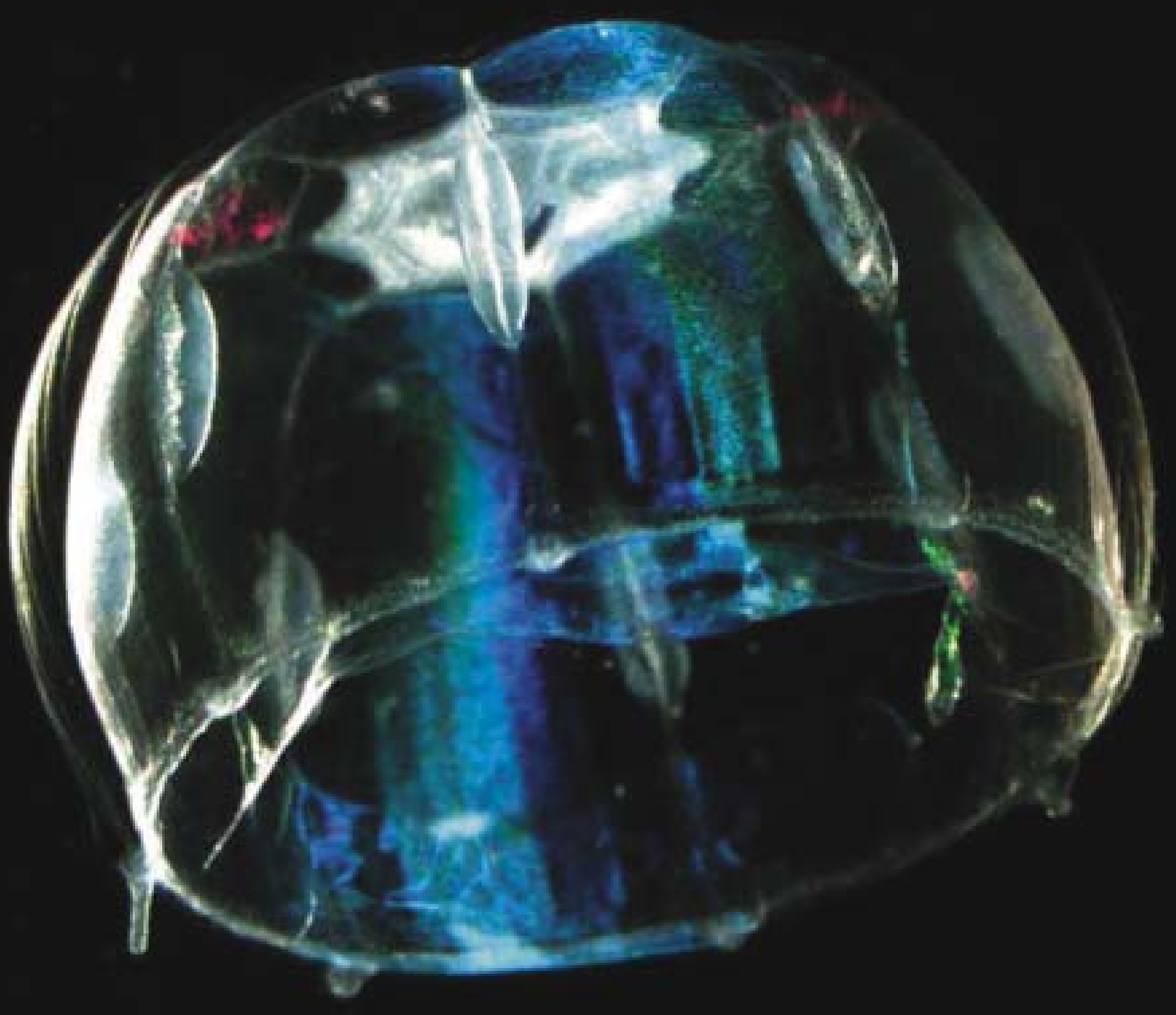
VOLUME 19 SPRING/SUMMER 2005

ARCTIC RESEARCH
OF THE UNITED STATES



INTERAGENCY ARCTIC RESEARCH POLICY COMMITTEE

About the Journal

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

Arctic Research contains

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

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

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

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

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

Cover

The medusa Sminthia arctica*, the most common species identified by video in the transition between the Pacific and Atlantic water layers of the Canada Basin, measured during an expedition to the Arctic Ocean in 2002. This gelatinous species is less than a millimeter in width.*

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SPECIAL ISSUE ON THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION'S RESEARCH IN THE ARCTIC

The Role of the National Oceanic and Atmospheric Administration in the Arctic Region

This article was prepared by Kathleen Crane, of NOAA's Arctic Research Office.

This issue of the *Arctic Research of the United States* profiles Arctic research carried out by the National Oceanic and Atmospheric Administration (NOAA). NOAA, an agency of the Department of Commerce, has four mission goals:

- To protect, restore, and manage resources in the oceans and the atmosphere;
- To understand climate change and variability;
- To fulfill weather and water information needs; and
- To support the commerce and transportation needs of the United States.

The breadth of science carried out at NOAA is spread between the NOAA National Weather Service (NWS), the primary source of weather data, forecasts, and warnings for the U.S.; the NOAA Ocean Service (NOS), responsible for the observation, measurement, assessment, and management of the nation's vast coastal and ocean areas; the National Environmental Satellite and Data Information Services (NESDIS), which provides timely access to global environmental data from satellites and other sources to promote, protect, and enhance the nation's economy, security, environment, and quality of life; NOAA's National Marine Fisheries Service (NMFS), which is dedicated to the stewardship of living marine resources through science-based ecosystem management; and NOAA's Oceanic and Atmospheric Research (OAR), which provides unbiased information to better manage the complex systems of the atmosphere, the climate, and ocean and coastal resources.

