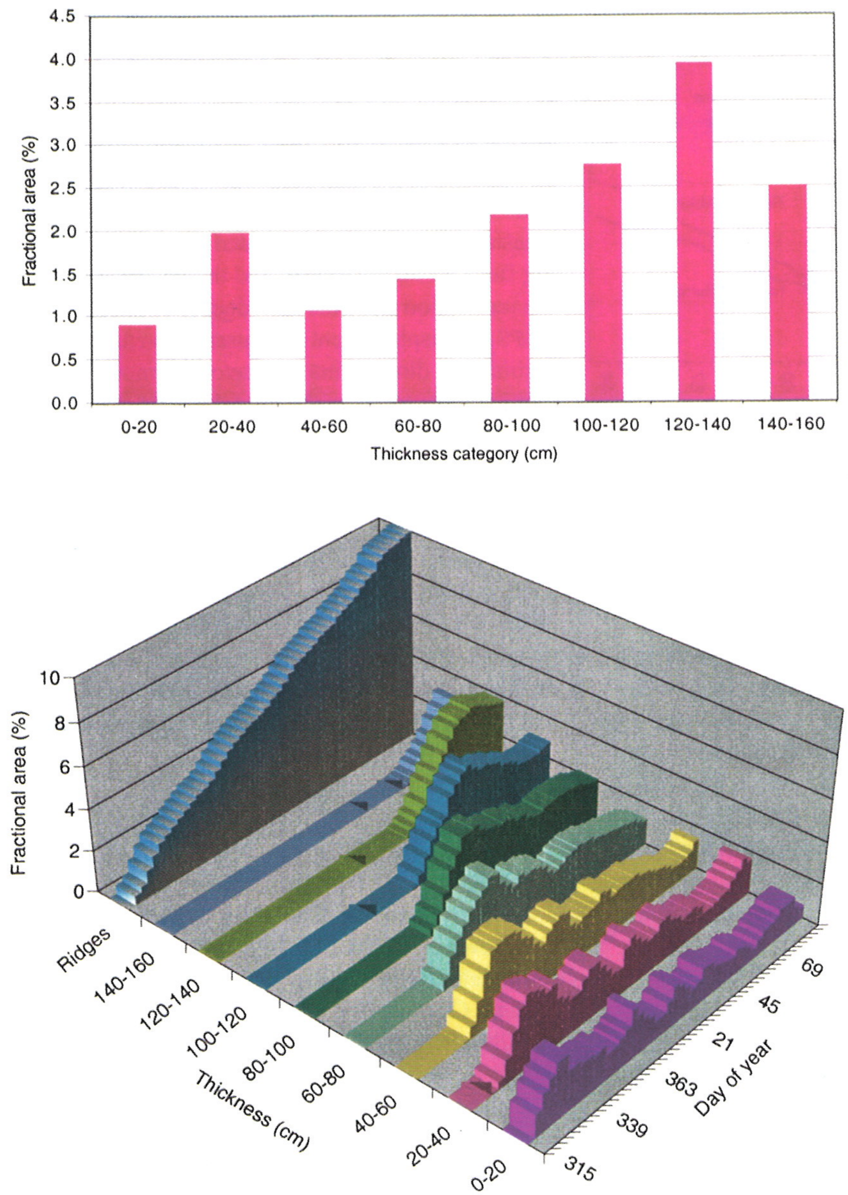
Divergence of cells over a six-week period from November 10 through December 21, 1996. The spatial character of the deformation of the ice cover shown here is sampled by more than 37,000 cells.

geographic location, its deformation history, and its thickness histogram. Here we examine some of these properties to illustrate the detailed character of the ice cover as revealed by 35,000 cells covering an area of approximately 3.5 million square kilometers over the Arctic Ocean.

The temporal and spatial variability of cell area change over three 14-day periods in November and December 1996 is shown in the figure above. Between November 10 and 23, the high concentration of convergent cells in the eastern Beaufort Sea above 75°N adjacent to the Canadian Archi-



Cumulative motion and deformation of the ice cover between November 1996 and March 1997. a) Divergence (fractional cell area change). b) Vorticity (clockwise rotation in blue and counterclockwise rotation in red; units in radians). c) Magnitude of shear. d) x-component of motion (red is to the right of the page; units in kilometers). e) y-component of motion (red is to the top of the page; units in kilometers). f) magnitude of the motion vectors (units in kilometers).



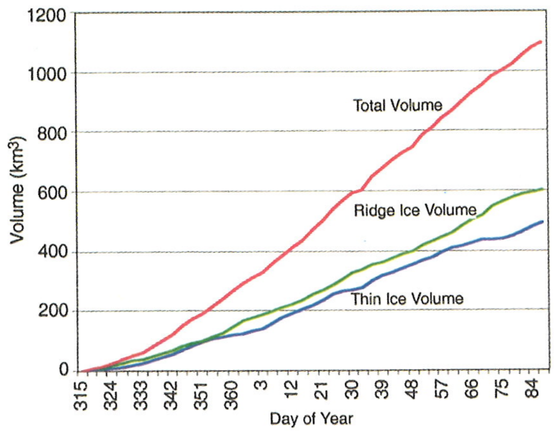
Ice thickness distribution at the end of March 1997 (top) and evolution of the thickness distribution between November 1996 and March 1997 (bottom).

pelago and Greenland coast indicates extensive pressure ridging of the ice cover. In contrast, the eastern Arctic toward Siberia has a more divergent character. Because of the convergence, the sampled ice cover lost approximately 3.5% of the area over this period. The next period, November 24 through December 7, shows very distinctive diamond-shaped intersecting lead patterns over the ice cover. Except for the regions near the ice margin, all the deformation is localized along leads while the rest of the ice cover remains unaffected. The length of some of the leads is quite remarkable; several leads can be seen to span a large fraction of the Arctic Ocean. The entire ice cover, except for the openings along the margin of the Beaufort Sea, stayed fairly quiescent, with minimal lead activity during the last period, December 8 to 21. The area of the sampled ice cover increased by 2% and 1% during the latter two periods, respectively.

The cumulative displacement and deformation of the ice cover are shown in the figure on the bottom of p. 12. Most of the divergent cells (cells with an area increase) are located next to the Alaskan and Siberian coasts. The cells in the central Arctic in general have smaller cumulative divergence. The ice cover west of the Canadian Archipelago, an area of extensive pressure ridging, has the largest cumulative convergence (blue). The Beaufort Gyre, a clockwise motion feature in the large-scale general circulation of the ice cover, shows up very distinctly as a blue region in the vorticity field and as alternating colors (red-yellow-blue) in the x- and y-component motion fields. At the center of the Beaufort Gyre, there is an area of low shear corresponding to the center of the rotating field. The other general circulation feature, the Transpolar drift stream that transports ice from the Siberian coast to Fram Strait, is also captured as large negative displacements in the y-component motion field.

The figure to the left shows the ice thickness distribution (0–1.6 m) at the end of March 1997 and the fractional coverage of each cell by each thickness category. Approximately 1%, 2%, and 1% of the area are covered by sea ice between 0 and 20 cm, 20 and 40 cm, and 40 and 60 cm in thickness, respectively. The spatial distribution of the thinnest ice category is a record of the most recent divergence in the ice cover. Only sea ice in the openings of the Arctic Ocean that has not ridged in convergent events can survive to grow into the thicker undeformed ice. At the end of March, approximately 10% of the area is covered by ridged ice formed in the intervening five months. The chart of the evolution of the seasonal ice thickness distribution shows the growth of seasonal ice in different thickness cateogories over time. Thin ice (between 0 and 20 cm) covers 1–2% of the ice cover over the entire period. In the winter the highest heat flux from the ocean to the atmosphere and the most salt flux to the ocean are from the areas covered by this category of ice.

The volume of sea ice produced by deformation between early November 1996 and the end of



Volume of sea ice produced between November 4, 1996 and March 28, 1997. The volume is computed from the thickness distribution estimates.

March 1997 is shown in the figure above. The ice volume production is computed directly from the thickness histograms. In the five months more than 1000 km^3 of seasonal sea ice was produced over the 3.5 million square kilometer area, with approximately equal volumes stored in ridges and undeformed ice. The maintenance of a stable Arctic sea ice cover depends on a balance between the seasonal ice growth, melt, and import/export of sea ice. The estimated volume is useful for understanding the ice cover mass balance and serves as a baseline for detecting long-term changes in the Arctic Ocean.

Conclusions

The Arctic has undergone measurable change this decade in several key indicators of climate warming. The four-year time record from Radarsat is fortuitously timed to potentially provide indicators of climate change through ice motion and age/thickness derivations that can be used to determine the surface heat and mass balance of the Arctic Ocean. The RGPS deformation measurements offer an unprecedented level of spatial and temporal coverage and detail for all seasons of the year. We have, for the first time, extensive measurements of the ice motion that can be used in concert with a variety of ice models for verification studies, for driving the models as forcing fields, and in data assimilation procedures. The ice production rates estimated with RGPS can be compared to those computed by models driven by the geostrophic wind and a force balance approach. The ice motion measured with RGPS can be used directly as a forcing field for an ice model, and the uncertainty in the ice motion can thus be reduced. Finally, the RGPS ice displacement measurements can be assimilated directly into an ice/ocean model so that ice trajectories in the model can be made to match the observed trajectories. The value of these uses for the RGPS products will increase as the observational record becomes longer and a greater variety of seasons are recorded. We have already seen preliminary results for two winter seasons—1996 and 1997—and they show that the ice in those two years evolved in markedly different manners. Ultimately a long record of the ice deformation and ice production rates can be developed that will contribute to the assessment of the climate of the Arctic Ocean.

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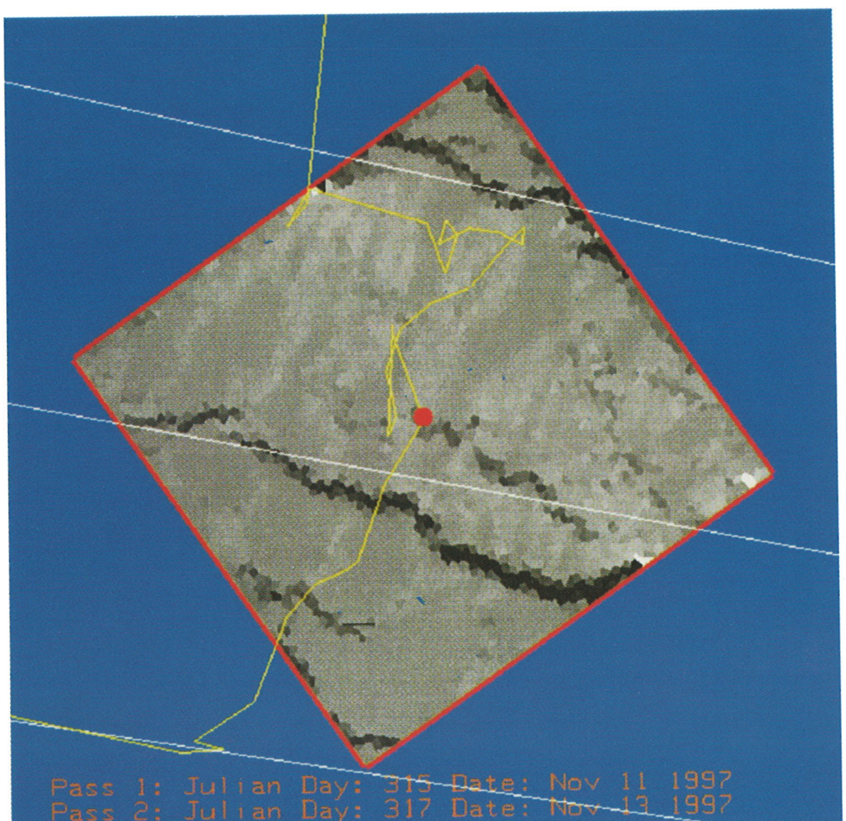
Observational and Theoretical Foundation for Improving Arctic Sea Ice Models

This report was prepared by James Overland, Pacific Marine Environmental Laboratory/ NOAA, 7600 Sand Point Way NE, Seattle, WA 98115; and Jacqueline Richter-Menge, U.S. Army Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, NH 03755.

A current goal of the Office of Naval Research (ONR) is to create a new version of the Polar Ice Prediction System (PIPS) model, which will improve ice forecasting capabilities by including better representations of ice movement, ice thickness distribution, and atmospheric and oceanic forcing of the ice cover. Climate studies show that thermodynamic processes that control the surface heat budget and mass balance of the sea ice cover can't be separated from the effects of ice dynamics. Thus, sea ice modeling projects by the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE), and the National Science Foundation (NSF) that are motivated by the influence of the Arctic on global climate change are converging to have the same modeling interests as the ONR project.



Example of the very-high-resolution model pack on November 1, 1997, after 24 hours of deformation. The dark areas denote regions where the ice has failed via the formation of a lead.

The PIPS model is being improved by including recent advances in understanding the fundamental processes that govern ice motion. These advances are based on satellite observations, in-situ observations from drifting buoys, and high-resolution numerical modeling. Taking full advantage of improvements in computational efficiency to produce models with spatial resolutions of 10 km (a ten-fold improvement over previous models) significantly enhances the impact of direct observations on model formulation. Coarser-resolution models were incapable of incorporating these advances in the understanding of sea ice processes.

The importance of understanding sea ice processes on spatial scales of 10–500 km was highlighted at an Arctic Sea Ice Dynamics workshop held in Seattle, Washington, on March 1–2, 2000. The workshop, attended by 28 investigators from around the world, was successful in summarizing recent research results and model capabilities and establishing recommendations for models of sea ice dynamics.

Key to understanding sea ice dynamics are sequential SAR images, used to estimate ice motion on scales of 5–10 km over a 100- to 1000-km^2 area. This is equivalent to placing thousands of drifting buoys on the ice. These ice motion investigations have revealed the presence of long linear discontinuities or sliplines in the velocity fields. Although individual Arctic ice floes are about 1 km across, they form aggregates of solid body motions separated by sliplines 30–150 km apart, similar to a granular plastic material.

To understand the theory of regional ice processes, a very-high-resolution granular model of the Arctic pack, composed of thousands of discrete floes in a 100- × 100-km area, has been employed. Each modeled floe has its own ice thickness distribution. Interactions between floes are modeled using parameterizations of pressure ridging and fracture. Currently the results from the recent Surface Heat Budget of the Arctic (SHEBA) experiment are being used to further develop and test the model. The model has been driven by wind stress measurements from the SHEBA experiment and boundary kinematics derived from satellite imagery of the pack surrounding SHEBA. At the beginning of a simulation the ice floes completely fill a square domain and are frozen together. Deformation of the model pack is driven by boundary floes with motions that are kinematically defined from satellite imagery. Deformation causes the floes in the interior of the domain to be pushed together to form pressure ridges and pulled apart to form leads. The ice thickness distribution within the floes changes in response to air and water temperatures and radiative fluxes. The simulation results are being compared with SHEBA field measurements of ice stress, strain, and thickness.

A major question considered at the workshop was whether the current generation of continuum sea ice models is capable of modeling sea ice at the 10- to 75-km scale. The answer is yes, with some additional considerations. The continuum models were originally designed to represent basin-scale processes, which were hypothesized to be plastic in nature. Examples of more recent continuum models with 10- to 15-km numerical resolution were shown at the workshop.

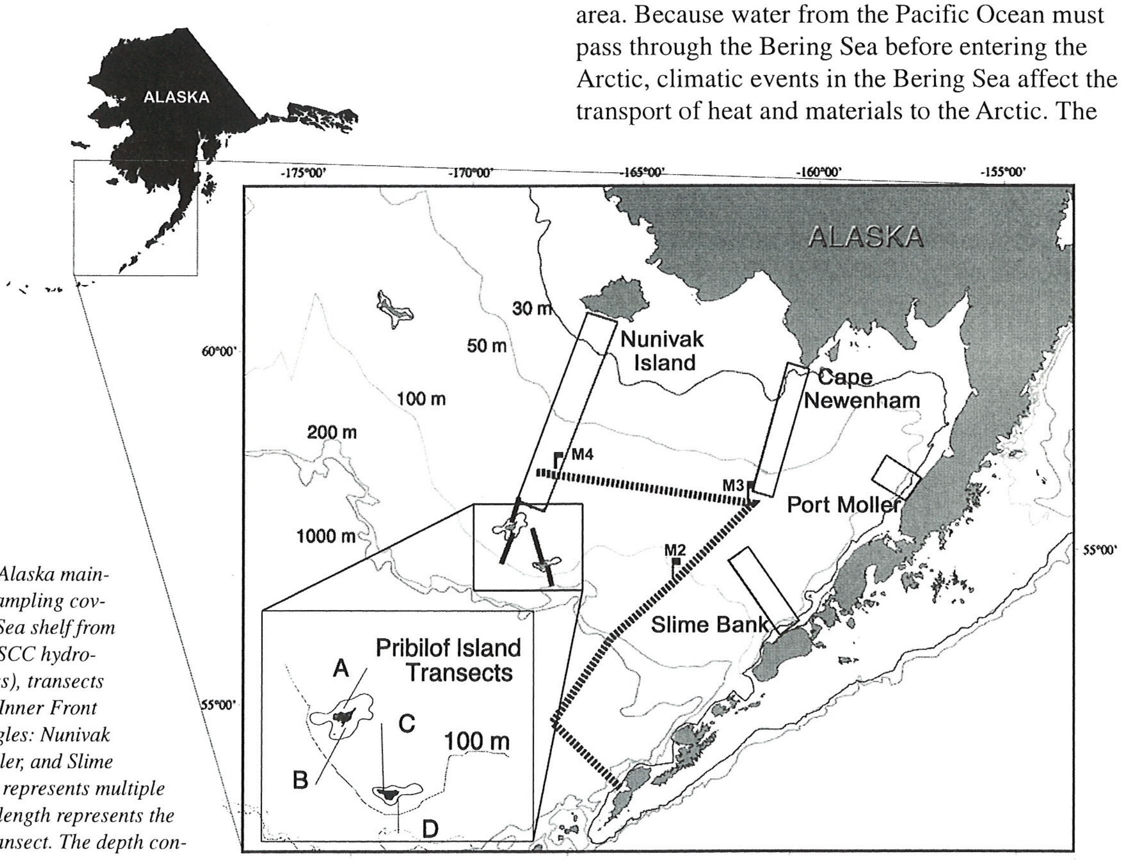
Comparing these results with SAR data, it is clear that transitioning the continuum models to a tool that can be used to represent finer-scale processes is not simply a matter of increasing the numerical resolution of the model. While the basic idea of sliplines is evident in the higher-resolution models, the damage zones are too wide and the secondary shear zones are not prevalent compared with SAR data. Having a multiple ice category representation as well as high resolution appears important.

Ecosystem Responses to Weather Patterns in the Southeastern Bering Sea

This report was prepared by G.L. Hunt, Jr., Dept. of Ecology and Evolutionary Biology, University of California, Irvine, CA 92697; and P.J. Stabeno, NOAA/ Pacific Marine Environmental Laboratory, Seattle, WA 98115.

Global climate models predict that global warming will have its greatest impacts at high latitudes. In particular, regions with seasonal ice cover may show large changes in the extent and duration of sea ice, such as is occurring in the Bering Sea and Arctic Ocean. For the North Pacific Ocean and the Bering Sea, U.S. GLOBEC (a multidisciplinary study of the effects of climate change on ocean productivity) in 1996 provided a series of predictions of how weather and ocean conditions might change with climate warming. Among the results were predictions that surface air and sea temperatures and storm frequencies would increase (as observed in 1997-98 and 1998-99, respectively) and that the average strength of the wind and sea ice extent would decrease (as observed in 1997 and 1998). The information acquired during our research provides insight into how the southeastern Bering Sea ecosystem might function in a warmer climate and demonstrates the speed and magnitude of its responses to changes in atmospheric forcing.