This issue of *Arctic Research of the United States* presents to the Arctic community slices of NOAA's Arctic research life. Articles cover Arctic atmospheric, ocean, ice, and marine life research, in particular, the topics of Arctic Haze, the Barrow Atmospheric Baseline Observatory, declines in Pacific Arctic snow and sea ice cover, Arctic sea ice and ocean observations, the Alaska Ocean Observing System, the Arctic Ocean exploration program, the Russian–American Long-term Census of the Arctic, ocean climate changes and the Steller sea lion decline, the status of Alaska groundfish stocks and salmon fisheries assessments, and the status of marine mammals in the Bering/Chukchi Seas. In addition, there are articles from individuals who receive external research funding from NOAA.

To wrap up these timely Arctic research topics, the National Snow and Ice Data Center presents an article on the creation of environmental data sets for the Arctic. Calling on the history of former International Polar Years, this article raises critical questions about the future role of data centers during the upcoming International Polar Year (IPY).

As the United States rapidly approaches the IPY of 2007–2008, NOAA is poised to make important, innovative, and far-reaching inroads into the further exploration and understanding of the Arctic region and to help create a legacy of polar research and observational platforms vitally important for the present-day and future understanding of the Arctic's influence on the climate of the earth.

NOAA's Arctic Ocean Exploration Program

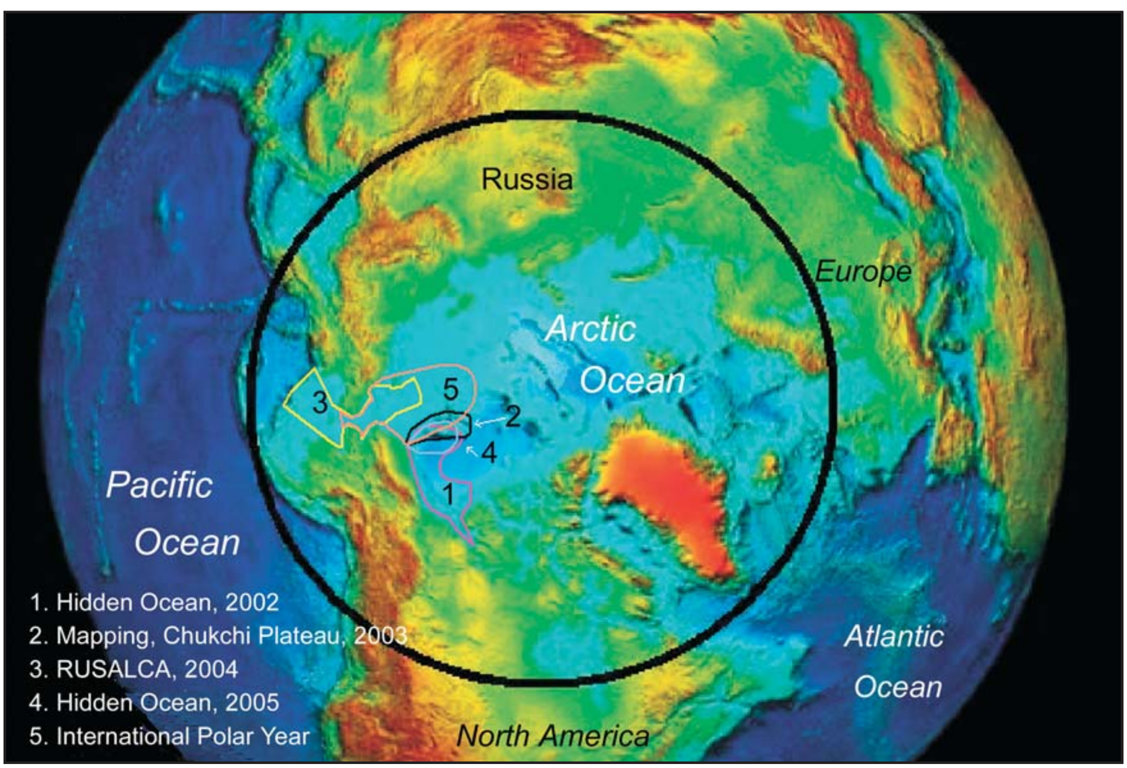
This article was prepared by Kathleen Crane, of NOAA's Arctic Research Office; Jeremy Potter, of NOAA's Office of Ocean Exploration; and Russell Hopcroft, of the University of Alaska Fairbanks.

The Arctic Ocean is largely unexplored, especially those aspects not visible to the human eye from a surface ship or to a satellite sensor. Some data collected for national defense purposes are now available, and they provide a better picture of the bathymetry and circulation of the Arctic Ocean. In addition, the International Arctic Buoy Programme contributes data on ice drift trajectories and surface meteorology. While there have been intensive research campaigns, such as the Surface Heat Budget of the Arctic (SHEBA) program that lasted about a year, the deeper portions of the Arctic Ocean and areas far from land-based facilities remain mostly unmapped, from the seafloor to the life and the currents within the sea.

Exploration Approach

NOAA and its domestic and international partners decided in 2001 to undertake expeditions of exploration and discovery in the Arctic Ocean, with initial emphasis on missions of discovery near the Pacific Gateway to the Arctic, the Canada Basin, and the Mendeleev Basin. Additional emphasis has grown to include a census of marine life plus the mapping and imaging of previously unmapped seafloor, including the continental shelves, major ridges, and deeper basins.

The original exploration plan set forth in 2001 stated that the most appropriate autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and acoustic technologies would

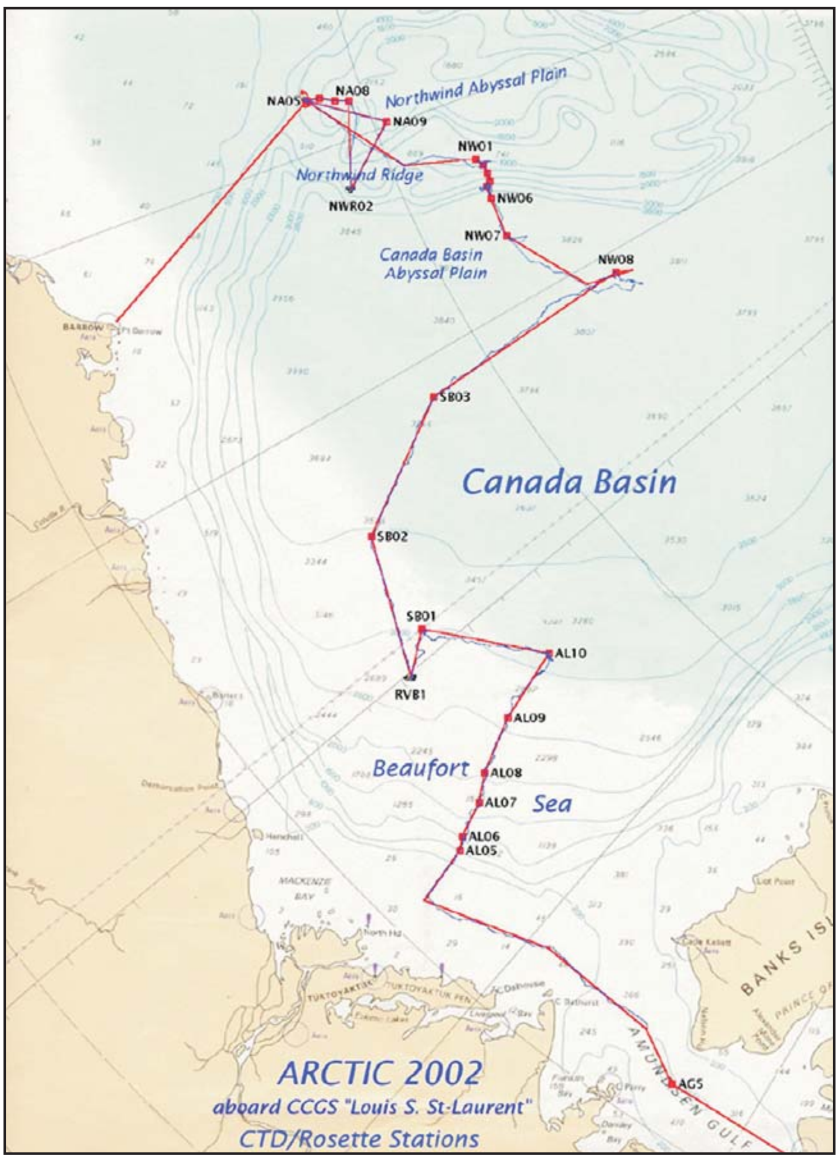


Locations of NOAA's past, present, and proposed Arctic Ocean Exploration Missions, 2002–2008.

be employed to complement more traditional wire-line sampling of the seafloor and water column. The use of aircraft and buoys was also proposed to extend the spatial and temporal range of the expeditions. Steps were also planned that would contribute to the search for new products from the sea. Since the summer of 2002, four Arctic Ocean exploration expeditions have taken place under the guidance of NOAA's Ocean Exploration Program.

The Hidden Ocean: Canada Basin

In 2002 the first of these expeditions focused on exploring the deep Canada Basin, located in the Arctic Ocean, together with the Department



Ship track of the Arctic 2002 expedition, with station numbers superimposed.

of Fisheries and Oceans, Canada, on the *Louis St. Laurent*, a Canadian Coast Guard icebreaker. In addition, both China and Japan carried out significant programs onboard the vessel.

This international team of 50 scientists from the U.S., Canada, China, and Japan participated in a collaborative effort to explore the frigid surface to the depths of the Canada Basin. Because of the region's heavy year-round ice cover, research in this region had been extremely limited. This expedition was the first of its kind. With the aid of an ROV called the *Ocean Explorer* (specially designed to operate under ice and at great depth), scientists examined the hidden world of life in the extreme Arctic conditions.

The Canada Basin may be geologically isolated from all the other deep-sea basins in the world's oceans because there *may* be no deep pathways connecting it to other regions of the Arctic. This lack of connectivity could severely limit the exchange of biota from the Atlantic and the other parts of the Arctic deep sea into the Canada Basin. What are the consequences of this biological isolation? Perhaps relict species of life still thrive in this remote basin. Perhaps new species have evolved here, isolated by the millennia. The expedition's scientists were eager to bring back samples and image the life in this ocean, from within the ice to the deep seafloor below.