The Bering Sea is important not only because it affects events in the Arctic, but also because it is a region of major biological production. The Bering Sea is located in the northernmost part of the North Pacific Ocean, and its broad eastern continental shelf constitutes approximately 44% of its area. Because water from the Pacific Ocean must pass through the Bering Sea before entering the Arctic, climatic events in the Bering Sea affect the transport of heat and materials to the Arctic. The



The southeastern Bering Sea, the Alaska mainland, the Alaska Peninsula, and sampling coverage of the southeastern Bering Sea shelf from 1997 to 1999. Shown are the SEBSCC hydrographic lines (||||), moorings (flags), transects near the Pribilof Islands, and the Inner Front cross-frontal survey areas (rectangles: Nunivak Island, Cape Newenham, Port Moller, and Slime Bank). The width of the rectangles represents multiple transects across the front and the length represents the offshore distance of the longest transect. The depth contour around the Pribilof Islands is 30 m.

broad eastern shelf region contributes over half of the U.S. fishery production, with a commercial catch of king crab, walleye pollock, and salmon worth one billion dollars in 1997.

Two of the scientific programs that have been active in the Bering Sea in the late 1990s are the Inner Front Project (IFP), sponsored by the National Science Foundation's Office of Polar Programs, Arctic Natural Sciences Section, and the Southeastern Bering Sea Carrying Capacity (SEBSCC) program, sponsored by the National Oceanic and Atmospheric Administration's Coastal Oceans Program. The IFP focused on the coastal portions of the Bering Sea and the mechanisms at the inner front that could sustain prolonged production and promote trophic transfer to upper-trophic-level organisms. The SEBSCC program focused on the middle and outer shelf regions and constituted a mix of monitoring and process-related studies. Since the two programs shared many principal investigators in common and were complementary in scientific goals, there was extensive collaboration between the two groups of investigators.

Between 1995 and 2000 the southeastern Bering Sea experienced anomalies that included an unusually delayed ice retreat (1999), higher-than-normal sea surface temperatures (1997 and 1998), an elevated heat content of the water column (1998), strong cross-shelf transport in spring 1998 and summer 1999, a deep draw-down of nutrients (1997), major blooms of coccolithophores (1997–2000), an increase in copepods on the inner shelf (1997 and 1998), salmon returns to western Alaskan rivers far below predited numbers (1997 and 1998), emaciation of shearwaters (1997 and 1998) and an unusually high rate of shearwater mortality in 1997, and the presence of baleen whales in greater numbers in waters of the middle shelf than previously reported (1997 and 1998). There were also large variations in the timing and magnitude of storm events, the extent and duration of seasonal ice cover, and the timing and magnitude of primary production. Some of these anomalies appear to be related to unusual weather patterns, while the causes of others remain unknown. Here we focus on:

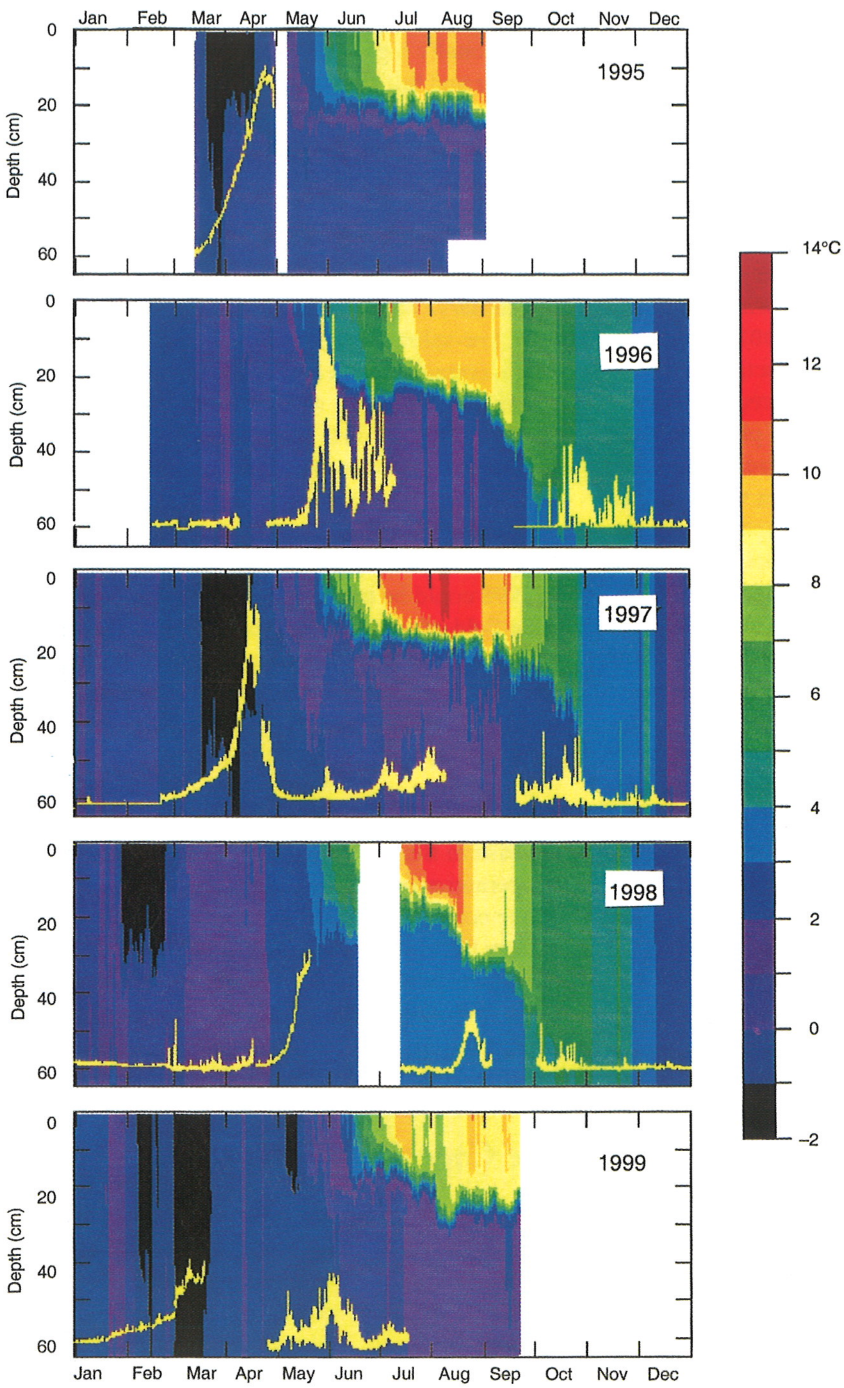
- How variation in the timing of ice retreat and the cessation of winter winds interact to determine the timing of springtime primary production;
- How events in 1998 interacted to enhance the export of warm, calcium-carbonate-laden water from the southeastern Bering Sea shelf to the Arctic Ocean.
- The occurrence of a bloom of a species of phytoplankton, the coccolithophore *Emiliania huxleyi*, that has never before been documented blooming in the southeastern Bering Sea; and
- Changes in the abundance of zooplankton over the inner shelf of the southeastern Bering Sea.

Our observations provide insight into how the southeastern Bering Sea ecosystem might function in a warmer climate and demonstrate the speed and magnitude of its responses to changes in atmospheric forcing.

The Southeastern Bering Sea Shelf

Waters of the southeastern Bering Sea shelf are differentiated by hydrographic and current domains associated with characteristic bottom depth ranges. Waters of the coastal domain (less than 50 m deep) typically are either weakly stratified or well mixed as a result of tidal currents and winds. Over the middle shelf domain (between 50 and 100 m deep), the mixing energy is not sufficient to stir the entire water column, resulting in a warm, wind-mixed surface layer and a tidally mixed bottom layer. Thus, during summer a strongly two-layered water column insulates the bottom layer. These deeper waters usually provide a reservoir of nutrients. The region separating the middle shelf and coastal domains is called the inner or structural front. Transition zones (middle front and shelf break front) also separate the middle shelf from the three-layered outer shelf (between 100 and 180 m deep) and the outer shelf from the slope waters.

Water in the coastal domain is a mixture of flow from Unimak Pass, river discharge, and saline oceanic water. Because adequate mixing energy exists, little or no vertical structure is present. Waters over the middle shelf are two-layered, with a wind-mixed surface layer (10–40 m deep) and a tidally mixed lower layer (approximately 40 m deep). The upper mixed layer readily absorbs heat in spring and summer. The estimated rate of heating is 2–2.5°C per month in the upper layer and approximately 0.5°C in the lower layer, compared to approximately 1.5°C per month in coastal waters. The temperature difference between the upper and lower layers can be greater than 8°C. During summer, changes in temperature dominate changes in salinity and hence are critical to determining the stability of the water column and its resistance to mixing by storms.



Profiles of temperature over time at Mooring 2. The dark colors in February and March are the result of cold meltwater being mixed into the water column. In 1997 this cold water was mixed to the bottom; in 1998 it was mixed to less than 40 m. The scale is in °C. The yellow trace in each panel is fluorescence from chlorophyll in the water.

During summer a marked transition exists in vertical structure in the vicinity of the 50-m isobath; a structural front often less than 10 km wide separates weakly stratified coastal waters from more strongly stratified middle shelf waters. This feature is evident along the entire southeastern shelf to north of Nunivak Island. A similar feature exists around the Pribilof Islands. The dynamics of the front are not well understood. A limited set of observations suggest a lack of cross-front advection and minimal horizontal fluxes of heat and salt.

Sea Ice Retreat, Winter Winds, and the Timing of Production

The changes in the timing of ice melt in the spring and the shift from the strong winter winds to the generally lighter winds of summer have important implications for the timing and duration of primary production. When the ice melts in February or early March, as was the case in 1998, there is not sufficient light to support high rates of primary production. Therefore, the spring bloom is delayed until sufficient daylight is available, the sun heats the upper water column, and thermal stratification stabilizes it. This stabilization prevents the mixing of phytoplankton cells deep into the water where there is insufficient light to support photosynthesis. Thus, when there is no ice, or ice retreats from the southeastern shelf by mid-March, the bloom is delayed until May or June.

When the ice melts in April or May, there is sufficient light in the upper water column to support high rates of photosynthesis. If the winds are sufficiently light so that stratification can occur, there is an ice-associated bloom. The density structure of the water column in spring is primarily the result of thermal stratification, which in May can be weak. When spring winds are sufficiently strong to mix below this weak thermocline, the result is prolonged, moderate spring production, as occurred in 1998.

These results suggest a paradox: an early retreat of the winter ice cover (before mid-March) usually results in a later spring bloom than when the ice retreats late in the spring. They also explain why scientists working in the mid-1970s on the Outer Continental Shelf Environmental Assessment Program (OCSEAP) emphasized the importance of an ice-edge bloom as the source of primary production in the southeastern Bering Sea, whereas those working in the Processes and Resources of the Bering Sea Shelf (PROBES) program emphasized the importance of a late-spring open water bloom. During the OCSEAP studies in 1976 and 1977, winters were long and cold, and the ice remained into April or even May. Thus, there were ice-associated blooms in those years. In contrast, in 1979–1981, ice retreat came much earlier, and the bloom occurred in open water in May. Since the mid-1990s, both ice-associated and open water blooms have occurred.

The duration and extent of ice cover also affect water temperatures on the shelf. The water temperature in spring is important because it influences which of the food webs in the marine ecosystem will benefit most by that spring's primary production. Scientists working in the PROBES program hypothesized that the fate of production in the southeastern Bering Sea is influenced by water temperature because the growth of phytoplankton is less sensitive to water temperature than is the growth of zooplankton. Thus, when water temperatures are low, zooplankton development will be retarded, and there will be few zooplankton available to consume the primary production. As a result, much of the production will sink to the bottom and support a benthic food web that includes clams, crabs, and near-bottom-dwelling fishes. In contrast, when water temperatures are higher, zooplankton growth will be accelerated, and zooplankton will be able to crop a larger proportion of the production. The zooplankton will then be available to support a pelagic food web that includes mid-water fishes.

Sea Ice and Water Column Heat Content

The extent, duration, and timing of seasonal sea ice over the eastern Bering Sea shelf affects both physical properties and biological processes. In winter, ice is formed in the northern Bering Sea and is advected southward over the shelf by northerly winds. At the leading edge, ice is continuously melting and releasing cold, relatively fresh water, which is then mixed into the water column by the moving ice and strong winds. This mixing of cold water throughout the water column facilitates the formation of a cold bottom layer that becomes isolated from the upper mixed layer when spring and summer heating warms the surface.

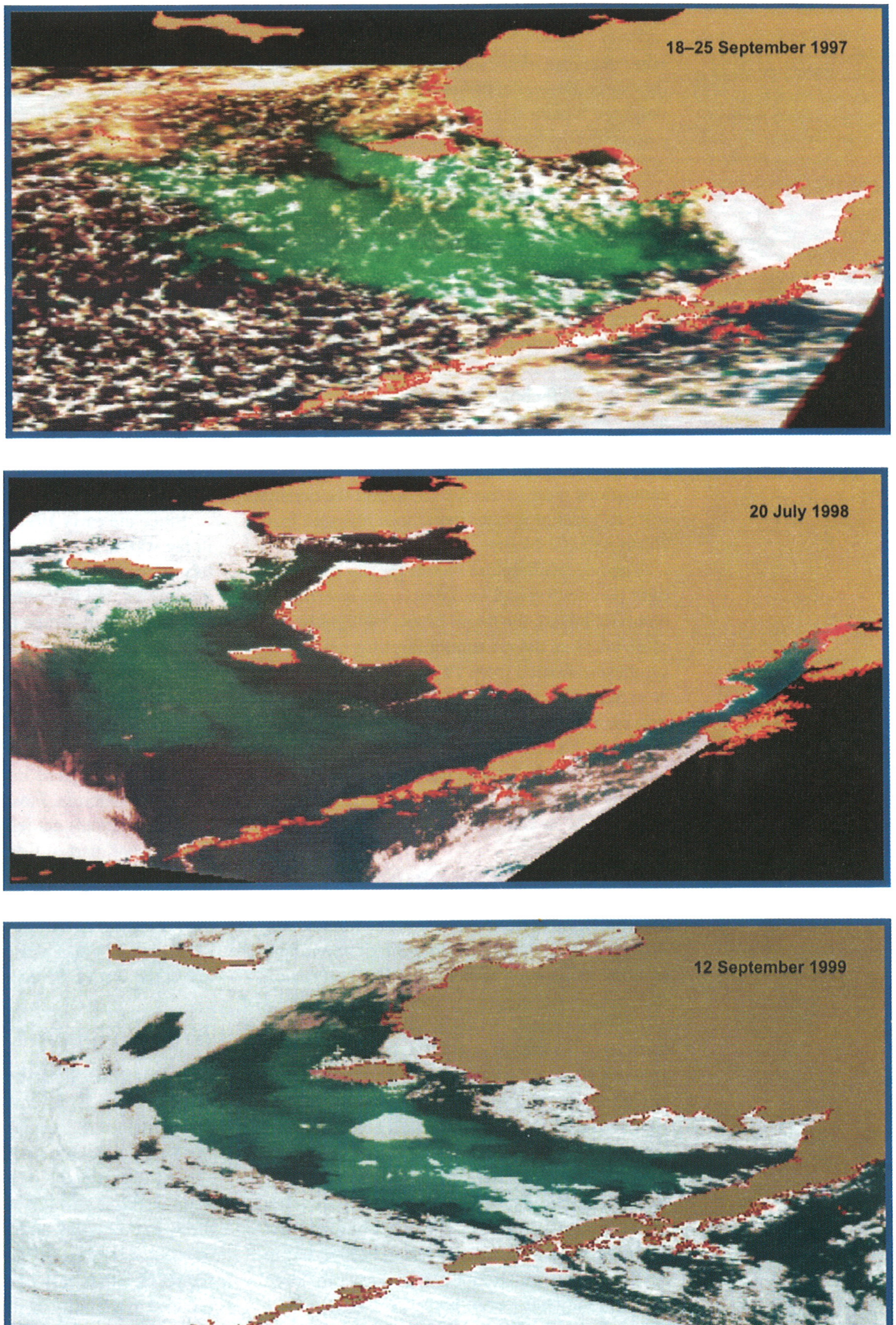
In 1997, ice was present in March and early April, and typical cooling of the water column occurred. Weak stratification followed spring warming. A strong storm in late May mixed the water column to 65 m or more, largely eliminating density differences between the warm upper layer and the colder water at the bottom. Weak winds following the storm produced a shallow mixed layer, and subsequent summer heating created exceptionally high surface temperatures. Late summer and fall storms mixed the layers, and heat was transferred to the bottom layer through the weak pycnocline. Consequently the winter of 1997-98 began with a relatively high heat content in the bottom layer.

In contrast to 1997, ice in 1998 was present over the southeastern shelf for only a brief period in February. Winds were insufficient to mix the cold, low-salinity water to the bottom. Thus, the depth-averaged temperature was higher, and the spring of 1998 began with unusually warm water at depth. This residual heat, coupled with summer warming, resulted in the water column over the middle shelf having unusually high heat content in the summer of 1998.

The northward movement of this warm water in 1998 could be traced in SeaWiFS (sea-viewing wide field-of-view sensor) images by its association with a bloom of the coccolithophore *Emiliania huxleyi* (described in detail below). The export of heat to the surface waters of the Arctic Ocean increases ice melt and sea-surface–atmosphere heat exchange in the Arctic. Although we did not measure the temperature of water flowing from the eastern Bering Sea into the Arctic, average temperatures on the shelf were approximately 2°C above normal. When the average heat content of eastern Bering Sea shelf waters becomes elevated, the typical northward flow of this water could affect the heat content of the Arctic Ocean. A change of this nature has important implications for global ocean circulation and heat budgets.

The Coccolithophore Bloom

Coccolithophores are small (5–20 μm) phytoplankton surrounded by calcium carbonate plates (called coccoliths). Because they contain dimethyl sulfide (DMS), they are important in the sulfur cycle of the ocean. And because DMS when airborne serves as a nucleus for the formation of condensation, coccolithophores may affect the reflectivity (albedo) of the earth and thereby global heat budgets. Coccolithophore blooms are common in the North Sea, Gulf of Maine, and coastal eastern North Pacific, and they characteristically occur in nutrient-depleted waters with a warm, shallow



SeaWiFS images from 18–25 September 1997, 20 July 1998, and 12 September 1999 showing the coccolithophore bloom over the shelf of the eastern Bering Sea. Note that in 1998 the bloom was being transported northward into Bering Strait.

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upper mixed layer. Most coastal blooms are on the order of 10,000 km^2 and last less than 40 days. High densities of coccoliths result in whitening of the water detectable by satellite. Although coccolithophore blooms have not been documented in the eastern Bering Sea, there have been satellite images of "white" water from there.

Aquamarine water, indicative of a coccolithophore bloom, was first observed on 3 July 1997 in the middle domain of the southeastern Bering Sea. By early August the bloom was at least 200 km wide, and by early September it covered much of the middle shelf and parts of the inner shelf. SeaWiFS imagery from 18–25 September 1997 showed pale water covering an area of approximately 210,000 km^2, and traces could be detected as late as October. This event was unusually large and prolonged when compared with most coastal blooms of coccolithophores. The maximum concentrations were in the top 15 m, and the densities were as great or greater than those reported from North Atlantic blooms.

The coccolithophore bloom greatly reduced light penetration and visibility in the water. Near Nunivak Island, the depth of the 1% light level, often taken as the maximum limit for net photosynthesis, shoaled from 18–33 m in June to 5–15 m in September in the bloom. At Slime Bank, outside the bloom, the depth of the 1% light level remained the same in spring and fall (27 m). Underwater videos taken near the Pribilof Islands documented cloudy bloom water ranging in depth from 7 to 44 m and extending to the bottom in several locations.

In 1998 the bloom was detected in SeaWiFS imagery as early as February, although it was not obvious from vessels until July. The bloom was still evident in October, a duration of about nine months. Its location was the middle shelf region, and in April the bloom was centered over the southeastern shelf. However, by July it was farther north than the bloom in 1997, with its center between Nunivak Island and St. Lawrence Island. In contrast to the 1997 bloom, which began in a well-stratified water column with a very warm upper mixed layer and nutrient depletion, the 1998 bloom began early in the year, when nutrients were still plentiful and the water column was almost unstratified. Thus in 1997 the coccolithophore bloom followed the spring diatom bloom, but in 1998 the coccolithophore bloom was coincident with and may have even preceded the diatom bloom. In both 1999 and 2000 the coccolithophore bloom was first detected by satellite remote sensing early in the year and later became visible at sea. Both of these years were cold and windy, and conditions were uncharacteristic of the situations in which blooms of *E. huxleyi* usually occur. It will be interesting to see how these blooms affect the trophic structure of the southeastern Bering Sea.