From intricate microscopic organisms found in the brine channels that run through the ice to the creatures that make the sea bottom their home, the science team studied the relationships between sympagic (ice-associated), pelagic (water-column), and benthic (bottom-dwelling) communities. They investigated the manner in which food energy is transferred from the surface of the ice, through the water column, and to the bottom of this harsh environment. In addition, they analyzed bottom sediments to determine their chemical makeup, as well as help reconstruct the climatic history and paleo-environmental events that formed the region.

Ice cores were taken at a total of ten stations (on the *Louis St. Laurent* and the *Xue Long*, a Chinese research vessel) and analyzed for ice temperature, salinity, chlorophyll, and ice faunal abundances. Ice fauna were mainly located in the bottom 10 cm of the sea ice. These life forms included turbellarians, copepods, and nematodes. The abundances of these in-ice fauna in the Canada Basin were about two orders of magnitude below estimates for coastal fast, first-year ice.

Carbon and nitrogen productivity of the water column was measured at 13 locations, including

R. Hopcroft examining a freshwater melt pond on the sea ice of the Canada Basin, 2002.

three ice stations. A chlorophyll maximum was observed at many stations at 50–60 m. Primary production under the ice is about an order of magnitude lower than in open water. The occurrence of amphipods and Arctic cod was also studied. Amphipods were less abundant than reported from other parts of the Arctic, occurring at mean abundances between 1 and 23 per m^2 at each station. Small schools of Arctic cod were discovered in narrow wedges along the ice edges, which were

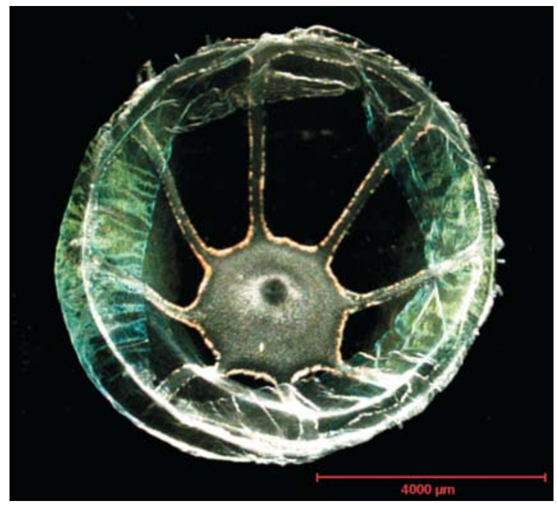
Arctic cod under the ice.

Qing Zhang, a member of the Chinese science team, removing a long cylindrical core of ice from the thick Arctic icepack. After the core had been drilled and extracted, scientists with the Primary Productivity Group could begin their sampling procedures.

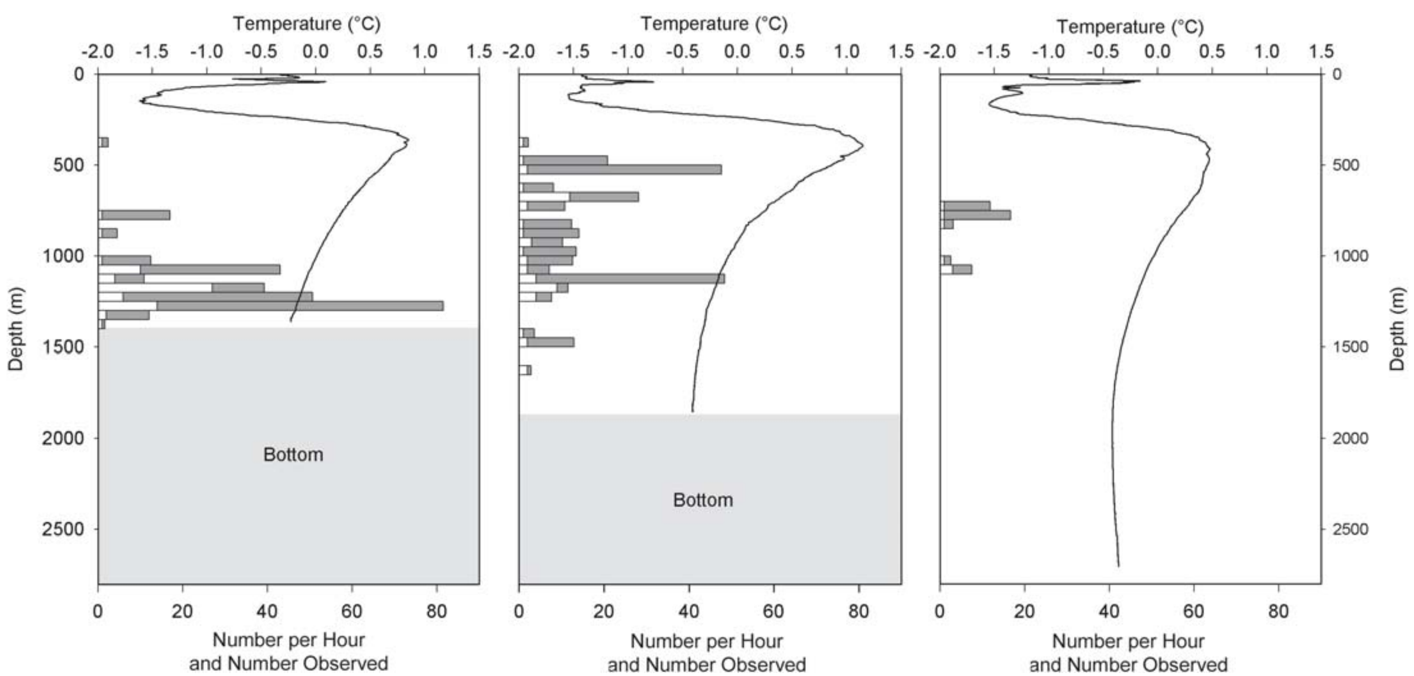
documented for the first time as important fish habitat. In addition, an unexpectedly high abundance of small-bodied copepod species was found in the water column under the ice, the importance of which has not yet been pursued in the Arctic.

Water column observations suggested a more abundant assemblage of gelatinous taxa than expected, with many species having distinct depth ranges, some extending to the bottom of the basin. The gelatinous zooplankton of the Canada Basin observed with the ROV fell into four main groups: cnidarians, ctenophores, chaetognaths, and pelagic tunicates. The vertical distributions of these gelatinous zooplankton showed several trends related to the physical properties of the water and the geographic locations within the basin. The most common gelatinous organisms in the surface waters were the ctenophores *Mertensia ovum* and *Bolinopsis infundibulum*. These two species were found in very large numbers in the near-surface mixed layer, immediately above a layer characterized by the large jellyfish *Chrysaora melanaster.* In the mesopelagic zone, siphonophores were common at the top of the Atlantic water layer, while below the transition between the Pacific water layer and the Atlantic water layer, the most common species was *Sminthea arctica.* Surprising numbers of the scyphomedusa *Atolla tenella* were found in the deep waters of the basin, along with an undescribed species of narcomedusa. Larvaceans were common in surface waters, were broadly distributed throughout the water column, and represent the most abundant holoplanktonic taxa below 2000 m. Chaetognaths were observed primarily in the upper 500 m, where plankton net collections revealed that the biomass of the most abundant chaetognath, *Eukrohnia hamata,* was exceeded only by the two species of *Calanus* copepods that classically dominate Arctic zooplankton collections.

The benthic infauna were sampled using box cores between 640 and 3250 m. A total of 90 benthic invertebrate taxa were identified from four biogeographic regions in the Canada Basin. At least three



The small medusa Sminthia arctica*, the most common species identified by video in the mesopelagic realm during the 2002 Canada Basin expedition.*

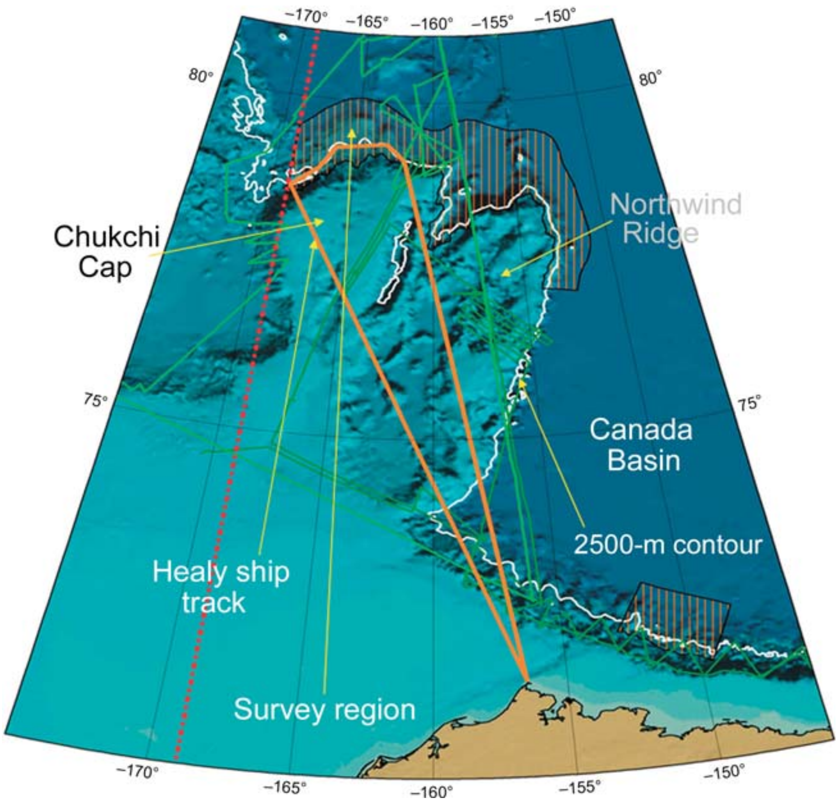


Vertical distribution of observed Sminthea arctica *in the water column from the top of the Chukchi Plateau (left), the edge of the Northwind Ridge (center), and the central part of the Canada Basin (right). Temperature profiles are superimposed. Because the time spent at each depth varied (all stations were less than one hour), the number of total observed specimens are indicated in light bars and the numbers of specimens standardized to one hour are indicated in dark bars.*