Zooplankton Abundance

In 1997 and 1998, acoustic and net sampling of the inner shelf regions of the southeastern Bering Sea revealed significant changes in the absolute and relative abundances of zooplankton taxa. In 1997 and 1998, copepods were one to two orders of magnitude more abundant compared to estimates from the mid-1970s and early 1980s. We do not know the cause(s) of the increase in copepods, although reduced predation pressure due to a northward shift in pollock populations is a possibility.

Since the early 1990s the biomass of jellyfish in the waters of the southeastern Bering sea shelf has increased greatly. The cause of this increase is not known, but it comes at a time when the populations of small forage fishes have declined. It is possible that some of the zooplankton formerly consumed by these fishes are now supporting jellyfish. The forage fishes are small species, or the young of larger species, that provide an important link in the food web between zooplankton and top predators such as large fishes, marine mammals, and seabirds. Few species of large fish or marine mammals eat jellyfish, though they do form a small part of the diets of some marine birds. However, for the most part, the large jellyfish that have become extraordinarily abundant over the eastern shelf have no predators. It remains to be seen how this new pathway for energy will affect the rest of the ecosystem.

Higher Trophic Levels

Short-tailed shearwaters nest in Australia and migrate to the North Pacific Ocean and Bering Sea during the austral winter. In the southeastern Bering Sea, previous studies have indicated that these shearwaters relied almost exclusively on adult euphausiids (krill) (*Thysanoessa raschii*) for their diets. In both 1997 and 1998, shearwaters were emaciated, and in 1997, shearwaters died in high numbers, apparently of starvation. It is likely that reduced availability of surface swarms of *T. raschii* was at least in part responsible for the emaciation of shearwaters in 1997 and 1998. Warm water temperatures inhibit the swarming of a related species of euphausiid in Japan, and water temperatures in the summers of 1997 and 1998 were well above those at which swarming is likely to cease. Also, the turbidity of the water caused by the high densities of calcium-carbonate-covered coccolithophores would have obscured all prey aggregations except those near the very surface of the water. Two factors may have helped to avert another die-off in 1998. In 1998, shearwaters included fish in their diets, and the availability of abundant age-0 walleye pollock just offshore of the inner front may have provided a critical food source not available in 1997. Also, in 1998, winds were of normal strength, and shearwaters were able to use energetically inexpensive dynamic soaring. In contrast, in 1997, winds for much of the summer were calm, and shearwaters had to resort to energetically expensive flapping flight in their search for prey.

In 1997 and 1998, returns of sockeye salmon to Bristol Bay, the world's largest wild sockeye salmon fishery, were considerably lower than in recent years and well below forecast levels of return. These fish spawn in fresh water, and after a year of development there they go to sea for two to three years. While at sea they forage widely across the North Pacific Ocean and Bering Sea. For the month before they return to the rivers to spawn, their major food in the southeastern Bering Sea is euphausiids. Since other species of salmon that also feed in the open North Pacific as well as over the shelf had poor returns in 1997 and 1998, it has been suggested that the failure of these salmon runs to meet forecasts may have been affected by a lack of food in the ocean.

Overview

Predicting what will occur with future global change can be facilitated by a combination of time-series studies that reveal correlations between atmospheric forcing and biological responses, and process studies that elucidate the causal linkages between aspects of physical forcing and the responses of marine ecosystems. The late 1990s provided the opportunity to study the Bering Sea in a period of unusually wide variation in ice cover, storminess, and water temperatures. The Inner Front Project and the Southeastern Bering Sea Carrying Capacity program examined how components of the inner shelf ecosystem responded to the unusually warm years of 1997 and 1998 and to the cold year in 1999.

In winter the strength and duration of cold, northerly winds determines the amount of ice melt available for cooling waters over the shelf. Winds in spring and summer determine the timing and strength of stratification and thus the timing and duration of the spring bloom. These winds also influence cross-shelf transport of biota and the advection of water to the Arctic. The water temperature over the shelf influences how plentiful zooplankton will be in spring. The coccolithophore blooms of 1997 and 1998 coincided with anomalously warm years, but those in 1999 and 2000 did not. We learned much about the factors that make the difference between survival and starvation for a marine bird dependent on near-surface aggregations of prey.

In this paper, we related how the ecosystem of the southeastern Bering Sea responded in anomalously warm and cold years. Although it seems unlikely that the warm years represented the beginning of another oscillatory decadal-scale change in the ecosystem (for example, a "regime shift" to a warmer condition) or were part of a longer-term secular change, they did provide an indication of how a warmer Bering Sea might function. We now have evidence of the magnitude and rapidity of ecosystem responses to changes in water temperature and wind forcing in the southeastern Bering Sea.

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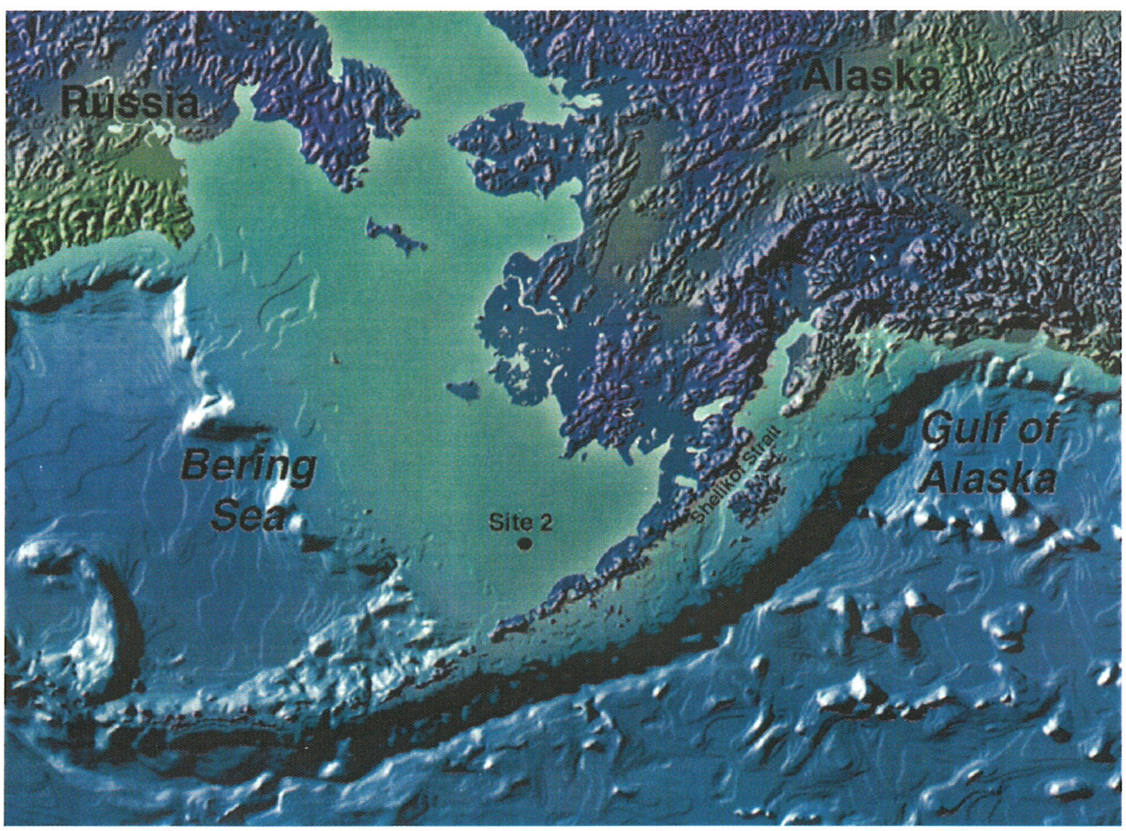
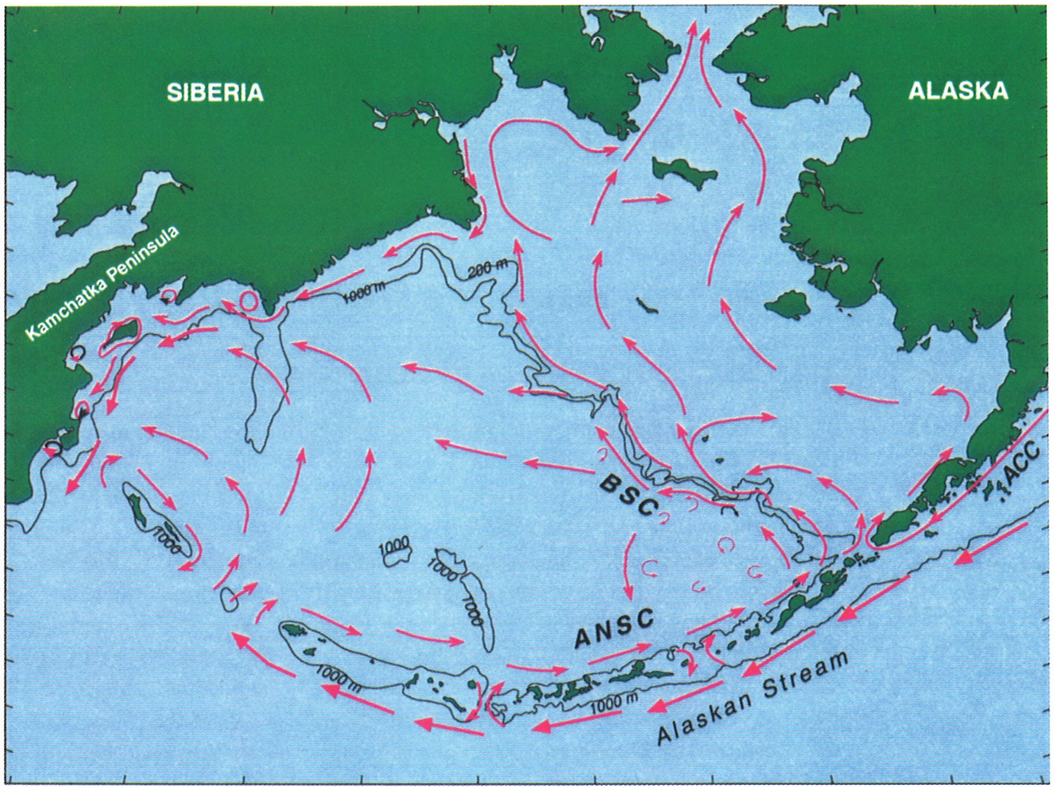
Marine Ecosystem Studies of Physical and Biological Interactions in the Eastern Bering Sea and Western Gulf of Alaska

This report was prepared by S. Allen Macklin, NOAA/PMEL, 7600 Sand Point Way NE, Seattle, WA 98115-6349 (206-526-6798; allen.macklin@noaa.gov), and Phyllis J. Stabeno, NOAA/PMEL, 7600 Sand Point Way NE, Seattle, WA 98115-6349 (206-526-6453; phyllis.stabeno@noaa.gov).

The Pacific Marine Environmental Laboratory (PMEL), part of the National Oceanic and Atmospheric Administration's Office of Oceanic and Atmospheric Research (NOAA/OAR), conducts fisheries oceanography and ecosystem studies in the Bering Sea and Gulf of Alaska. The principal research program, Fisheries-Oceanography Coordinated Investigations (FOCI), is a cooperative venture between PMEL and the National Marine Fisheries Service's Alaska Fisheries Science Center. Additional funding comes from a variety of sources, including the National Ocean Service's Coastal Ocean Program, the International Arctic Research Center, and the North Pacific Marine Research Program. This funding has enabled academic partnerships with researchers at the University of Alaska, University of Washington, and University of California. FOCI's goals are to increase understanding of the Alaskan marine ecosystem, specifically examining the role of walleye pollock as a nodal species in the ecosystem. Pollock are an important economic commodity and play a pivotal role in the bioenergetic balance, preying on zooplankton and being themselves the food for other fish, marine mammals, and seabirds. FOCI scientists research the character and dynamics of the



The southeastern Bering Sea and western Gulf of Alaska, where FOCI conducts ecosystem research. Most research is concentrated on the continental shelves north of the Aleutians and in the vicinity of Shelikof Strait. Site 2 is the location of a biophysical mooring and focus for shipboard sampling.



Principal currents contributing to circulation of the Bering Sea. (ANSC is the Aleutian North Slope Current; BSC is the Bering Slope Current.) Water flows into the Bering Sea through passes in the Aleutian Islands and out of the Bering Sea through Kamchatka Strait and, to a lesser degree, Bering Strait. Circulation is cyclonic in the basin and northwestward on the eastern shelf.

biophysical environment through field and laboratory experiments, computer simulations, and conceptual models.

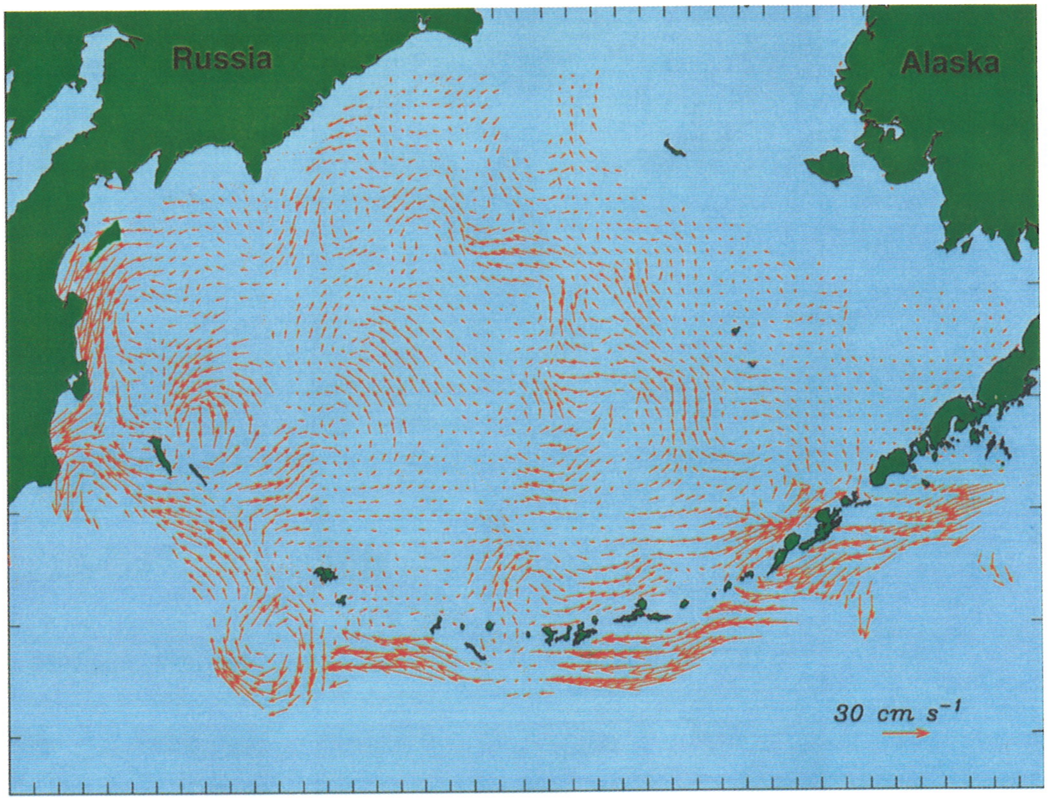
Understanding the southeastern Bering Sea is particularly important because it is the most productive marine ecosystem in the U.S. and one of the most productive in the world. In both the Bering Sea and Gulf of Alaska regions, research concentrates on long-term environmental variability and decadal shifts that influence the ecosystem, as well as physical and biological processes that support the first few months of pollock life. It is during this brief period that most mortality occurs. In the Bering Sea, pollock spawn over a vaster area and longer interval than in Shelikof Strait, where spawning is confined to a small location at the southwestern end of the Strait and a few weeks during March. Another significant difference between the Bering and Gulf systems is the presence of sea ice over the southeastern Bering Sea shelf. The extent and duration of sea ice, for example, are controlling factors in the annual spring bloom that feeds the zooplankton that are prey for pollock larvae.

Bering Sea

In the Bering Sea, FOCI has refined our understanding of Bering Sea circulation, documented the stock structure of walleye pollock, determined the biophysical processes leading to the survival of young pollock, monitored interannual ecosystem variability (including near-shelf-wide blooms of coccolithophores during the last four summers), and demonstrated that seasonal pack ice directly affects the primary productivity of the shelf. From these and other findings, FOCI is developing a predictive ability for Bering Sea pollock.

General Circulation

The general circulation over the deep basin is characterized by a cyclonic gyre. There are three well-defined, distinct currents: the Kamchatka Current along the western boundary; the Bering Slope Current (BSC) along the eastern boundary; and the Aleutian North Slope Current (ANSC) connecting inflow from the Alaskan Stream through Amukta Pass and Amchitka Pass with the BSC. Transport within the gyre can vary by more than 50%. Modeling studies have simulated such large



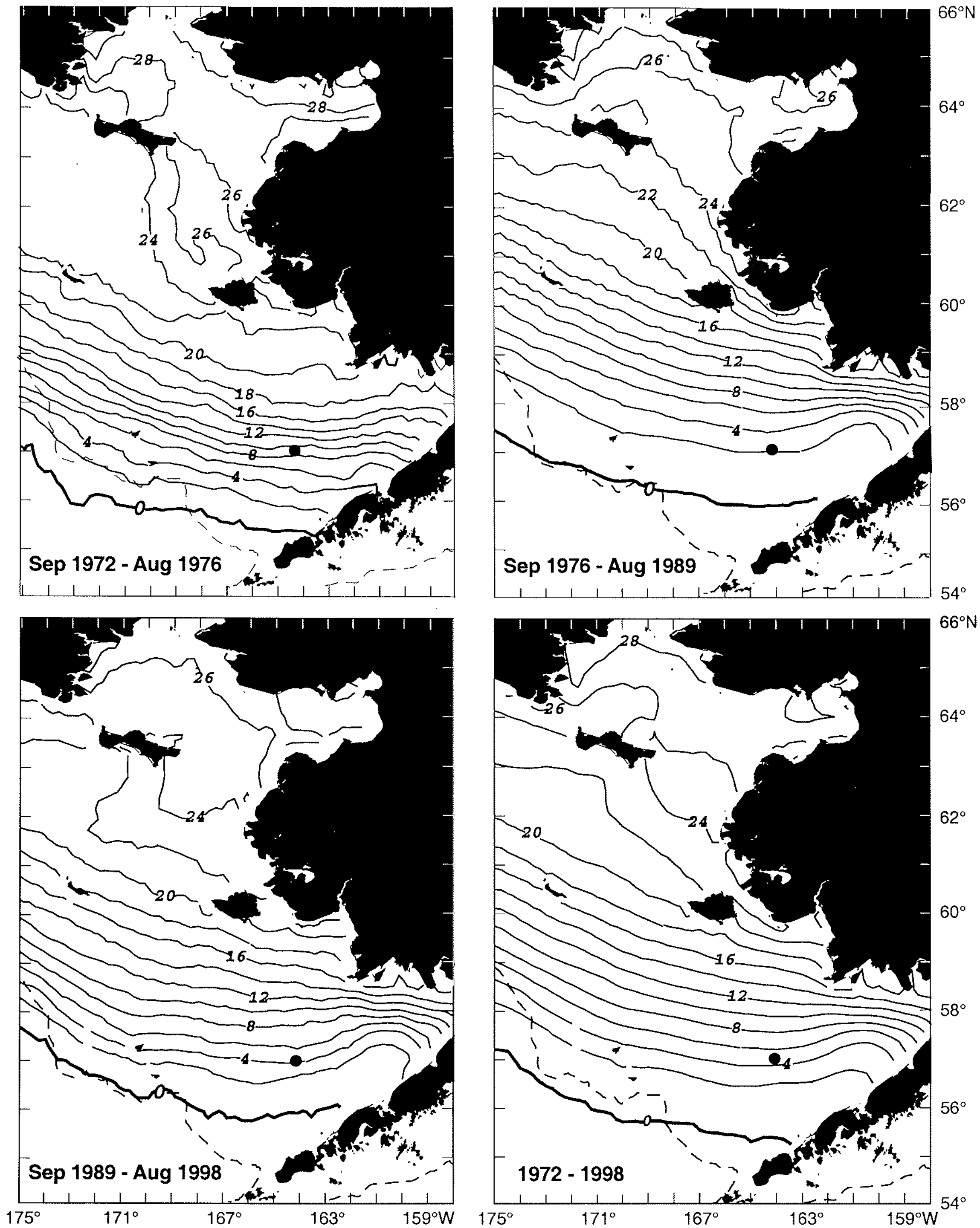
Current velocities at 40 m deep derived from satellite-tracked drifters, showing the dominant currents of the Bering Sea basin.

changes in transport and identified the causes to be fluctuations of the Alaskan Stream inflow and/or changes in the wind-driven transport within the basin. Circulation in the Bering Sea basin may be more aptly described as a continuation of the North Pacific subarctic gyre. Circulation on the eastern Bering Sea shelf is generally northwestward. The net northward transport through the Bering Strait, while important to the Arctic Ocean, has virtually no effect on the circulation in the Bering Sea basin. It does, however, play the dominant role in determining the circulation on the northern shelf. The currents of the Bering Sea have been examined principally through inferred baroclinic flow and to a lesser extent by satellite-tracked drift buoys, current meter moorings, and models. Satellite-tracked buoys led to the discovery and characterization of the ANSC by PMEL's FOCI scientists. It is best documented between 174°W and 167°W by hydrographic surveys, satellite-tracked drifting buoys, and more recently, current meter records.