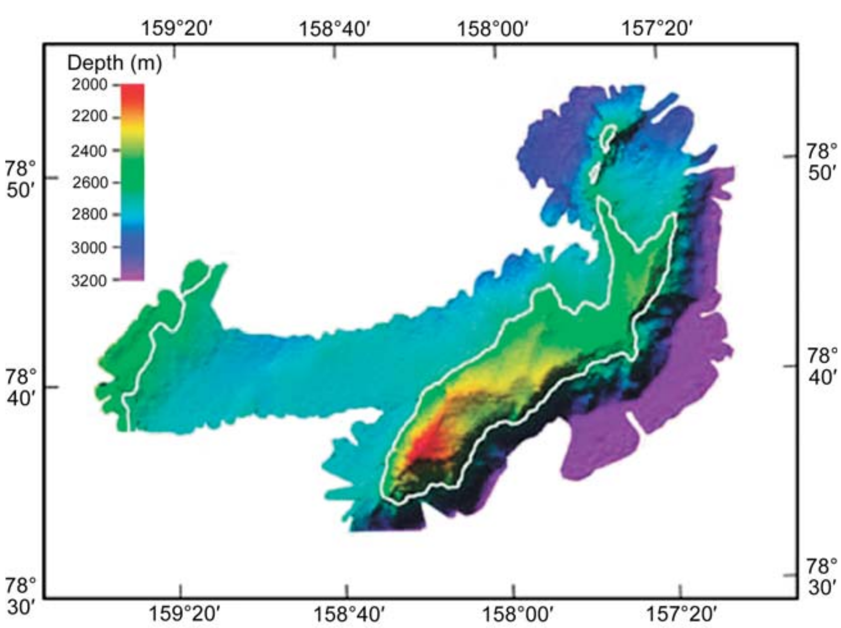
new species of isopods were discovered. However, the benthic abundance of life and the biomass are very low in the Canada Basin. Total abundances and biomass were highest in the shallow Amundsen Gulf and lowest in the deep basin. Polychaetes and crustaceans were most abundant in the samples, while polychaetes and mollusks dominated the biomass. ROV surveys revealed epifauna (life on the seafloor) where hard substrate was available for attachment.

Abyssal and midslope Arctic benthic fishes were sampled by still photography and videography using the ROV *Global Explorer*. The species diversity of the observed fishes was very low, with only six species; the diversity varied among stations sampled. Qualitative ROV video analysis suggests that demersal fish may be selecting habitats based on the presence or absence (or density) of other benthic animals. Stable isotope analysis suggests that most of the primary production is consumed by water column grazers and that the benthos primarily relies on food taken from sinking grazers and their products. This information suggests that there is a long food web of four trophic levels, which suggests low food availability.

Overall, the 2002 Canada Basin exploration revealed fundamental discoveries about the distribution and types of life that inhabit this ocean.



High-priority multibeam mapping sites on the Chukchi Cap and Northwind Ridge, 2003.



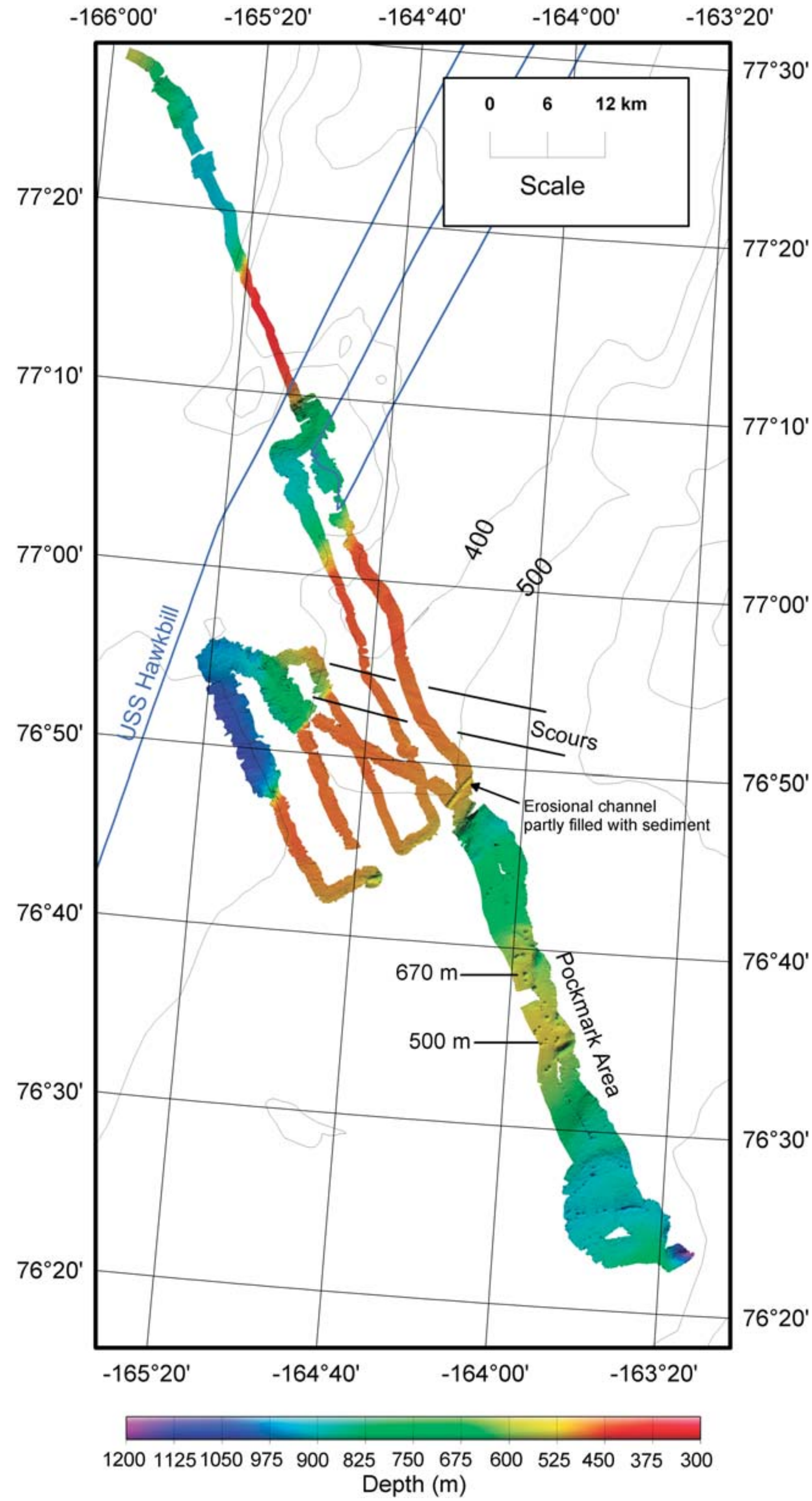
Seamount discovered on the northern boundary of the Chukchi Plateau, 2003.

Mapping the Arctic: Exploring the Chukchi Plateau

In September 2003, Arctic and hydrographic researchers, led by Dr. Larry Mayer from the Center for Coastal and Ocean Mapping at the University of New Hampshire, embarked on a 10-day Arctic Ocean mapping expedition along the Chukchi Plateau and Northwind Ridge. This mission focused on creating detailed bathymetric maps in a unique area located in the U.S. Exclusive Economic Zone (EEZ) north of Alaska.

The team sailed aboard the U.S. Coast Guard icebreaker *Healy*. The vessel was equipped with a hull-mounted Seabeam multibeam sonar capable of sensing the ocean floor at great depths. The bathymetric and backscatter imagery data created by the multibeam sonar provided important information about the tectonic processes affecting the ocean basin.

In particular, the research team addressed questions regarding the extent of grounded ice on the Chukchi Plateau. Confirmation of the extent of ice grounding in this region is of great importance for understanding the history of Pleistocene glaciation in the Northern Hemisphere.



Multibeam bathymetry of a section of the Chukchi Plateau, revealing a field of pockmarks and deep iceberg plow marks. The data were collected during the 2003 USCG icebreaker expedition.

In addition to mapping the 2500-m contour surrounding the Chukchi Plateau, the team discovered a seamount taller than Mount Rainier and uncovered evidence suggesting the outgassing of methane from the top of the Chukchi Plateau.

Russian–American Long-term Census of the Arctic

On July 23, 2004, a Russian research ship, the *Professor Khromov*, left Vladivostok, Russia, packed with U.S.- and Russian-funded scientists. It marked the beginning of a 45-day collaborative journey of exploration and research in the Russian Arctic. It was also a historic day for Russian–U.S. relations.

Stemming from a 2003 Memorandum of Understanding for World Ocean and Polar Regions Studies between NOAA and the Russian Academy of Sciences, this cruise was the first activity under the Russian–American Long-term Census of the Arctic (RUSALCA).

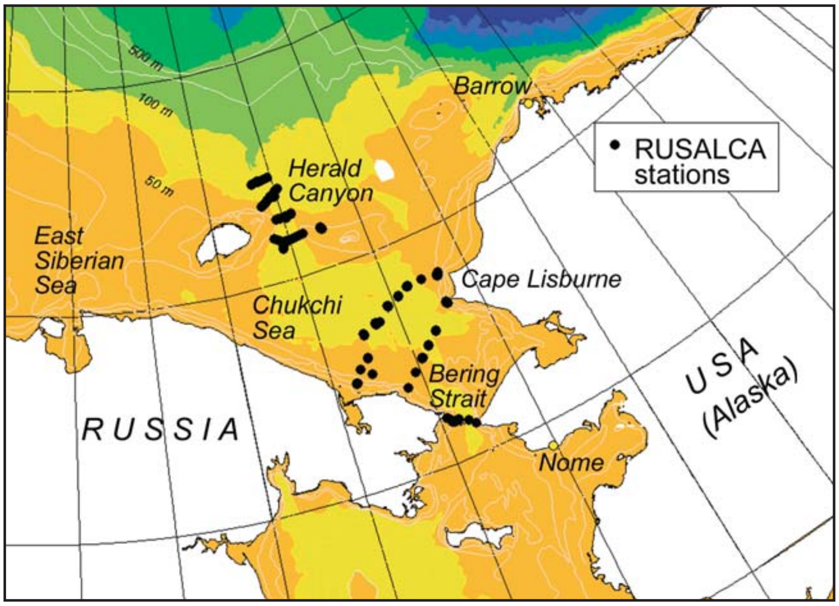
The expedition took place in the Bering and Chukchi Seas. These seas, and the life within, are thought to be particularly sensitive to global climate change, because they are centers where steep thermohaline and nutrient gradients in the ocean coincide with steep thermal gradients in the atmosphere. The Bering Strait acts as the only Pacific gateway into and out of the Arctic Ocean. As such, it is critical to the flux of heat between the Arctic and the rest of the world.

Monitoring the flux of fresh and salt water, as well as establishing benchmark information about the distribution and migration patterns of the sea life, is particularly important prior to the installation of an Arctic climate-monitoring network.

The cruise was divided into two integrated legs. Both included sampling and instrument deployment in U.S. and Russian territorial waters. The cruise objectives supported the U.S. interagency Study of Environmental Arctic Change (SEARCH) program and the NOAA Ocean Exploration Program.

The Hidden Ocean II: Canada Basin

In June–July 2005 a second exploration expedition to the Canada Basin took place, building on the exploration of the deep Canada Basin in 2002. This program also included collaboration with



Location of the RUSALCA leg 2 stations in the Bering and Chukchi Seas, 2004.

Russian and Chinese scientists. Like the previous expedition, it utilized an ROV, the *Ocean Explorer*, and sub-ice divers in conjunction with a deep-ocean camera package and more traditional sampling tools.