The general northwestward circulation over the eastern shelf is important to the distribution of eastern Bering Sea pollock. Most spawning occurs in the southeastern sector near the continental slope and on the shelf. Larvae are slowly transported northwestward, and most juveniles are found on the northern shelf, many in Russian waters. Despite the transport of pollock to other areas of the Bering Sea, they appear to return to their birth areas to spawn. Genetic analysis of pollock has shown that the stocks on the east and west sides of the Bering Sea are discrete. Although the basin is rich in nutrients, it has relatively poor supplies of the zooplankton on which larval pollock prey, compared to the shelf. It is not likely that there is a spawning stock of pollock indigenous to the basin.

Eddies

As elsewhere in the world's oceans, eddies are ubiquitous in the Bering Sea. They occur on horizontal scales ranging from approximately 10 to 200 km. Proposed mechanisms for the creation of these eddies include instabilities, wind forcing, strong flows through the eastern passes, and topographic interactions. Every year, eddies form in the southeastern corner of the Bering Sea basin and northward along the shelf break. These eddies coincide with an area known as the Green Belt, a

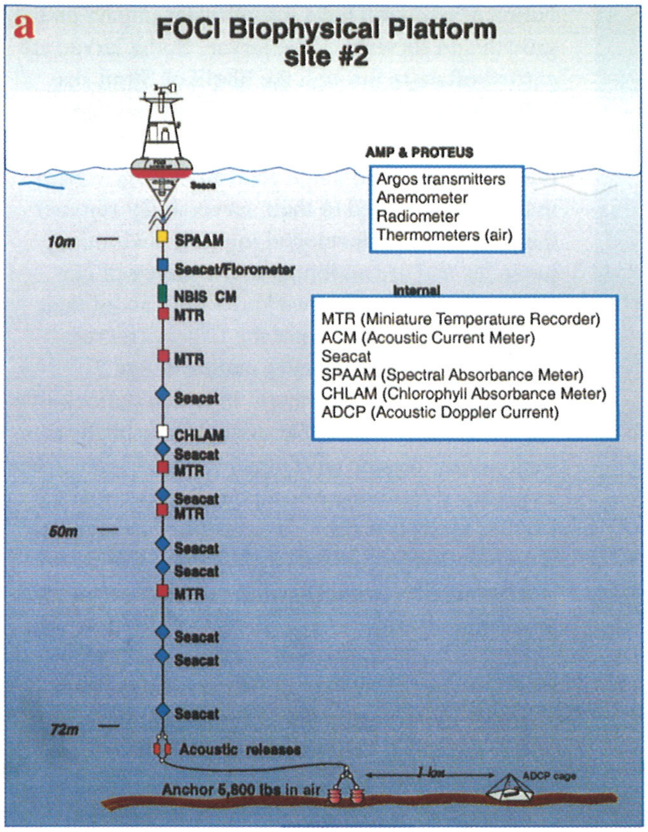


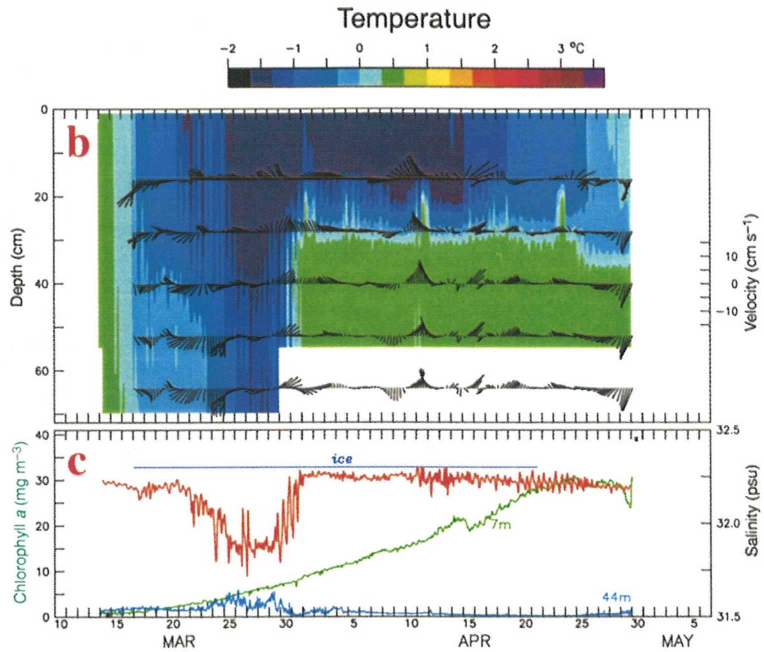
Average maximum sea ice extent and duration in weeks for cold (1972–1976), warm (1976–1989), and weaker cold (1989–1998) regimes and the entire 1972–1998 record. Site 2 is marked by a dot in each panel; the shelf break is indicated by a dashed line.

region of high productivity and biological diversity. Evidence supports the hypothesis that eddies play an important role in prolonging production, and they are important contributors to the transport of nutrient-rich basin water to the shelf. In more than one instance, eddies detected by satellite-tracked drifters have coincided with above-average abundance patches of pollock larvae.

Sea Ice

A defining characteristic of the eastern Bering Sea shelf is the annual advance and retreat of sea ice. Beginning in November, ice is formed along



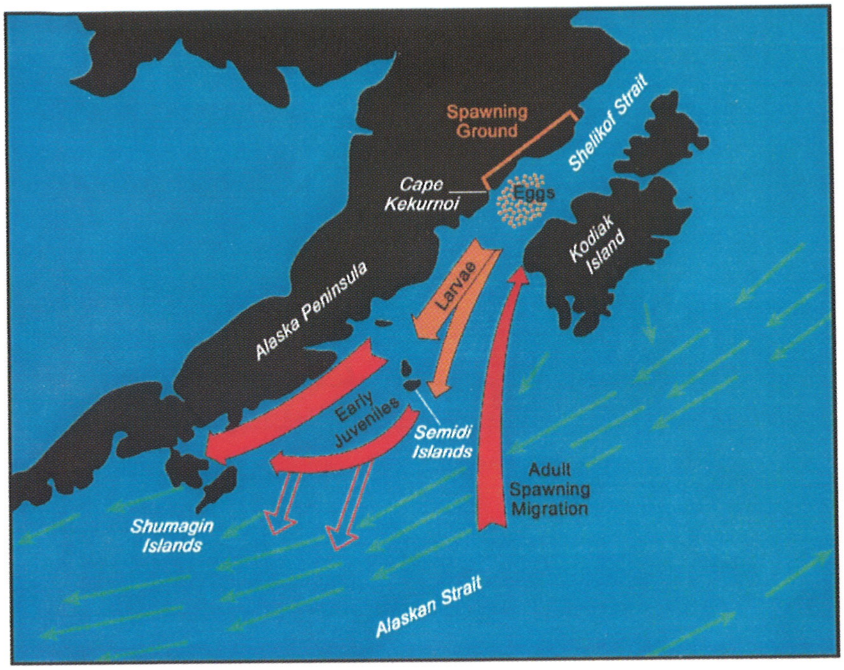


Mooring diagram and data from the deployment of a FOCI biophysical platform at site 2 during 1995. Water temperature and velocity to 60 m deep indicate rapid cooling of the water column as sea ice arrived and melted at site 2 during the last two weeks in March while winds vertically mixed the water column. Because of strong density gradients established by solar heating of the upper layer during spring, the bottom layer (cold pool) remained below 1.2°C through August. Ice presence, salinity, and chlorophyll at 7 and 44 m show that when ice overlay the mooring site, the water freshened as the ice melted, and an early spring bloom began at the same time as ice arrived.

the leeward sides of islands and coasts. It is advected southward, freshening and cooling the water column as it melts at its leading edge. The maximum ice extent typically occurs in late March, and ice can remain over areas of the southeastern shelf into June. The extent and duration of ice cover vary with climatic regime shifts such as the Pacific Decadal Oscillation. For example, the period from 1972 through 1976 was cold, and ice often covered the shelf out to and over the upper continental slope, arriving in January and retreating in May. From 1977 to 1988—a warm period—ice did not extend as far seaward, and its residence time was typically 2–4 weeks less than during the cold period. Since 1989 there has been a return to a weaker cold period, and sea ice has been more extensive than in the warm period but not as extensive as in the early 1970s.

The extent and timing of sea ice cover over the eastern Bering Sea shelf dramatically affect the time and space characteristics of primary and secondary production and thus food for larval pollock. In years when ice is not present, the spring bloom typically occurs as late as May or even June. When ice is present over the southern shelf after mid-March, it induces an early spring bloom of phytoplankton. This early bloom strips the upper layer of nutrients, precluding a later spring bloom. Because zooplankton may not be present in sufficient abundance to graze the early bloom, most of it settles to the bottom, enriching the benthic community. Such was the case in 1997. An early, ice-associated spring bloom depleted the upper-layer nutrients, and a late May storm mixed nutrients from the lower layer to the upper layer, where they were rapidly depleted. The warmed, nutrient-depleted water was not the proper environment for typical Bering Sea shelf phytoplankton. Instead, a vast coccolithophore bloom occurred that summer and has recurred each summer since. Although sediment analysis suggests that coccolithophores may have occurred sometime in the past, the present blooms are unprecedented.

The maximum annual extent of sea ice also has other biological effects. For example, it determines the size of the cold pool of bottom water on the shelf. Because Bering Sea pollock are cannibalistic, with adults preying on juveniles, their distribution and survival are partly determined by



Locations where pollock spawn at the same time and place each spring in Shelikof Strait. After hatching, the larvae are advected by local currents. Some are lost to the Alaskan Stream; others remain on the continental shelf in nursery waters where they develop into juveniles.

the extent of the cold pool. When the cold pool is large, juvenile pollock are crowded to the outer portion of the shelf, where they are subject to predation by adults.

Gulf of Alaska

FOCI research in the Gulf of Alaska began in 1984 and is focused on the early life history of walleye pollock in Shelikof Strait. Adult fish return to spawn in the coastal water and Alaska Coastal Current (ACC) at the southwest end of Shelikof Strait during March and April each year, with each female producing about one-half million eggs. The dense, localized spawning pattern creates large patches of eggs that develop over about a two-week period near the bottom. Larvae hatch and rise into the mixed layer, where they drift southwestward with the ACC. Physically mediated variations in production, standing stock, and distribution of plankton have a significant impact on the growth and survival of the larvae. Some larvae are carried offshore through the Shelikof Strait sea valley, where they are swept away by the fast-moving, nutrient-poor Alaskan Stream. Others remain on the continental shelf in nursery waters that are more suited to their survival. By summer the pollock have developed into free-swimming juveniles and are no longer at the mercy of currents. After this period we know little about their life history until they enter the fishery (recruitment) and become sexually mature at age 2.

The physical environment in which pollock live varies on many scales. Decadal climate changes such as the "regime shift" that occurred in the late 1970s have profound effects on abundance. On a smaller scale, larval survival may be enhanced by incorporation into eddies with lifetimes of days to weeks. Finally, larval survival may be determined by a single storm.

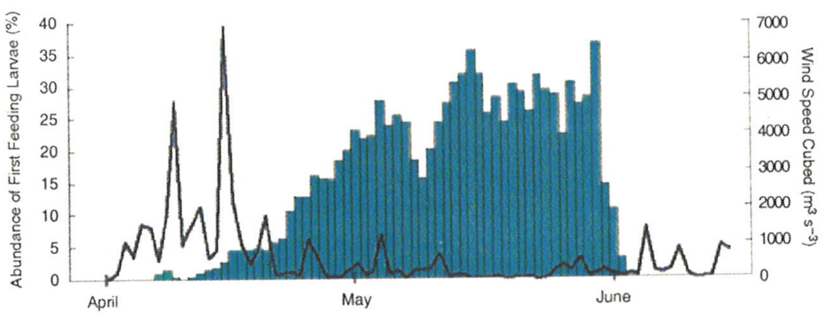
FOCI forecasts Shelikof Strait pollock recruitment from relationships of fish survival to phenomena of various scales: baroclinity, transport, wind mixing, and climate forcing. In FOCI's conceptual model of recruitment, all environmental conditions must be favorable for a pollock to advance from one life stage to the next. Processes identified with pollock survival are ocean climate, circulation, wind mixing, and eddy potential. Although FOCI scientists understand conceptually how these environmental conditions affect survival, research remains to be completed to understand what mechanisms actually come into play and how they operate. Using time series associated with the processes identified in the conceptual model, FOCI has forecast recruitment of Shelikof Strait pollock since 1992.

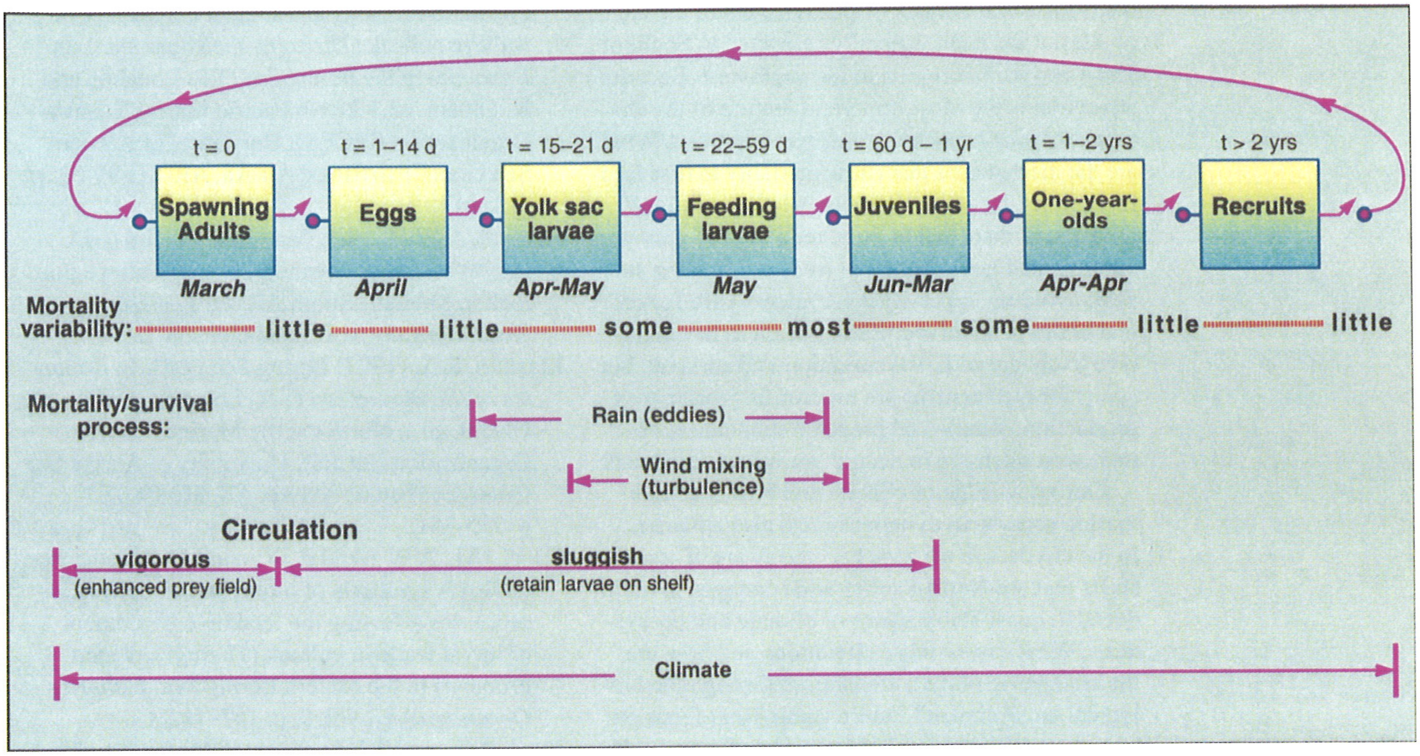
FOCI has developed a biophysical model of the Shelikof Strait system. The model merges three components: a three-dimensional hydrodynamic model to determine ocean circulation, a spatially explicit nutrient–phytoplankton–zooplankton model to determine the prey field for pollock larvae, and a spatially explicit, individual-based model of pollock through the late larval stage of development. FOCI is generating an archive of model runs for each year back to 1976.

Future Directions

While our knowledge of the ecology of the Bering Sea and Gulf of Alaska has expanded greatly

Abundance of first-feeding pollock larvae (blue bars) and wind speed (black line) in 1988. The larvae that survived to be sampled were most abundant during periods of relatively calm winds.





FOCI's conceptual model of the processes that affect survival of Shelikof Strait pollock from one life stage to the next.

To learn more about the ecosystem and fisheries oceanography research that PMEL conducts in the Arctic, visit the following Web sites: the Fisheries-Oceanography Coordinated Investigations home page (http://www.pmel.noaa.gov/foci/) and the Southeast Bering Sea Carrying Capacity home page (http://www.pmel.noaa. gov/sebscc/).

over the past few decades, many phenomena are not understood, primarily because observations are limited or nonexistent. Processes on a variety of scales—from climate to microstructure—must be investigated to supply answers to questions about these ecosystems. Some are more easily addressed than others, but in all cases there is the need to monitor critical ecosystem factors at appropriate periods and locations. That a vast percentage of the Bering Sea lies within the domains of two nations has not facilitated research programs that could provide the needed observations. Further, while the eastern continental shelf continues to have ongoing research programs, and interest in the role of physical processes over the western shelf is growing, the deep basin remains largely unexamined.

While it is recognized that flow through the Aleutian passes is a primary source of circulation within the basin, many questions remain regarding the current systems of the Bering Sea. Particularly needed is information on spatial and temporal variability in the Kamchatka, BSC, and ANSC. Dynamic processes within these currents provide nutrients to the euphotic zone and are responsible for the region of prolonged biological production known as the Green Belt. While the processes are unknown, the results of their interactions are evident. The continental shelf of the Bering Sea exhibits extremely high productivity, and this richness applies throughout the food chain. Not only are there vast quantities of commercially valuable species, but the eastern shelf is the summer feeding ground for numerous marine bird and marine mammal populations of the North Pacific Ocean. The eastern Bering Sea provides an ideal location to examine exchange mechanisms between slope water of an eastern boundary current and a continental shelf. Because the coast and its inherent topographic and coastal convergence processes are far removed from the slope, the processes involved in shelf/slope exchange should provide a clear signal. The continental shelf of the western Bering Sea is bounded by a typical western boundary current, so studies of contrasts of processes between the eastern and western shelves should be fruitful.

In the Gulf of Alaska, too, questions remain to be answered. Fundamentally, why is the northwestern shelf so productive? The basis for this production is enigmatic, given that downwelling winds prevail throughout most of the year and that the shelf receives a massive coastal influx of nutrient-poor fresh water. The ACC is a crucial habitat for young-of-the-year pollock and other species. Physical processes within the ACC could enhance the aggregation of zooplankton and therefore be critical to recruitment success. What are the upstream physical and biological conditions that precondition Shelikof Strait as an adequate feeding environment for larval pollock? FOCI research in the Gulf of Alaska has been generally restricted to Shelikof Strait and its exit region to the southwest. Because advection is the most important feature of the circulation, what happens upstream is important. What are the mechanisms that cause mortality to first-feeding pollock larvae during high wind conditions? Dilution or dispersal of prey, reduction of prey production, and larval behavior (reduced feeding success, avoiding upper-layer turbulence) are factors that could be involved. Eddies seem to be conducive to enhanced larval condition and survival, but again the mechanisms are unclear. Is greater prey production, diminished predator abundance, or increased retention in near-shore waters involved?

Our knowledge of climate and how it affects marine ecosystem dynamics must also advance. In the last decade we have become aware of regime shifts that are North-Pacific-wide changes in multidecadal, quasi-stable states of climate and ecosystems. What causes these alterations and how are the changes in climate transferred through the biological environment? Future studies that focus on how the extant physical phenomena affect marine populations offer the best opportunity to enhance our understanding of ecosystem dynamics. This, in turn, could lead to management strategies aimed at sustainable production to ensure a rich ecosystem for our future generations. The observational database is not adequate in spatial and temporal coverage to answer most of the questions noted above. In addition to further observations, modeling efforts need to be improved, especially for the Bering Sea. A primitive equation basin-shelf model that couples both outflow through Bering Strait and exchange in the North Pacific Ocean is a likely starting place. Once the model provides accurate simulations of the physical features, then biophysical processes and rates can be incorporated. Some of the questions that must be addressed to understand the ecosystem are best investigated by modeling efforts.

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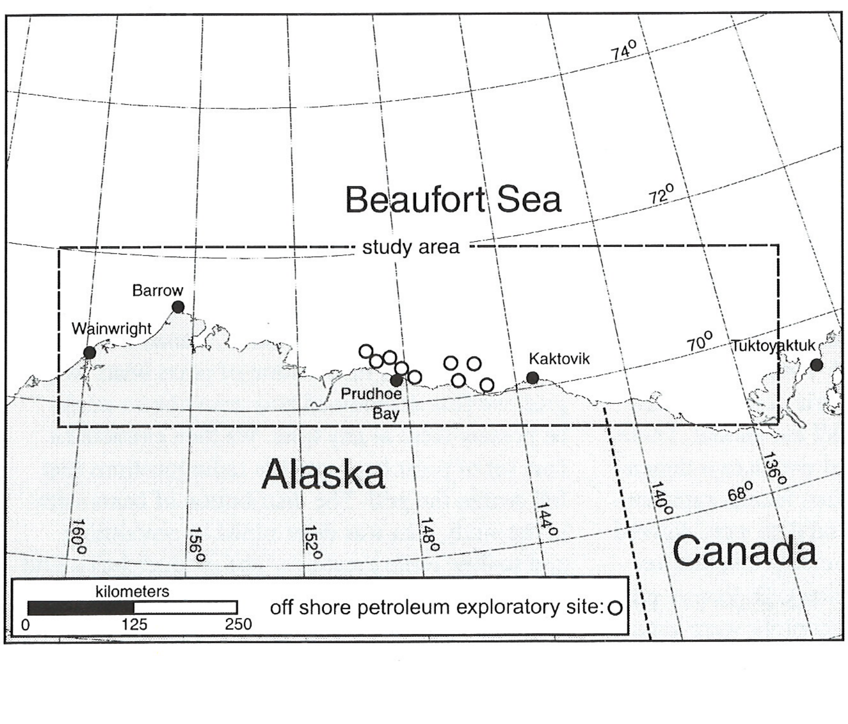
Estimating the Impacts of Oil Spills on Polar Bears

This report was prepared by George M. Durner and Steven C. Amstrup, U.S. Geological Survey, Alaska Biological Science Center, 1011 E. Tudor Rd., Anchorage, Alaska 99503; and Trent L. McDonald, WEST, Inc., 2003 Central Ave., Cheyenne, Wyoming 82001.

The polar bear is the apical predator and universal symbol of the Arctic. They occur throughout the Arctic marine environment wherever sea ice is prevalent. In the southern Beaufort Sea, polar bears are most common within the area of the outer continental shelf, where they hunt for seals along persistent leads and openings in the ice. Polar bears are a significant cultural and subsistence component of the lifestyles of indigenous people. They may also be one of the most important indicators of the health of the Arctic marine environment. Polar bears have a late age of maturation, a long inter-birth period, and small litter sizes. These life history features make polar bear populations susceptible to natural and human perturbations.

Petroleum exploration and extraction have been in progress along the coast of northern Alaska for more than 25 years. Until recently, most activity has taken place on the mainland or at sites connected to the shore by a causeway. In 1999, BP Exploration–Alaska began constructing the first artificial production island designed to transport oil through sub-seafloor pipelines. Other similar projects have been proposed to begin in the next several years.

The proximity of oil exploration and development to principal polar bear habitats raises concerns, and with the advent of true off-shore development projects, these concerns are compounded. Contact with oil and other industrial chemicals by polar bears, through grooming, consumption of tainted food, or direct consumption of chemicals, may be lethal. The active ice where polar bears hunt is also where spilled oil may be expected to concentrate during spring break-up and autumn freeze-up. Because of this, we could expect that an oil spill in the waters and ice of the continental shelf would have profound effects on polar bears. Assessments of the effects of spills, however, have not been done. This report describes a promising method for estimating the effects of oil spills on polar bears in the Arctic marine environment. It uses enough real data to illuminate necessary calculations and illustrate the value of the methods. The results and conclusions presented here are only examples of possible scenarios resulting from a new estimation method. Final assessment of the potential impacts to polar bears of an oil spill remains a work in progress.



Study area, place names used in the text, and offshore petroleum exploratory and extraction sites along the southern Beaufort Sea coast.

Methods

Oil Spill Trajectories

We are using hypothetical oil spill scenarios created by the Minerals Management Service (MMS) with modifications of their Oil Spill Risk Analysis (OSRA) model. Based on a review of oil spills in similar environments, MMS predicted that oil spills resulting from catastrophic events might range in size between 102 and 1580 barrels. MMS predicted that spills under the sea ice could be as large as 2956 or even 5912 barrels if all detection and prevention devices failed for extended periods. These large accumulations of oil under the ice could behave as catastrophic releases when the ice melted in spring. In this example, we will focus on worst-case scenarios and present a method to evaluate the effects on polar bears from oil spills of 2956 and 5912 barrels. Although such large spills may be possible only through undetected chronic releases, we will treat them as if they were instantaneous discharges. We also make the conservative assumptions that weathering and clean-up do not occur.

We hypothesized that the effects of an oil spill would be most severe during summer and autumn. Summer (22 August – 30 September) is the period of open water, when we hypothesize the spread of spilled oil would be greatest. Polar bears are at their lowest near-shore densities at that time. Nonetheless, many bears could be affected because of the potentially great spread of oil. During autumn (1 October–9 November), when broken ice is prevalent, polar bears are at their highest near-shore densities. Oil spread might be hampered by ice but still could travel great distances, and risks to polar bears, we hypothesize, would be highest.

The behavior of oil on water can be thought of as a plume or fan-shaped pattern spreading over the surface. The characteristics of the plume are determined by winds and currents. MMS simulated oil spills by modeling the movements of hundreds of particles pushed by winds and currents and impeded by ice. In this approach to oil spill modeling, we convert those linear particle paths to aerial coverages by treating each particle as a disk of oil on the water. Studies have shown that oil on water will spread only until reaching a terminal thickness. That terminal thickness, along with the volume of oil spilled, determines the diameter of each disk. We refer to these disks of oil as spillets. Available wind and current data would allow up to 500 independent spills, or trajectories, each month. Each trajectory is composed of 500 spillets. Spillets are assumed to describe a continuous path, and each path of a spillet can be viewed as a swath with a width specified by the spill size. Here, we develop examples to show how such spill trajectories might interact with polar bears.

Two general circulation models were used to simulate the movement of oil. Within the shorefast ice (within the 20-m bathymetric contour), wind was the only determinant of oil movement. There, ocean currents were simulated with a two-dimensional hydrodynamic model that incorporated barrier islands and coastline. Wind data were derived from the TIROS operational vertical sounder, or TOVS (NOAA-operated satellites). Trajectory paths beyond the 20-m bathymetry contour were simulated using a three-dimensional coupled ice–ocean hydrodynamic model. Offshore trajectory motion is based on ocean currents and wind when ice concentration is below 80%. When ice concentration *exceeds* 80%, trajectory motion is determined by ice movement only.

Estimation of Polar Bear Numbers

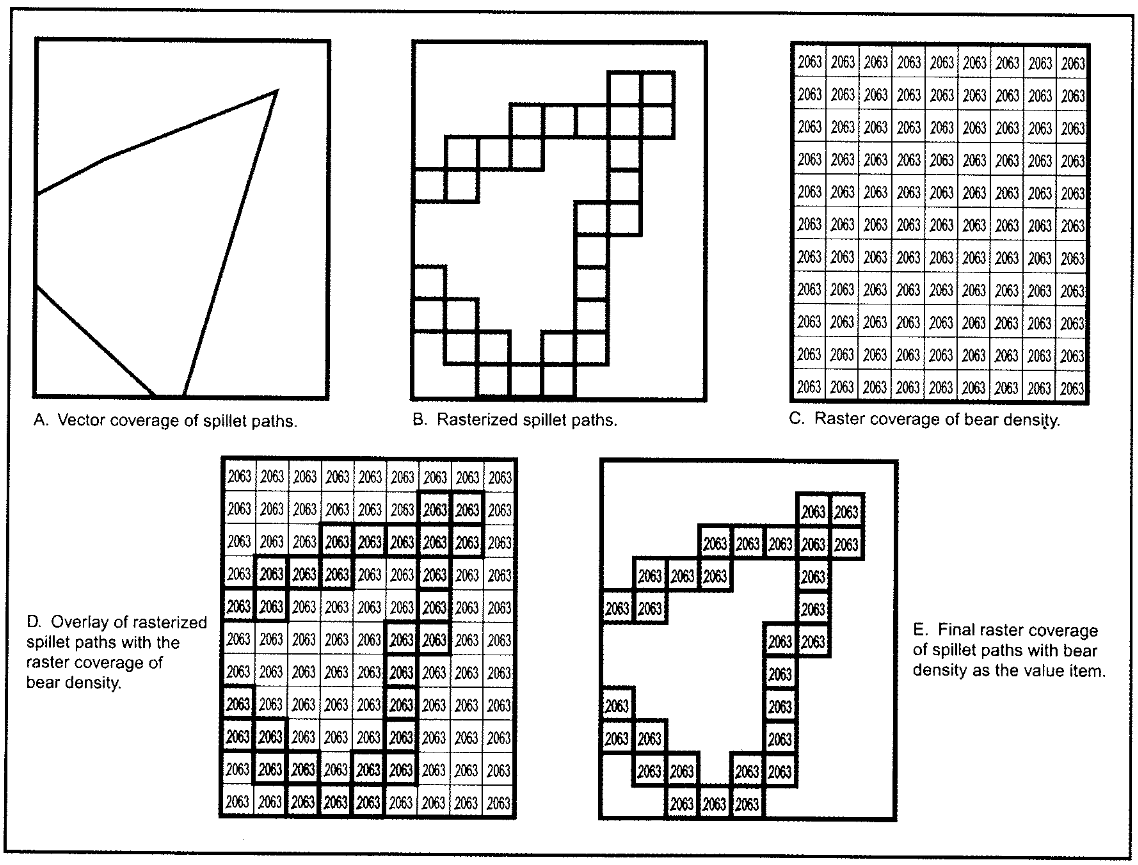
Research scientists with the USGS Alaska Biological Science Center have captured polar bears in the Chukchi and Beaufort Seas since 1967 as a part of ongoing polar bear ecological studies. Between 1985 and the present, we deployed satellite radio collars, or platform transmitter terminals (PTTs), on female polar bears for investigations of movements, maternal dens, and survival. PTTs employ an ultra-high-frequency (UHF) signal that is received by polar-orbiting satellites and processed by the Argos Data Collection and Location System (ADCLS). Argos data include the geographic location of the bear, its activity, and the temperature of the collar it wears. We also obtained Argos data collected by the Canadian Wildlife Service in the southern Beaufort Sea.

We generated a population distribution grid of polar bears based on PTT locations and estimates of population size in the Chukchi, southern Beaufort, and northern Beaufort Seas. This estimate of the polar bear population size was distributed within the grid. The number of bears apportioned to each cell of the grid was determined by smoothing and scaling the actual radio-tracking locations in each cell, that is, cells with many radio locations had a greater proportion of the population than cells with few radio locations. Hence, the distribution of polar bears in the study area was not uniform.

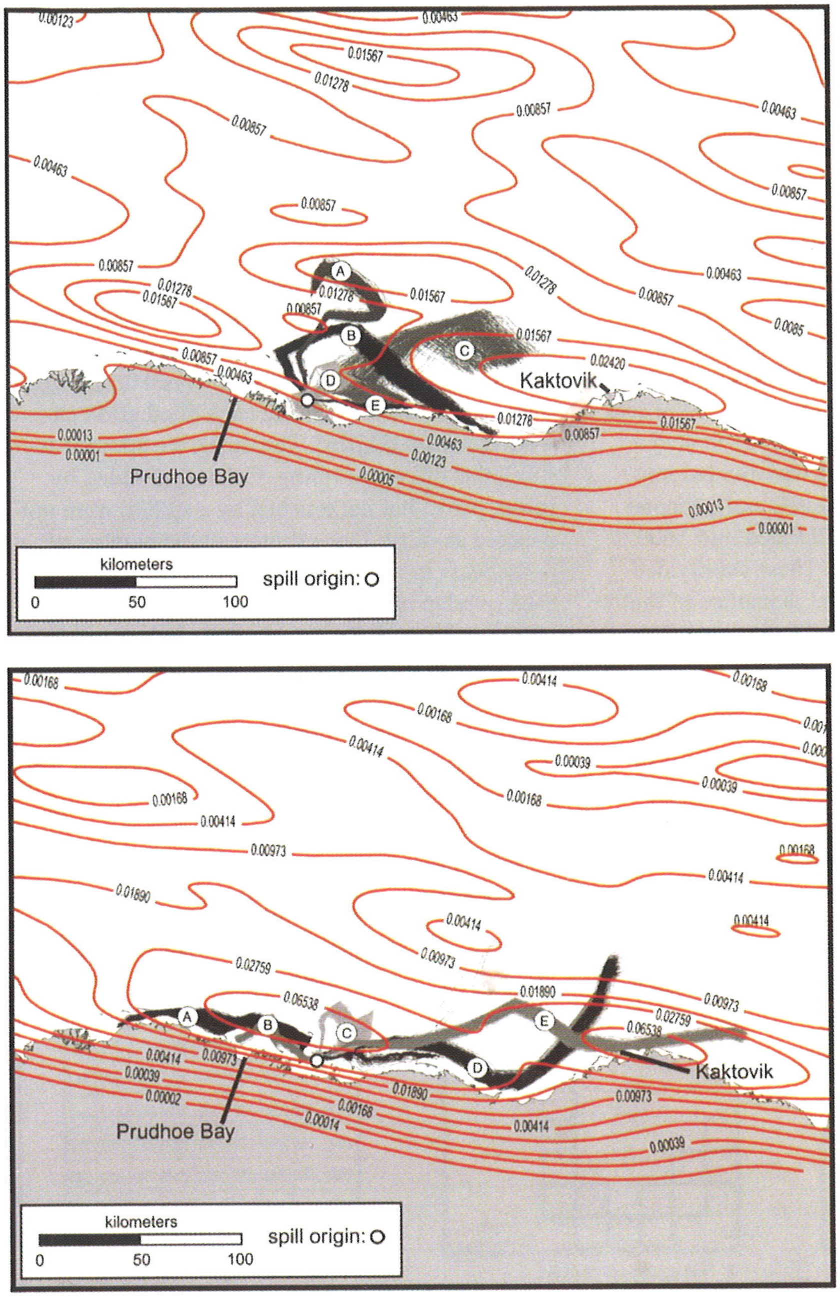
We defined our study area as a grid that included the area that could potentially be affected by oil originating from off-shore production islands near Prudhoe Bay. This grid was 1024 × 256, or 262,144 total cells, where each cell was 1000 m on a side (1 km^2). This grid extended west to Wainwright, Alaska, and east to Tuktoyaktuk, Canada. To estimate the seasonal distribution of polar bears in the grid, we first determined how many bears might be present there at any time. We then extracted a data set of polar bear satellite radio locations that fell within the grid. The distribution of bears within the study area was determined by smoothing and scaling radio locations. The product was a grid of polar bear distribution that included x- and y-coordinates, bear density, and standard error (SE) of density for each cell. This grid was converted to an ARC/INFO raster coverage of estimated bear density and SE.

Because oil spillet paths were estimated to have a maximum spread diameter of 47 m (for the larger of the two spill sizes we modeled), only a small proportion of any 1-km^2 density cell would be intersected by the narrow spillet path. Thus, we felt it would be unreasonable to count an entire 1-km^2 density cell as oiled when a spillet path intersected it. To prevent an overestimation of oiled bears, we subdivided the grid twice so that the proportion of a cell, rather than the entire cell, might be counted as oiled. We first generated a grid in which each 1-km^2 cell was divided into 400 cells (50 × 50 m, or 2500 m^2) and a second grid where 1-km^2 cells were divided into 1600 cells (25 × 25 m, or 625 m^2). These subdivided cells corresponded with spillet diameters of the two sizes (25 and 50 m) of spills we wanted to evaluate in this exercise.

Recall that the oil-spill trajectories provided by MMS were linear paths showing how wind and current patterns moved each spillet. Also recall that spillets represented a volume of oil (either 2956 or 5912 barrels). Because of this, we converted line coverages of oil spill trajectories from linear paths to GIS raster (grid) coverages with cells that were either 25 or 50 m wide. Bear density and SE values were assigned to trajectory grid cells by matching each trajectory grid cell with the closest cell center from the bear density or SE grid. These cells were considered "oiled." A cell could be oiled only once per trajectory. Therefore, if a spillet path doubled back and re-crossed a cell, or if multiple spillet paths crossed the same grid cell, the number of bears oiled remained unchanged. Bears estimated to populate each oiled grid cell were considered killed. Therefore, we allowed no sub-lethal effects of oiling. Cells surrounded by spillet paths, but not touched by a spillet, were not counted as oiled. One estimate of the number of polar bears impacted by an oil spill resulted from each overlap of a spill trajectory grid with a polar bear density grid. Because each trajectory was simulated under different and independent weather and sea state conditions, each trajectory could be regarded as a simple random sample of oil spills from a larger (infinite) population of oil spills that might occur in the future.



Procedure used to convert a linear oil spillet path to a footprint that can be overlapped with a grid depicting polar bear numbers.



Polar bear density contours (bears/km²) and five trajectory examples during summer (22 August–30 September) (top) and autumn (1 October–9 November) (bottom).

Hypothetical example of five summer and five autumn oil spill trajectories, number of bears estimated to be oiled, and total area oiled. Data were derived by matching grids of bear density to grids of 5912 barrel oil spill trajectories.

Trajectory	*Number of bears oiled*	*Number of cells oiled*	*Area oiled (km²)*
	Summer		
A	7	228,746	571.87
B	11	381,373	953.43
C	24	453,844	1,134.61
D	3	157,633	394.08
E	1	51,984	129.96
	Autumn		
A	32	235,499	588.75
B	11	82,045	205.11
C	29	158,366	395.92
D	51	499,470	1,248.68
E	60	472,832	1,182.08

Results

We utilized 10,913 satellite radio observations of 289 polar bears to determine the distribution of polar bears in the Beaufort Sea and adjacent areas. Of those, 255 observations of 69 polar bears were used to estimate the distribution of polar bears in the study area during summer. Another 322 observations of 95 polar bears were used to generate the autumn distribution of polar bears. This distribution was not uniform during either time; however, polar bears generally were more scattered in summer than they were in autumn. Pockets of relatively high density in summer reflected areas where polar bears frequent beaches and broken ice in northern reaches of the study area. Peak autumn densities occurred just offshore of Prudhoe Bay and Kaktovik and were nearly an order of magnitude greater than in summer. Overall, near-shore densities of polar bears were two to five times greater in autumn than in summer.

For example, here we match five trajectories with bear density cells, resulting in as few as one bear oiled or as many as 24 during summer. The area affected by trajectories ranged between 130 and 1135 km². During autumn, five trajectories showed a range of less than 11 to as many as 60 bears oiled and 205–1249 km² affected. This sample provides a glimpse of what we may expect from this kind of analytical approach. A full understanding of the potential effects of oil spills on polar bears, however, will be achieved only after analyses of hundreds of simulated oil spills and thousands of spillet paths with statistical estimates of likelihood included.

Discussion

Proposed industrial developments in wild areas require assessment of how that action could affect wildlife populations. Prevention and mitigation procedures depend on an understanding of what can be expected if problems occur. To proceed with an assessment, the first step is to develop effective and reliable techniques. We have outlined a practical method for determining how oil spills in the Arctic marine environment may affect the population of polar bears in the southern Beaufort Sea of Alaska. Our procedure makes use of the best available information on oil spill response in the lagoons and near-shore waters of the Beaufort Sea. It also takes advantage of current knowledge of polar bear movements and population size to develop a density distribution within the region of interest. By merging two data types—oil spills and bear density—we have a means of forecasting the range of scenarios that could result should a catastrophic oil spill occur.

The example computations suggest that the response of oil on the lagoons and offshore waters on the Beaufort Sea will be highly variable. Winds and currents, in addition to possible sea ice conditions, can generate very different patterns of oil spread within and among seasons. The number of polar bears that encounter oil clearly will be determined by a multitude of spill possibilities and the seasonal distribution of bears. Investigation of the effects of oil spills on polar bears, using the methods described here, will provide an important component of the assessment of risks of offshore oil developments.

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Eighth Biennial Report of the Interagency Arctic Research Policy Committee to the Congress

February 1, 1998, to January 31, 2000

Prepared by the National Science Foundation for the Interagency Arctic Research Policy Committee

Background

Section 108(b) of Public Law 98-373, as amended by Public Law 101-609, the Arctic Research and Policy Act, directs the Interagency Arctic Research Policy Committee (IARPC) to submit to Congress, through the President, a biennial report containing a statement of the activities and accomplishments of the IARPC. The IARPC was authorized by the Act and was established by Executive Order 12501, dated January 28, 1985.

Section 108(b)(2) of Public Law 98-373, as amended by Public Law 101-609, directs the IARPC to submit to Congress, through the President, as part of its biennial report, a statement "detailing with particularity the recommendations of the Arctic Research Commission with respect to Federal interagency activities in Arctic research and the disposition and responses to those recommendations." In response to this requirement, the IARPC has examined all recommendations of the Arctic Research Commission since February 1998. The required statement appears in Appendix A.

Activities and Accomplishments

During the period February 1, 1998, to January 31, 2000, the IARPC has:

- Prepared and published the fifth biennial revision to the United States Arctic Research Plan, as required by Section 108(a)(4) of the Act. The Plan was sent to the President on July 7, 1999.
- Published and distributed four issues of the journal *Arctic Research of the United States*. These issues reviewed all Federal agency Arctic research accomplishments for FY 96 and 97 and included summaries of the IARPC and Arctic Research Commission meetings and activities. The Fall/Winter 1999 issue contained the full text of the sixth biennial revision of the U.S. Arctic Research Plan.
- Consulted with the Arctic Research Commission on policy and program matters described in Section 108(a)(3), was represented at meetings of the Commission, and responded to Commission reports and Recommendations (Appendix A).
- Continued the processes of interagency cooperation required under Section 108(a)(6), (7), (8), and (9).
- Provided input to an integrated budget analysis for Arctic research, which estimated $185.7 million in Federal support for FY 98 and $221.5 million in FY 99.
- Arranged for public participation in the development of the fifth biennial revision to the U.S. Arctic Research Plan as required in Section 108(a)(10).
- Continued to maintain the Arctic Environmental Data Directory (AEDD), which now contains information on over 400 Arctic data sets. AEDD is available on the World Wide Web.
- Continued the activities of an Interagency Social Sciences Task Force. Of special concern is research on the health of indigenous peoples and research on the Arctic as a unique environment for studying human environmental adaptation and sociocultural change.
- Continued to support an Alaska regional office of the Smithsonian's Arctic Studies Center in cooperation with the Anchorage Historical Museum to facilitate education and cultural access programs for Alaska residents.
- Supported continued U.S. participation in the non-governmental International Arctic Science Committee, via the National Research Council.
- Participated in the continuing National Security Council/U.S. Department of State implementation of U.S. policy for the Arctic. U.S. policy for the Arctic now includes an expanded

focus on science and environmental protection and on the valued input of Arctic residents in research and environmental management issues.

- Participated in policy formulation for the ongoing development of the Arctic Council. This Council incorporates a set of principles and objectives for the protection of the Arctic environment and for promoting sustainable development. IARPC supports the contributions being made to projects under the Council's Arctic Monitoring and Assessment Program (AMAP) by a number of Federal and State of Alaska agencies. IARPC's Arctic Monitoring Working Group serves as a U.S. focal point for AMAP.
- Approved four coordinated Federal agency research initiatives on Arctic Environmental Change, Arctic Monitoring and Assessment, Assessment of Risks to Environments and People in the Arctic, and Marine Science in the Arctic. These initiatives are designed to augment individual agency mission-related programs and expertise and to promote the resolution of key unanswered questions in Arctic research and environmental protection. The initiatives are intended to help guide internal agency research planning and priority setting. It is expected that funding for the initiatives will be included in agency budget submissions, as the objectives and potential value are of high relevance to the mission and responsibilities of IARPC agencies.
- Convened formal meetings of the Committee and its working groups, staff committees, and task forces to accomplish the above.

Appendix A: Interagency Arctic Research Policy Committee Responses to Recommendations of the Arctic Research Commission

Section 108(b)(2) of Public Law 98-373, as amended by Public Law 101-609, directs the IARPC to submit to Congress, through the President, as part of its biennial report, a statement "dealing with particularity the recommendations of the Arctic Research Commission with respect to Federal interagency activities in Arctic research and the disposition and responses to those recommendations." In response to this requirement, the IARPC has examined all recommendations of the Arctic Research Commission since January 1998. The previous IARPC report, submitted in January 1998, responded to Commission recommendations through 1997. Many of these recommendations deal with priorities in basic and applied Arctic research that ongoing agency programs continue to address.

The following recommendations are from the Arctic Research Commission report "Goals and Opportunities for United States Arctic Research" (1999). Commission statements and recommendations are highlighted in boldface.

Recommendations for Agencies

At the request of the IARPC agencies we are including specific recommendations for these agencies and interagency groups in order to make clear to them our view of the opportunities.

National Science Foundation

The National Science Foundation Arctic Science Section in the Office of Polar Programs has made great strides in recent years in their interest in and efforts on behalf of research in the Arctic. We are pleased with several developments in recent years, including the partnership with the Commission in support of the ARCUS Logistics Study, the participation of the Section's staff on the Commission's field trips to Greenland and Arctic Canada, and the Foundation's support for the swath bathymetric mapping system deployed in 1998 as part of the SCICEX Program. Nevertheless, there still remains a substantial disparity between support for research in the Antarctic and in the Arctic. A new era is about to dawn in Arctic research because of the arrival in 2000 of the new Coast Guard icebreaker *Healy*. *Healy* has the potential to become the most important ship for Arctic research ever launched. On the other hand, it may languish at the dock making only occasional forays into the Arctic. The National Science Foundation has committed to *Healy* by ending its support for the ARV design activity conducted by the University National Oceanographic Laboratory System. *Healy* will be the principal U.S. resource for surface studies of the Arctic Ocean. Having committed philosophically to *Healy* it is essential that NSF find the resources to operate *Healy* as a research vessel with a minimum operating schedule of approximately 200 days per year. Without sufficient operating support, the NSF commitment to *Healy* will be a hollow one. The FY 99 budget for the Foundation contains a substantial increase in funding for Arctic Logistics needs.

NSF appreciates the Commission's comments on the great strides in recent years by the Arctic Science Section, Office of Polar Programs, on behalf of research in the Arctic. NSF's commitment to supporting Arctic research in all areas remains strong, but NSF is not the sole Federal sponsor for Arctic studies. As the Commission is aware, both NSF and the Office of Polar Programs must continually find the appropriate balance of support for a wide variety of disciplines and activities. In the specific case of supporting research that requires the use of the *Healy*, NSF's FY 00 budget request included funding for initial testing for scientific applications of the *Healy*. In FY 00 the Foundation also hopes to support limited research on the *Healy* during the science system testing cruises.

Long-term planning (FY 01 and beyond)

includes continued support for research on the *Healy*. Support for up to 100 operating days is planned, although it is unclear whether the amount required to fully fund 200 operating days, including science costs, would be available for this purpose from NSF. NSF will work with other user agencies to develop mechanisms for science support for the *Healy*.

Department of Defense

A number of activities fall under the Department of Defense. Chief among these is the SCICEX Program of the Department of the Navy. The 109th Airlift Wing of the New York Air National Guard provides LC-130 support for both Arctic and Antarctic research operations. In addition, DOD is conducting a program entitled Arctic Military Environmental Cooperation (AMEC) jointly with the Norwegian and Russian ministries of defense. The Commission encourages the Department of Defense to continue to provide support for Arctic research and environmental studies and to communicate with the Commission on any new programs.

The level of interest in Arctic research continues to wane at the Office of Naval Research. The fact that the Arctic Ocean is no longer considered an area of strategic threat is due to the decrease in tensions with Russia. The result has been a precipitous decline in funding for Arctic studies at the Office of Naval Research. The Commission believes that the decrease in Arctic operations is a reason for maintaining research levels in the Arctic in order to maintain the national capability in the region. Research is generally much less expensive than operations and the knowledge base created and maintained by research in the region may be of vital national interest in the future, particularly as access to the Arctic Ocean improves, a fact made likely through the observed thinning of Arctic sea ice. Reduced military activities in the region do not justify reduced research efforts and may be an excellent justification for maintaining and even increasing research.

With this in mind, the Commission commends the efforts of the Navy in carrying out the SCICEX cruises. The Commission notes the substantial effort made by the Navy to support this program in the face of shrinking resources and facilities. These expeditions into the Arctic Ocean aboard operational fast attack nuclear submarines show an extraordinary interest in the support of science by the Navy. The question of the continuation of these cruises after 1999 and the retirement of the last of the Sturgeon Class submarines is of great concern to the Commission, and the Commission recommends that the Navy explore with the scientific community the means to continue this invaluable access to the Arctic Ocean.

The SCICEX Program began in 1998 to collect swath bathymetric data in the Arctic for the first time from a submarine. This instrument, known as the Seafloor Characterization And Mapping Pods (SCAMP), has been made possible by the enthusiastic support of the National Science Foundation's Office of Polar Programs. These data collected by SCAMP will be of great value for students of the region from many disciplines. The regions surveyed in 1998 and 1999 will comprise only a moderate fraction of the area of the deep water portion of the Arctic Ocean. The means to continue gathering swath bathymetry with the SCAMP system should be developed for the future, preferably using Navy nuclear submarines. This recent development in submarine capability is a reinforcing reason to continue the SCICEX Program. A corollary issue is the declassification of archived bathymetry data collected on previous operations. These data are a valuable resource for the research community. A continuing program should be established to bring these data out from the classified realm respecting the security concerns, which may surround the collection of these data. The construction of the new U.S.–Russian Arctic Ocean Atlas CD shows that these difficulties may be overcome.

As a further indication of the utility of Navy nuclear submarines for research in the Arctic Ocean, the Commission also notes the cooperation of the Navy in attempting to carry out a test of the submarine as a receiving ship for seismic refraction measurements. This test, when completed, will indicate the suitability of the submarine for such experiments, and the Commission encourages further investigation of this concept. The Commission also notes the cooperation of the Navy in the declassification of bathymetric and ice profile data collected by Navy nuclear submarines in the Arctic. The value of these data is indicated by the importance attached to the bathymetric data by the international community in connection with the update of the GEBCO chart of Arctic Ocean

bathymetry. Navy data will at least double the data base available for this update.

Finally, the Commission recommends that the Navy cooperate fully in a study of the costs and benefits of retaining a Sturgeon Class submarine as an auxiliary research platform for worldwide use by the civilian science community as discussed above.

The Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover is a national treasure. In the current climate of budget stringency the pressure on Army labs is growing. The Commission wishes to be on record in support of the vital national resource that exists at CRREL. Serious reductions at CRREL might be helpful in the short term but a detriment to the national welfare over the long term. The Commission encourages continued support for CRREL.

The Commission has recently discussed with CRREL the importance of understanding the effects of global climate change on the permafrost regime. The Commission looks forward to CRREL's plans for further study of climate change and permafrost, supports the concept and encourages support for these studies by all of the IARPC agencies.

The Department of Defense invests in R&D priorities consistent with mission requirements and resources. First and foremost, the Science and Technology investments within DoD are undertaken to ensure that warfighters today and tomorrow have superior and affordable technology to support their missions and to give them revolutionary war-winning capabilities. Thus, the DoD S&T investment is directly linked to the assessment of current and future security threats. While the interest of the Department of Defense and the Office of Naval Research in Arctic research and environmental studies remains strong, the prioritization of S&T funding is subject to the fiscal realities and must consider present strategic and operational requirements. The Department remains committed to funding Arctic research at a level commensurate with the mission requirements. Contrary to the Commission's assertion, the decrease in military operations in the Arctic is not a rationale for maintaining or expanding departmental S&T efforts in the region.

From an S&T perspective, the Department of Defense supports the Navy's ongoing examination of the feasibility of continued Arctic research using Navy submarines. Such analysis is taking into account DoD's national security mission, the national security requirements for submarine operations, downsizing of the operational fleet, and the life-cycle costs of implementation of an extension of the SCICEX research program. Further, the Navy is cooperating with NSF and its contractors in an ongoing study of the costs and benefits of retaining a Sturgeon Class submarine as an auxiliary research platform for civilian science applications operated on a reimbursable basis.

National Oceanic and Atmospheric Administration

NOAA has been the leading U.S. agency for AMAP. In this role, NOAA has supplied both staff efforts and funding to the AMAP. These efforts have been largely conducted on a goodwill basis without organized programs or a satisfactory funding base. NOAA deserves great credit for these efforts and the Commission commends and supports their efforts. NOAA has conducted an Arctic Initiative beginning in 1996 at a funding level of approximately one million dollars. The Commission supports this initiative and recommends that it continue in the coming fiscal year and eventually becomes an ongoing part of the NOAA program.

NOAA appreciates the recognition by the Commission of its role as U.S. lead agency for the Arctic Monitoring and Assessment Program (AMAP). It is NOAA's intention to continue its participation in AMAP, to coordinate interagency AMAP projects in a partnership effort, to increase outreach to impacted Alaskan communities, and to promote greater involvement in AMAP activities by Alaskan people and organizations at both local and statewide levels.

NOAA also appreciates the Commission's support of the Arctic Research Initiative (ARI), a peer-reviewed research effort that we have administered jointly with the Cooperative Institute for Arctic Research at the University of Alaska Fairbanks. After a start at the $1.0 million level in FY 97, the ARI received $1.5 million in FY 98 and $1.65 million in FY 99. NOAA intends to continue this program, and the President included support for the ARI as part of NOAA's base budget request for FY 00. NOAA completed a report on the first three years of the ARI and provided copies of the report to the Commission.

As the Commission is doubtless aware, in FY 00 NOAA is combining ARI funds with International Arctic Science Center funds in a joint announcement of opportunity. This announcement was released to the Arctic science community on August 18, 1999. It invites proposals on global change and its effects on the Arctic, including detection; interactions and feedback; paleoclimates, Arctic haze, ozone and UV; contaminants; and impacts and consequences of change. The announcement is available on the IARC web page at http://www.iarc.uaf.edu and on the CIFAR web page at http://www.cifar.uaf.edu.

In order to focus our Arctic research efforts more sharply, we have established an Arctic Research Office within NOAA's Office of Oceanic and Atmospheric Research.

The National Undersea Research Program (NURP) has had a long and perilous history. Only occasionally has it appeared in the President's budget. The Commission believes that NOAA-NURP can be a valuable asset to the research community. In particular, the Commission takes note of the report of the "Blue Ribbon Panel," which spelled out a new paradigm for NURP. The Commission's interests in NURP's activities in the Arctic include the use of unmanned and autonomous underwater vehicles in the Arctic as well as the employment of the Navy's nuclear submarine assets under the SCICEX Program noted above. The Commission believes that the time has come for an organic act for NURP that will establish it as an ongoing activity with a structure based largely on the recommendations of the "Blue Ribbon Panel." As part of their mission NURP should undertake to fulfill the commitment made in the SCICEX MOA to support the research infrastructure costs of the SCICEX Program.

Following the reinvention of the National Undersea Research Program (NURP), which began in 1997, the program has been included in the President's budget each year at increasing levels. The Blue Ribbon Panel report was taken into account in the restructuring of the program, and an organic act supporting the reinvention is under review by the Administration.

Regarding the SCICEX program, the Director of NURP serves on the National Science Foundation's Study Steering Committee to examine and analyze the costs and benefits of employing a U.S. Navy nuclear submarine dedicated to global oceanographic science. This would be a follow-on to the SCICEX program. Based on the results of this study and future budget levels, NURP will determine its contributions to support infrastructure and research costs in any follow-on to the SCICEX program.

NOAA operates a suite of National Data Centers including the National Snow and Ice Data Center, the National Oceanographic Data Center, the National Geophysical Data Center, and the National Climate Data Center. These data centers are charged with the responsibility for data rescue in the former Soviet Union. The Commission recommends that the national data centers communicate the nature of their data rescue activities to the Commission and expand them as necessary to collect data vital to our understanding of the Arctic, especially the dispersal of contaminants in the region.

The NOAA National Data Centers (NNDC) continue their long history of cooperative data exchange with counterpart institutions in the former Soviet Union (FSU). The following summary highlights some of the oceanographic, meteorological, and geophysical data sets recovered and made public in the past few years as a result of this cooperation. While these data are significant contributions to our knowledge of Arctic regions, our FSU colleagues indicate there are enormous holdings still in manuscript form or on outdated magnetic tapes. Reasonable estimates to acquire these additional data and make them available far exceed the resources available to NNDC.

The National Oceanographic Data Center (NODC) has an active, proposal-driven program of "data archaeology and rescue" for oceanographic and ancillary meteorological data for the world ocean. These activities are funded by NOAA's Office of Global Programs and by the NOAA/NESDIS Environmental Services Data and Information Management program. As a result of this project, substantial amounts of data for the sub-Arctic and Arctic have been made available internationally without restriction on CD-ROM as part of "World Ocean Database 1998" (WOD98) and the "Climatic Atlas of the Barents Sea 1998: Temperature, Salinity, Oxygen" products. The majority of these rescued data are from Russian institutions. There are an estimated 500,000 Russian Nansen casts from the Barents Sea and surrounding areas still not available, many of these data being in manuscript form.

The Ocean Climate Laboratory of NODC also is working with the Murmansk Marine Biological Laboratory to construct and publish a "Plankton Atlas of the Barents Sea." A second atlas on the physical properties of the Barents Sea will be expanded to include the Kara and White Seas. Russian institutions have expressed interested in developing atlases, databases, and joint research projects, mainly for the sub-Arctic. For example the Arctic and Antarctic Research Institute (AARI) of St. Petersburg is proposing to prepare such products for the Greenland–Norwegian Sea region. If funding becomes available, AARI and the Ocean Climate Laboratory will co-develop this database and analyses.

Recently, Arctic and sub-Arctic oceanographic data from Sweden, Poland, the U.S., and Canada were added to WOD98, and more data are being processed for future updates.

The National Geophysical Data Center (NGDC) has several ongoing data rescue and exchange programs with Russian counterparts to rescue, digitize, and render available geophysical data from Russia. Most of these are part of larger data exchange programs. Likewise, the National Snow and Ice Data Center (NSIDC), in collaboration with NGDC, has been involved in extensive Russian and former Soviet Union data rescue activities. The NOAA/NESDIS Environmental Services Data and Information Management program has funded most of these activities. A list of rescued data sets at NSIDC is available to the Commission. Many more data sets are in need of rescue and publication. These include ice station seismic refraction stations, borehole temperature measurements, and additional years of sea ice data.

Since 1989 the National Climatic Data Center has been exchanging meteorological and climate data on an annual basis with the All-Russian Research Institute for Hydrometeorological Information (RIHMI) under the "U.S.–Russia Agreement on the Cooperation in the Field of Protection of the Environment and Natural Resources." Data exchanged include three- and six-hourly synoptic weather reports (since 1966), daily temperature and precipitation (since 1884), daily snow (since 1874), daily snow in heavily wooded areas (since 1996), monthly total precipitation (since 1890), and upper air data (since 1960).

In 1996 a project was initiated with RIHMI to rescue synoptic weather observations contained on 10,000 magnetic tapes at risk of being lost due to age and deterioration. The data from approximately 80 observing sites from 1891 to 1935, 700 stations from 1936 to 1965, 1300 sites from 1966 to 1984, and 2000 sites from 1985 to the present were copied to new media. In addition, daily precipitation data were extracted from the observations and provided to the National Climatic Data Center for the preparation of a U.S.–Russian precipitation data set for research.

During 1999 a cooperative project was initiated to make available to NCDC the upper air data from the Russian Arctic drifting stations (data beginning during the 1950s).

Environmental Protection Agency

The Environmental Protection Agency's Office of Research and Development (ORD) has shown little interest in the study of the special environmental concerns in the Arctic. Although the EPA-ORD was closely engaged in the Arctic and a principal support for the activities of the Arctic Environmental Protection Strategy up until 1994, subsequent involvement has been minimal. This has left the United States committed to programs under the Arctic Environmental Protection Strategy, particularly in AMAP, for which the appropriate agency (Environmental Protection) refrained from providing support. The Commission considers this to have been a short-sighted decision and recommends strongly that the EPA-ORD make a substantial effort in the study of contaminants in the Arctic. The U.S. has been judged an underachiever by the international community involved in the AEPS and the current discussion on the future of AMAP under the Arctic Council has become very difficult given that there are no plans for EPA-ORD to directly support AMAP efforts.

The Commission notes the workshop held in Fairbanks in the summer of 1996. The Commission also notes that the intention, announced at the 1996 Meeting by the Head of the Office of Research and Development, to establish an Arctic baseline study station at Denali National Park fails to understand that the Park is not in the Arctic, that experimental opportunities in a National Park are extremely limited, and that there are a number of superior sites in Alaska, notably Toolik Lake and the Barrow Environmental Observatory, which would provide a superior site where EPA could take advantage of ongoing studies by many scientists.

The ability of EPA to interact with the Native residents of the Arctic is compromised by the application of their risk assessment paradigm. This paradigm has led to the conclusion that the U.S. Arctic population is not of high prior-

ity because of its small size. This ignores the closeness of the relationship of these people to their environment (roughly 50% of their annual caloric intake comes from native plant and animal species), the environmental stresses on village life (almost 50% of Alaskan villages use the "honey bucket" system for human waste disposal), and their vast and ancient store of traditional knowledge of the Arctic environment.

There are important efforts in the Arctic sponsored by the EPA's Office of International Programs. EPA's Office of International Activities (OIA) has supported the study of contaminants in umbilical cord blood samples from Arctic residents. This AMAP-sponsored program was ignored during the AMAP initial assessment activities but has been resurrected with the assistance and support of EPA-OIA. EPA-OIA has proposed other activities in the Arctic including projects to assess and reduce sources of mercury and PCBs. The Commission commends EPA-OIA for their efforts and urges support for their activation and expansion.

The Arctic Research Commission expressed appreciation for ongoing research sponsored by the Office of International Activities (OIA) on contaminants in cord blood of Native infants, and strong concerns about the lack of investment by the Office of Research and Development (ORD). Below are responses to these concerns, and a brief outline of EPA's relevant activities.

Support of AMAP

EPA's decision to withdraw from the AMAP process in 1994 was based on issues other than recognition of the importance of this activity. EPA has re-engaged with AMAP by directly supporting the Heavy Metals workgroup and conducting other work relevant to contaminant issues in the Arctic.

In March 1999 the Office of Research and Development (ORD) agreed to chair the Heavy Metals Team during AMAP Phase II. To that end, EPA organized and sponsored a workshop "Heavy Metals in the Arctic" in September 1999 to produce a final AMAP Phase II heavy metals research plan and to establish an international heavy metals team. ORD has committed to producing a Phase II report in 2003 that includes unreported U.S. data from Phase I and new data from Phase II. The ecosystem-level risk assessment process will serve as the conceptual framework for organizing research results. EPA's ability to launch major new research programs to fulfill AMAP research plans is problematic. Available funds will have to be used strategically to focus on the most essential portions of the AMAP Phase II plan. For success, efforts will be made to find matching funds through partnerships and coordination.

AMAP is targeting "effects" and plans a special workgroup on combined effects during Phase II. The ORD has also targeted this as an issue and is planning a combined symposium and workshop for multiple stressors and combined effects on the Arctic Bering Sea during FY 00. Workshop results will be framed by the risk assessment process and offered to AMAP as an alternative approach for addressing this scientific challenge.

Arctic Research

The Denali National Park Demonstration Intensive Site Project under the Environmental Monitoring and Assessment Program was designed to establish an air quality station with UV-B monitoring capability. Data collected there can and do provide very useful information about changes in UV-B radiation in northern regions as well as long-range transport of airborne contaminants from parts of the world very remote from Alaska. However, EPA agrees that the Denali National Park research station is outside of the Arctic and recognizes the need for additional Arctic research. To further development of an Arctic research program, ORD established an Arctic Program office in Anchorage, Alaska. Program staffs are directly involved in AMAP and the Bering Sea Regional Geographic Initiative (see "Risk Assessment" below).

The Office of International Activities (OIA) has been a lead in supporting basic research with international implications characteristic of Arctic environmental concerns. OIA, in partnership with the ORD National Effects Research Laboratory and in coordination with NOAA and DOE, installed a new state-of-the-art mercury Tekran speciation monitoring unit at the NOAA research station in Barrow, Alaska. The equipment became operational in January 1999 and confirmed the "Arctic Sunrise" phenomenon this spring. In addition, OIA has continued its support of the Alaska Native Cord Blood Monitoring Program. The program is designed to monitor the levels of selected heavy metals (including mercury) and persistent organic pollutants (including PCB congeners) in umbilical cord and maternal blood of indigenous groups of the Arctic. The study will generate 180 infant–mother specimen pairs and will include two groups of infants, those previously tested (including infants from the Faroe Islands, Greenland, and Canada) and infants recruited from the Alaska Native American populations. Other OIA activities include the Multilateral Cooperative Pilot Project for Phase-Out of PCB Use, and Management of PCB-Contaminated Wastes in the Russian Federation.

EPA Region 10 continues to support contaminants research through a new partnership with the Sea Otter Commission to expand efforts in monitoring persistent, bioaccumulative, and toxic pollutants (PBTs) in subsistence foods in Alaska. The Traditional Knowledge and Radionuclides Project, conducted in partnership with the Alaska Native Science Commission, is ongoing.

Risk Assessment

Risk assessment has a varied history of development and use in EPA. Within the last 10 years, the process and its application have broadened dramatically from single-stressor-driven assessments to complex integrated ecosystem assessments for multiple stressors and combined effects. While it is true that EPA tends to target most resources toward environmental issues impacting areas of greater population density, this is a priority setting exercise rather than an application of the risk assessment process.

EPA has found the broadened risk assessment approach to be very effective in bringing together scientific research and management strategies. Specifically it allows communities to use available scientific information (and, particularly in the Arctic, traditional knowledge) to better understand what complement of stressors may be causing undesirable change in important values, key scientific questions that need to be investigated, and alternative problem solving strategies designed to achieve environmental results.

It is within this broader frame of reference that EPA is focusing resources and time in the Arctic. The risk assessment process involves multiple steps, including planning (establishing shared goals), problem formulation (using available knowledge to develop conceptual models), analysis (exposure and effects data), and risk characterization (establishing relationships). The Bering Sea Regional Geographic Initiative, sponsored by Region 10 and ORD, is focused on planning and problem formulation to help make sense of the enormous amount of available data and to give direction to future research in the Bering Sea. The Traditional Knowledge and Radionuclides Project sponsored by Region 10 is helping redefine the risk management process with tribes and may offer new ways to re-frame how risk assessment is used in the Arctic. In a similar vein, ORD has begun planning and problem formulation for the Pribilof Islands in partnership with the people of St. Paul to develop a demonstration case study of the process within a Native community. Risk assessment will also provide the conceptual framework for reporting on heavy metals for AMAP Phase II.

These activities will provide significant lessons within the Arctic about how to establish management direction, identify data gaps and research opportunities, link research to management concerns, and provide a legitimized use of traditional knowledge.

Department of State

The Department of State is responsible for the negotiation and operation of our international agreements in the Arctic. The Department seeks input from the IARPC agencies and others through the Arctic Policy Working Group, which meets monthly with the Polar Affairs Section at State. Over the years a disconnect has occurred between the Department and the officials in other agencies making the vital decisions affecting our participation and performance in international programs. This stems principally from the lack of coordination between what the agencies will actually do and the policies expressed in these programs. The most obvious case was the failure of the United States to participate in the AMAP health study of contaminants in umbilical cord blood. While endorsing this program and its goals on the one hand, no samples were actually sent for analysis even though samples existed. The result is that the United States has been viewed with a certain amount of scorn in AMAP meetings (the Commission notes that this program has finally begun under the auspices of the EPA Office of International Activities). The cure for this is certainly not simple. The most important step, however, is that the Department of State must, in the future, meet with Agency policy officials to review their recommendations, spell out the equivalent commitments to action by agencies, and modify their positions accordingly. These meetings must be carefully prepared so that the issues to be discussed are clearly spelled out and that the nature of the commitment required from the agencies is understood well

beforehand so that the agencies can come to the table prepared to make commitments.

The complexity of this problem can be seen in the state of affairs in October 1998. In October the United States took over the chair of the Arctic Council. At the same time, agency budget appropriations were passed for FY 99 but virtually no specific budget commitments were identified as supporting investigations relevant to Arctic Council needs. Many relevant activities occur in agency programs which could demonstrate U.S. commitment to the Arctic Council but there is no system to collect results and report on relevant U.S. activities to the Council and no financial support for these activities. This problem needs to be addressed immediately for FY 00 and beyond.

The Department of State is puzzled by the Arctic Research Commission's recommendations for the Department with regard to facilitation of U.S. Arctic Research. The entire first paragraph is, verbatim, what was reported in their "Seventh Biennial Report to Congress," which was submitted last year and which covered the period of February 1, 1996 to January 1, 1998. The incident that they highlight as an example of an "interagency disconnect" that resulted in "complete failure" of the United States to participate in an Arctic Council program occurred in 1996 and involved a Federal agency outside of the control of the State Department. From the perspective of the Department, it appears that the Arctic Research Commission has not seen our response to this same evaluation last year. In that initial response, we explained in detail what the State Department's role is with regard to facilitating U.S. research in the Arctic and the formulation of U.S. Arctic policy. It appears that the Arctic Research Commission has failed to take this into consideration. With regard to the additional language that the Commission has submitted this year, the Department would like to emphasize that all queried Federal agencies, with the exception of one, offered general support for the U.S. chairmanship of the Arctic Council. While we are not in a position to comment on the contents of the budgets of other agencies with regard to support for the U.S. chairmanship, we note that the Department received financial support in the amount of $250,000 for its Arctic Council chairmanship in FY 99 and has requested financial support for the Arctic Council in its FY 00 budget request. We also note that a number of other agencies, among them the Departments of Commerce/National Oceanic and Atmospheric Administration, Energy, Interior/Fish and Wildlife Service, and Environmental Protection Agency, have committed both financial resources and staff time to assist with chairing the Arctic Council. We also note that the Department of State has been generally pleased with the level of participation and leadership from the aforementioned U.S. agencies and others within the Arctic Council's working groups.

U.S. Coast Guard

The U.S. Coast Guard is the principal provider of research time on icebreakers for U.S. scientists not collaborating with other nations. In the past, the lack of an open system for soliciting participants and planning cruises has produced friction and disagreement as well as some important successes. With the advent of *Healy*, the new Coast Guard icebreaker, a new system must emerge. The dialog between the scientific community which will be using *Healy*, Coast Guard designers, and ship builders has been substantially improved. The formation of the Arctic Icebreaker Coordinating Committee has been successful and has led to substantial improvements in the design of research facilities aboard *Healy*. In the near future the need for liaison and coordination will change from the construction team to operations. The Commission anticipates that the Coast Guard will work closely with the AICC drawing upon the U.S. academic community's substantial level of experience in oceanographic operations generally and in Arctic studies in particular.

The AICC and the closer cooperation in which it is participating will not help to produce the potential for a new era of U.S. Arctic research unless a commitment to operating funds for icebreaker utilization is forthcoming. The Commission has recommended to the National Science Foundation that it provide funds for full utilization of Coast Guard icebreakers at up to 200 operating days per year as appropriate depending on funding. The Coast Guard should support NSF in its efforts to provide these funds.

The Coast Guard will depend heavily on the Arctic research community to participate in determining scheduling priorities for *Healy*. The UNOLS-Ship Time Request System will be the primary mechanism for fielding and sorting requests for ship access. There is a clear need for subsequent scheduling meetings to occur. A specific plan for arbitrating competing scheduling demands has yet to be defined. A discussion of how this process should work is an agenda item for the January 2000 Arctic Icebreaker Coordinating Committee meeting. The Coast Guard envisions a process where it provides information on ship availability and operational access to specific areas and where the science community takes responsibility for prioritizing research goals that will result in actual ship access for investigators. Input from the Arctic Research Commission, the National Research Council, and the National Science Foundation will be key to developing an equitable system that meets the national research requirements.

Interagency Task Force on Oil Spills

There is a substantial dearth of knowledge about oil spills in Arctic conditions. The Commission has long recommended a substantial research program on the behavior of oil in ice-infested oceans based in part on the research agenda spelled out in Appendix I. In addition, the Commission has had substantial discussions with the Oil Spill Recovery Institute. The Commission, in collaboration with the Alaska Clean Seas Association and others, has recommended test burns in the Arctic Ocean to study the variety of questions associated with this highly effective method of disposing of oil on the sea. The Commission recommends that the Interagency Task Force commence such a program soon, before the question is made imperative by an accident in the Arctic.

The Coast Guard supports the ARC in its recommendation to commence a research program on the behavior of oil in ice-covered waters, although no funds are currently available to support such a program. The Coast Guard continues to endorse the preparedness and response efforts of the Emergency Preparedness Prevention and Response Working Group of the Arctic Council, as well as individual national research.

The task force was established as the Coordinating Committee on Oil Pollution Research (CCOPR) under Title VII of Public Law 101-380, otherwise known as the Oil Pollution Act of 1990. The Committee has not been funded since FY 95. As a result the Coordinating Committee has focused on ensuring that the research and development projects of its member agencies are discussed and the results of that research and development are shared with Federal, state, local, and private sector researchers. The Coordinating Committee has been unable to initiate any research not already approved by an agency as part of the agency's mission-specific activities. Thus, a proposal for the Committee to initiate and manage a research and development program to study methods of disposing of oil in Arctic waters is not viable at this time. The Arctic Research Commission may wish to propose meeting with the Coordinating Committee to discuss proper research foci with attendant partnership funds to the individual agencies that comprise the Coordinating Committee.

National Aeronautics and Space Administration

The Commission has been briefed on the programs undertaken by NASA in the Arctic or having a substantial component in the Arctic. These programs are clearly of a high caliber. The Commission notes, however, that these programs are poorly publicized outside of the community of NASA Principal Investigators. The Commission recommends that NASA carry out a program of outreach to the Arctic Research Community to publicize these programs and to encourage broader participation. NASA is always at risk for the engineering side of their programs to overwhelm scientific uses and needs. The Commission believes that by broadening the participation of the research community in their programs, NASA can benefit from the resulting community support.

The Commission also notes that NASA is a participating agency in the International Arctic Research Center and supports the Alaska Synthetic Aperture Radar Facility at the University of Alaska. The Commission supports these efforts and looks forward to their continuation and expansion.

NASA welcomes the support of the Arctic Research Commission for its Arctic research program. NASA is sympathetic to the need for outreach of its programs within the broader scientific community. NASA has established procedures by which it seeks to inform the broader community of its goals and vision.

NASA publishes a Science Implementation Plan for the Earth Science Enterprise, which includes Arctic research. This document is reviewed outside NASA and provides an opportunity for scientists to understand the scope of planned activities and their relationship to overarching science goals. NASA has invested in the development of effective user interfaces at its Data Active Archive Centers, realizing how important these are to the productive use of mission data. In continued recognition of this, NASA initiated a National Research Council Polar Research Board review of its polar geophysical products during 1999, with a view to obtaining independent and science-driven advice on how best to provide data sets for Arctic researchers. Furthermore, through this review, NASA seeks to develop a strategy for broader use of its polar data sets by the research community.

In recognition of the important role that the Arctic plays in global climate, NASA will continue to support Arctic research. The Alaska SAR Facility and the International Arctic Research Center each have important roles to play in encouraging innovative and collaborative Arctic research.

National Institutes of Health

Under the Arctic Environmental Protection Strategy the United States has become involved in programs concerning the health of Arctic residents, particularly the indigenous people of the region. In particular, the AMAP health study has been focused on environmental effects on health in the region. When the United States undertook to sign the AEPS Declaration (and subsequently the Arctic Council Declaration) the message to agencies was that there would be no new money requested or appropriated for these activities. As a result, the U.S. effort in the AMAP health program has been paltry. It is clear that the responsibility for the national effort in this regard falls to the National Institutes of Health, particularly the National Institute for Environméntal Health Studies. Unfortunately, the NIH-NIEHS effort has been virtually nonexistent. The Commission recommends that NIH immediately organize an Arctic Environmental Health Study focused primarily on the measurement program outlined by the Arctic Monitoring and Assessment Program. In addition, the study of incidences and trends in the major causes of morbidity and mortality in the Arctic should be included in Arctic Council activities, perhaps as an initiative in sustainable development. The effects of both communicable diseases such as tuberculosis, systemic diseases such as diabetes and cancer, and external causes of illness and death such as alcoholism and accident have profound effects in the Arctic.

The NIH should undertake to become the focal point for Arctic Council health studies in both AMAP and the sustainable development activities of the Council. To this end NIH should provide secretariat support for U.S. Arctic Council health-related activities and take on the responsibility to see that the myriad relevant efforts at NIH and elsewhere are collected and reported to the Arctic Council as the U.S. contribution. This activity should also include a program, in collaboration with relevant State of Alaska agencies and institutions, to synthesize these results and return them to the Arctic community in understandable language along with their implications for life in the Arctic.

The Arctic Research Commission observed that, despite the agreement that the United States participate in the Arctic Environmental Protection Strategy (AEPS) and subsequently the Arctic Council, no new monies were requested or appropriated. U.S. efforts in AMAP (Arctic Monitoring and Assessment Program) were considered paltry. The ARC recommended that the National Institutes of Health (NIH), particularly its component, the National Institute of Environmental Health Sciences (NIEHS), organize an Arctic Environmental Health Study, focused on AMAP measurements. A study of the major causes of morbidity and mortality was suggested to be included in Arctic Council activities (but perhaps as part of Sustainable Development), and the NIH should become a focal point for reporting health studies to the Arctic Council, including informing the Arctic community of implications for life in the Arctic.

The NIH, and its sister agencies within the Public Health Service (PHS), namely the Centers for Disease Control and Prevention (CDC) and the Indian Health Service (IHS), are pleased to note considerable progress in supporting several programs under the Arctic Council, including both AMAP/ Human Health and Sustainable Development.

AMAP Monitoring Program

Although the initial focus of AMAP was on the exposures to, and effects of, anthropogenic pollution, there has been a broadening of its sphere of interest, especially among the Human Health expert group, to include ancillary aspects that are related to the central focus.

The Alaska Native Tribal Health Consortium, which derived from, and closely affiliates with, the Indian Health Service, is sponsoring the Alaska Native Cord Blood Monitoring Program, with the additional financial and moral support of many other Federal, state, and local organizations. Such a monitoring program comprised a "core activity" of AMAP in its first phase, during which the U.S. was not able to participate. Now, however, during the second phase of AMAP, the U.S. is a full partner in the Arctic region monitoring efforts.

AMAP Biomarkers Conference

It is evident that there would be tremendous value in utilizing more sensitive indicators of exposure to, and of the possible adverse effects of, the various anthropogenic pollutants found in the Arctic environment. Applicability of very sensitive "biomarkers" based on genetic or biochemical tests could be expected to advance the research agenda considerably if properly understood and applied. With this in mind the National Institute of Environmental Health Sciences, NIH, is sponsoring the International AMAP-2 Biomarkers Conference, in Anchorage, Alaska, in early May 2000. The conference will bring together Arctic health researchers and experts on the use of biomarkers, with the purpose of achieving cross fertilization of ideas and identifying opportunities.

Emerging and Re-emerging Infectious Diseases

The Arctic Investigations Program of the Centers for Disease Control and Prevention is contributing to the Human Health research agenda through its program to study emerging and re-emerging infectious diseases in the Arctic. This is especially apropos because of the suspected relationship of the adverse health effects of pollution on an individual's resistance to infections (e.g. due to an impaired immune response), especially in newborns, infants, and youth.

Arctic Environmental/Health Database

Under consideration is a proposed computerized database that would incorporate traditional environmental/health knowledge from indigenous Arctic populations as well as available data entries in the National Library of Medicine (NLM, NIH) Medline database. The challenge is how to acquire and codify such traditional knowledge in a machine-readable format. If the project can be implemented, it would include education and training of Arctic populations on the access to, and use of, the database, which would also provide a means of disseminating the activities of the Arctic Council AMAP, Sustainable Development, and other working groups.

Arctic Telemedicine

In support of the Sustainable Development initiative proposed by the State of Alaska, the PHS, which chairs the White House Joint Working Group on Telemedicine, is providing input to the Telemedicine Initiative. NIH components that will be involved include the National Library of Medicine (extramural grants support program) and the NIH Clinical Center (intramural telemedicine project).

Department of the Interior

The U.S. Geological Survey has led the effort by IARPC agencies in the assembly of a data structure for Arctic research. Unfortunately, there has never been a satisfactory funding base for this program. In the past, many IARPC agencies have contributed to this effort but these contributions have faded. Only NSF continues to provide support. The Commission recommends that the USGS and the Department of the Interior accept that this program belongs to them and should be fully supported. The USGS should have the full support of the other IARPC agencies. It is particularly important that an effort be staged to save important earth science data from the former Soviet Union. Much useful data is collected in old paper records which are even more vulnerable now that fuel has become scarce in many places. The Commission has recommended that the NOAA National Data Centers undertake a data rescue project coordinated with the USGS.

The Commission is correct in stating that the data collection effort by the U.S. Geological Survey is not a funded effort. Consequently the U.S. Geological Survey is able to continue this work only as a collateral effort. The latest budget information indicates that this picture will not improve in the foreseeable future. However, the USGS intends to continue this work as best it can and will continue to seek partners to help support the program.

The USGS Water Resources Branch has recently reduced the number of hydrologic monitoring stations in the Arctic. Data from these stations are urgently needed for testing and improving the predictions of large-scale of freshwater runoff in the Arctic. In addition, freshwater runoff affects the stratification of the Arctic Ocean and the distribution of nutrients, tracers, and contaminants brought to the Arctic Ocean from the land. The World Climate Research Program - Arctic Climate System Study maintains an Arctic Runoff Data

Base for these purposes. The Commission recommends that the USGS rebuild a strong program of Arctic hydrologic measurements.

The measurement of Arctic rivers and streams has never enjoyed sufficient funding, so there are just two rivers that flow directly into the Arctic that have stream gages in operation. The cost of maintaining a stream gage on an Arctic river that requires helicopter access is prohibitive. Consequently, unless the budget picture improves significantly, it is unlikely that the U.S. Geological Survey can increase the density of gages in the Arctic. However, the USGS will continue to gather as much information as possible and also promote cooperation with other interested parties whenever possible.

Members and staff of the Commission have visited the National Park Service research logistics housing facility at Nome, Alaska. The Park Service is to be commended for this effort and other agencies should consider the Park Service's example as a model to follow.

The Department thanks the Commission for its continuing endorsement of the National Park Service program.

The Fish and Wildlife Service of the Department has been a stalwart in the work of the Arctic Council's working group on the Conservation of Arctic Flora and Fauna. The Commission recommends that other divisions of the Department follow the example of the Fish and Wildlife Service in their support of Arctic Council Activities.

The Department thanks the Commission for its continuing support for the Fish and Wildlife Service's Arctic Council activities.

Department of Energy

The energy needs of Arctic villages in Alaska are extreme. Poor transportation to remote villages, small communities unable to take advantage of the economies of scale usually associated with municipal energy systems, a mixed economy with only modest cash flow, and the lack of a sophisticated technical infrastructure all make the provision of adequate energy resources in the Arctic difficult. The Commission has no specific programs to recommend but will undertake a review of DOE's village energy programs in FY 99. This study will lead to a Commission Special Report with specific recommendations for research and development of appropriate technology for the Arctic.

The State of Alaska faces many unique challenges in helping to ensure that its citizens have access to affordable and reliable electric power. These challenges are particularly evident in rural areas of the state, where electricity is primarily produced by small, expensive, and difficult to operate and maintain diesel power plants. At present the cost of electricity for rural customers is eased somewhat by the availability of the Power Cost Equalization (PCE), an electric rate subsidy program administered by the Alaska Department of Community and Regional Affairs (DCRA). However, funds for the PCE are derived from the sale of oil from Prudhoe Bay and are projected to be exhausted in 2000 or 2001, and when that occurs, electricity rates in rural areas could rise substantially. Faced with higher electricity costs, and the potential danger of environmental damages related to the use of petroleum energy in a fragile Arctic ecosystem, various Alaskan entities are now exploring ways in which renewable sources of energy can aid in the production of electric power. To better understand the role that renewable energy can play, the DOE's Wind Energy Program is engaged in collaborative efforts with a number of Alaskan organizations at the state and local levels to explore ways in which wind can make a greater contribution in the production of electric power.

The Department of Energy has been an important source of technology transfer to the Russian nuclear power reactor program. Unfortunately, budget reductions threaten this vital activity. The Commission is concerned that the future of U.S. participation is in jeopardy and that in the future nuclear energy production particularly in the Russian Arctic may proceed without the support of the Department of Energy. The budget for interaction with Russia on nuclear power systems should be supported and reinforced.

The concerns of the Commission are noted. The Department agrees that nuclear safety in the Russian Federation remains an important focus of international concern.

The Commission fully supports the activities in the Arctic under the Agency's Atmospheric Radiation Measurement (ARM) Program. The ARM Program is an important research effort and is also an outstanding example of close cooperation between researchers and Native

communities and stands as an example for other research programs.

The Department thanks the Commission for its continuing endorsement of the ARM Program.

Interagency Arctic Research Policy Committee (IARPC)

Unfortunately, the current budget stringency has caused the IARPC agencies to become hesitant about Arctic research in the face of the many other demands on their scarce resources. At the same time, however, the national commitment to activities in the Arctic has grown. This is particularly true in the case of the Arctic Council. The Commission recommends that the NSF, in its role as lead agency for Arctic research, call together the IARPC Seniors to agree on a plan of research to support U.S. participation in the Arctic Council which goes beyond the current rhetoric and demonstrates the national commitment to carry on the goals of the U.S. Arctic Policy expressed by the President on 29 September 1994. Since the appropriation of new money to meet these commitments depends on timely consideration of the nation's participation in the Arctic Council, which we currently chair, and the submission of budget requests to allow agencies to meet their responsibilities as member and chair of the Council, it is imperative that the IARPC agencies come to the table with the intention to request and redirect resources to carry out this task.

The biennial revision to the U.S. Arctic Research Plan for 2000–2004, as approved by the IARPC, includes a multiagency focused initiative that is intended to support U.S. participation in the Arctic Council. The Department of State is the lead agency for the Arctic Council. The Department of State has assigned personnel and resources to support the Arctic Council secretariat, although no separate resources were requested to support the research program. Several agencies are conducting research that supports Arctic Council priorities.

On another front, the United States agencies need to update the IARPC plan for a comprehensive study of the Arctic Ocean. While current experiments are important and of high quality, there is no current plan for the study of the Arctic Ocean which provides context for these studies. The National Science Foundation has commissioned the formulation of a strategy for the study of the Arctic Ocean. The other IARPC agencies with responsibilities for research in the Arctic Ocean include Navy, NOAA, USGS, USCG, EPA, NASA and parts of several others. IARPC should organize an interagency meeting of the principal agencies responsible for Arctic Ocean research. The Commission has recommended such a plan in the past and feels even more strongly that an organized effort is needed given the increasing evidence for rapid and substantial change in the Arctic Ocean. The Commission recommends that IARPC update the 1990 IARPC report "Arctic Oceans Research: Strategy for an FY 1991 U.S. Program" on a multi-agency basis and that this program be submitted to the Office of Management and Budget and the Office of Science and Technology Policy for consideration on a budget-wide basis.

The biennial revision to the U.S. Arctic Research Plan for 2000–2004, as approved by the IARPC, includes a multiagency focused initiative on Arctic Marine Sciences. This is IARPC's update of the 1990 IARPC report "Arctic Oceans Research: Strategy for an FY 1991 U.S. Program."

The Commission also notes their recommendation above that IARPC publish an annual report on Bering Sea research.

The IARPC biennial report of agency accomplishments, to be published in the IARPC journal *Arctic Research of the United States* (Spring/Summer 2000), will highlight Bering Sea research.

Report of Meeting

Interagency Arctic Research Policy Committee

Committee Members and Agency Representatives Present: Rita Colwell (Chair), Karl Erb, Charles E. Myers, and Thomas Pyle, National Science Foundation; Garrett Brass and George Newton, Arctic Research Commission; Delores Etter, Steven King, and CAPT David L. Martin, Department of Defense; Merrill Heit and Ari Patrinos, Department of Energy; Philip S. Chen, Jr., Department of Health and Human Services; Ray Arnaudo and Tracy Hall, Department of State; Jon Berkson, CDR George Dupree, and CAPT Charles T. Lancaster, Department of Transportation; Suzanne Marcy and Norine Noonan, Environmental Protection Agency; Jack Kaye and Kim Partington, National Aeronautics and Space Administration; John Calder, David Evans, and Tom Murray, National Oceanic and Atmospheric Administration; William Fitzhugh and Robert W. Fri, Smithsonian Institution; Richard Cline and Barbara C. Weber, U.S. Department of Agriculture; James Devine and Bruce Molnia, U.S. Geological Survey; James Morison, University of Washington, guest.

15th Meeting: March 8, 2000

Dr. Rita Colwell, IARPC Chair and Director of the National Science Foundation, convened the meeting at the National Science Foundation in Arlington, Virginia.

Arctic Policy Review

Dr. Colwell called on Raymond Arnaudo, Department of State, to provide an update on U.S. Arctic policy. Mr. Arnaudo also provided an overview of the Arctic Council's activities. He stated that the Arctic Council was established as a vehicle for international cooperation. This is the second year in which the U.S. chairs the Arctic Council. He noted that the Arctic Council has proposed several major initiatives, including:

- An Arctic Climate Impact Assessment;
- An action plan to remediate environmental problems; and
- Sustainable development projects such as cooperation in telemedicine.

Mr. Arnaudo reported on the Arctic Monitoring and Assessment Program (AMAP), one of the original pillars of Arctic cooperation.

Comments from the Arctic Research Commission

George Newton, chair of the Arctic Research Commission (ARC), provided an update on ARC activities. The ARC is preparing its biannual report on goals for Arctic research. The ARC recently adopted a new timetable for this report, so it will be available in draft by summer 2000 and circulated for comment in Alaska and the science community. Priorities to be recommended for Arctic research include:

- Study of the Bering Sea ecosystem;
- Study of global change in the Arctic; and
- Study of Arctic health.

Discussion of Letter from Science Advisor

Dr. Colwell referred to the October 5, 1999, letter from Neal Lane, Assistant to the President for Science and Technology, to the IARPC. The letter urged the IARPC to carry out the U.S. Arctic Research Plan, particularly in areas where the Plan included multi-agency efforts that relate to the U.S. global change research program. Dr. Colwell suggested that one program, the Study of Environmental Arctic Change (SEARCH), appeared to be ready for increased agency attention. She called on Dr. James Morison, University of Washington, to provide background information on the SEARCH project.

Presentation on Arctic Environmental Change

Dr. Morison reported that the Arctic is in the midst of a major change involving impacts on the atmosphere, oceans, land, ecosystems, and society. Arctic change is connected to changes in the atmospheric circulation of the Northern Hemisphere. The future course of the change is unknown, but change in the Arctic may be a fingerprint of global warming. To study these changes, long-term programs in observation, analysis, and modeling will be required.

Dr. Morison shared several charts and graphics describing the changes in the Arctic and concluded that there is a need for a coordinated program of long-term observations in the Arctic. There is a need for modeling and process studies to understand Arctic change.

Action Items

Dr. Colwell requested that the IARPC review two proposed action items:

> *RESOLVED, that the Interagency Arctic Research Policy Committee authorizes the establishment of a Working Group on the Study of Environmental Arctic Change (SEARCH).*

David Evans noted that NOAA was prepared to chair a Working Group on SEARCH. Dr. Colwell requested support for the resolution to formalize the working group. This resolution was approved.

> *RESOLVED, that the Interagency Arctic Research Policy Committee authorizes the Working Group on the Study of Environmental Arctic Change (SEARCH) to develop a multi-agency research program and a coordinated approach to implementation.*

Dr. Colwell asked the IARPC to approve the second draft resolution. This resolution was approved.

Information Items

Arctic Climate Impact Assessment. John Calder, NOAA, reported on the Arctic Climate Impact Assessment (ACIA), sponsored by the Arctic Council and the International Arctic Science Committee (IASC). An ACIA steering committee has been established, and ACIA intends to produce a scientific document that describes what is known about Arctic climate change. ACIA also will prepare a policy document with recommendations for government action. The U.S. has agreed to be the international lead on the Arctic Climate Impact Assessment.

New Icebreaker Healy. Commander George Dupree, U.S. Coast Guard (USCG), provided an update on the new Coast Guard icebreaker *Healy*. He reviewed the characteristics of the ship, ship control systems, personnel, and science labs. The USCG is planning on operating the *Healy* 280 days per year as a dedicated Arctic research platform. The first unrestricted science cruise is scheduled for March 2001.

Dr. Colwell commended the Coast Guard. She concluded that the *Healy* provides a tremendous opportunity for Arctic research. Dr. Colwell noted that the *Healy* was named for Captain Michael Healy, an African-American captain who sailed in the Arctic in the 1880s.

Barrow Area Research Support Workshop. Dr. Tom Pyle, NSF, reviewed the NSF cooperative agreement with the Barrow Arctic Science Consortium (BASC). The agreement is for management and logistics support for research in Barrow, Alaska, and the North Slope. He shared recommendations from the Barrow Area Research Support Workshop report along with a regional map showing areas for research and specific projects in the region. The need now is to determine agency interests in Barrow and coordinate them with the NSF research support and logistics program.

Alaska/Arctic Geospatial Data Clearinghouse Network. Bruce Molnia, U.S. Geological Survey, provided an update on the Alaska/Arctic Geospatial Data Clearinghouse. The USGS proposes to provide, through the Clearinghouse, tools to make maps on demand to meet research needs.

Recognition of Staff

Dr. Colwell distributed certificates and letters of appreciation to the IARPC staff in recognition of their work on the U.S. Arctic Research Plan.

Interagency Arctic Research Policy Committee Staff

The following individuals are the principal staff representatives for the Interagency Arctic Research Policy Committee. Additional staff support is provided by the Federal agencies for specific activities through working groups, as necessary.

Richard Cline
U.S. Forest Service
Department of Agriculture
Washington, DC 20090
dcline/wo@fs.fed.us

John Calder
National Oceanic and Atmospheric Administration
Department of Commerce
Silver Spring, Maryland 20910
john.calder@noaa.gov

Captain Frank W. Garcia, Jr.
Department of Defense
Washington, DC 20301
frank.garcia@osd.mil

Merrill Heit
Department of Energy
Washington, DC 20545
merrill.heit@oer.doe.gov

Suzanne K.M. Marcy
U.S. Environmental Protection Agency
Anchorage, AK 99513
marcy.suzanne@epamail.epa.gov

Philip S. Chen, Jr.
National Institutes of Health
Department of Health and Human Services
Bethesda, Maryland 20892
pc17w@nih.gov

James Devine
U.S. Geological Survey
Department of Interior
Reston, Virginia 22092
jdevine@usgs.gov

Waleed Abdalati
National Aeronautics and Space Administration
Washington, DC 20546
wabdalat@hq.nasa.gov

Charles E. Myers
National Science Foundation
Arlington, Virginia 22230
cmyers@nsf.gov

William Fitzhugh
Smithsonian Institution
Washington, DC 20560
fitzhugh.william@nmnh.si.edu

Sarah K. Brandel
Department of State
Washington, DC 20520
brandelsk@state.gov

Commander George Dupree
U.S. Coast Guard
Department of Transportation
Washington, DC 20593
gdupree@comdt.uscg.mil

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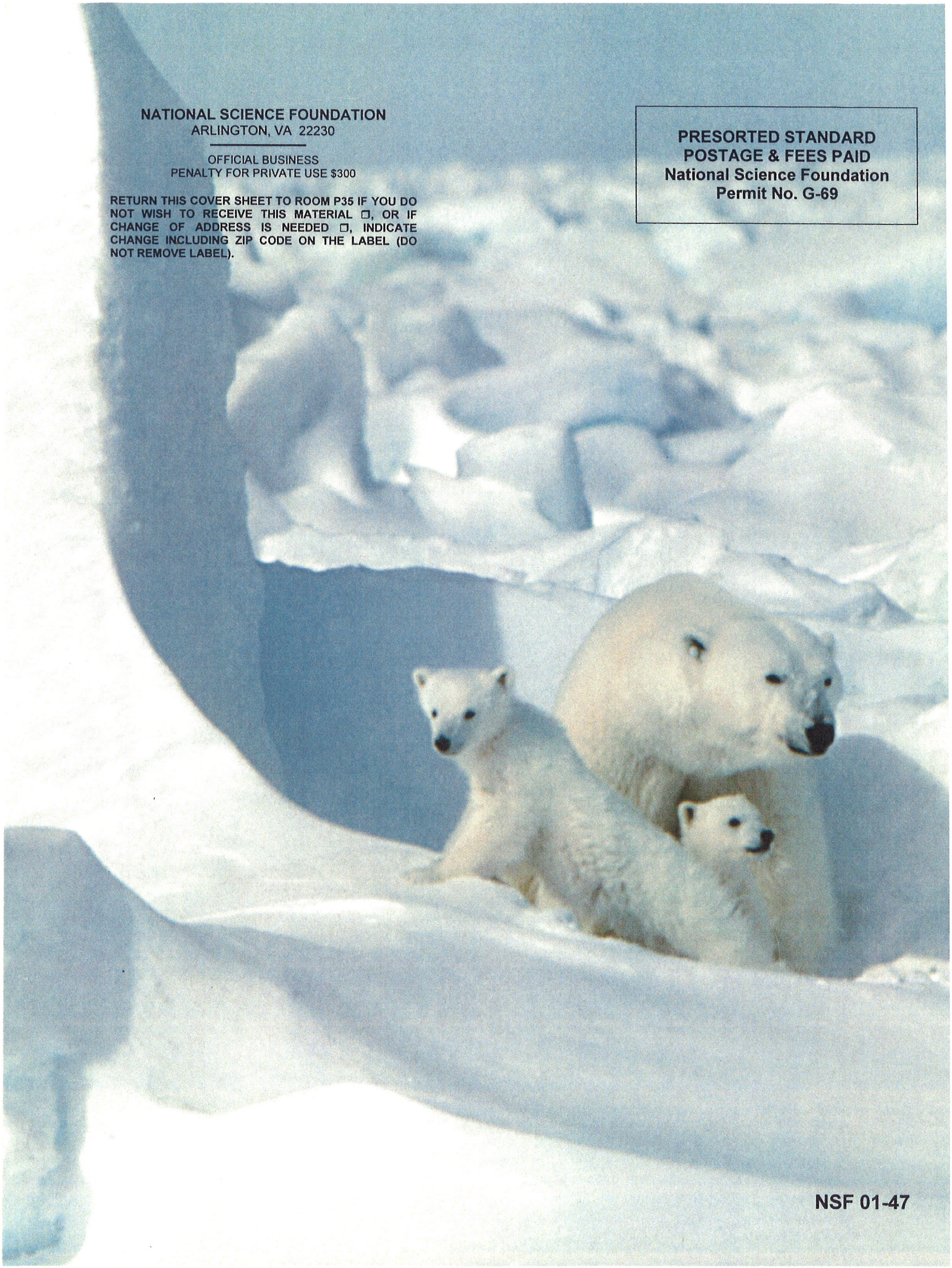

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