Education and Outreach

Educators, media specialists, and data managers have been involved from the beginning of the Arctic Ocean Exploration Initiative. *National Geographic* magazine participated during the 2002 Canada Basin Expedition and was an integral part of the ROV development and operations. In 2004 a reporter from Reuters participated onboard the RUSALCA expedition. Data management for the 2004 RUSALCA expedition will be coordinated with the National Oceanographic Data Center, the National Climate Data Center, the National Geological Data Center, the National Snow and Ice Data Center, and the World Data Center at Obninsk, Russia, along with universities and other relevant institutions.

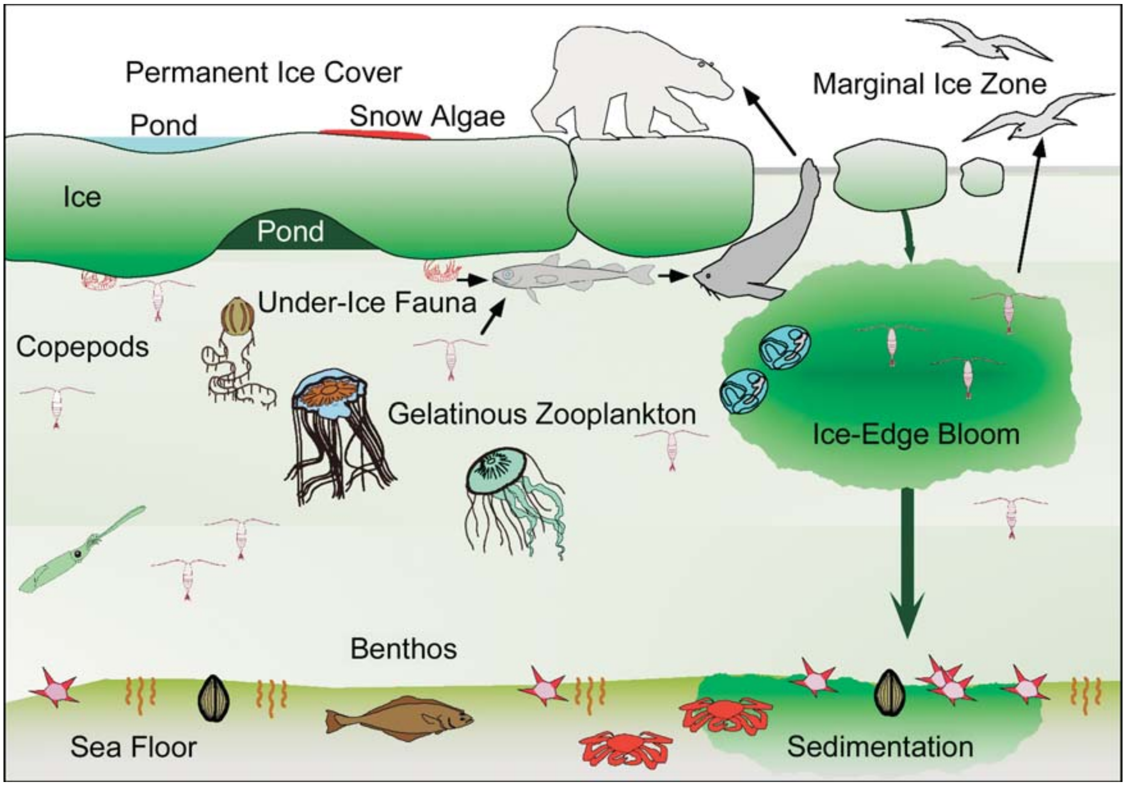
Partners

NOAA has involved partners from other Federal agencies (such as NSF, DOD, DOI, and Homeland Security), universities, its joint institutes, and the National Ice Center in the Arctic Ocean Exploration expeditions. NOAA also cooperates with appropriate international Arctic research institutions, such as those in Canada, Germany, Norway, Sweden, China, Korea, Japan, and the Russian Federation. In addition, private sector organizations were invited to participate, especially to facilitate international collaboration and the public outreach aspects of the Ocean Exploration Office.

Arctic Ocean Diversity

At the same time as NOAA was developing its plans for an Arctic Exploration Program, the international Census of Marine Life (CoML) program was also in development. Officially launched in 2003, the program established an Arctic project in 2004. The Arctic Ocean Diversity (ArcOD) project aims to increase our basic knowledge of biodiversity in the three major biological realms by consolidating existing biological information, filling gaps in our knowledge by new sampling efforts, and synthesizing what is known by 2010. The steering group contains representatives from Canada, Denmark, Germany, Norway, Russia, and the U.S. to foster international collaboration and a pan-Arctic perspective on marine biodiversity. Within the U.S., NOAA's Offices of Arctic Research and Ocean Exploration have been the primary supporters of this initiative because of their overlapping and complementary interests. ArcOD-associated scientists have been major participants on the 2002 and 2004 NOAA expeditions, as they will be on the upcoming 2005 expedition as well. Their attention to ecosystem-wide biodiversity will help lay the foundation for assessing the impacts of climate change on biological communities within all Arctic marine realms.

A copepod, Paracuchaeta*, with its late summer egg mass. This species is abundant in the Canada Basin.*



The Arctic food web.

International Polar Year

During 2007 and 2008, the Ocean Exploration Program plans to support multiple projects in both the Arctic and the Antarctic in conjunction with the International Polar Year. The type and level of support provided will be project-specific. The Office of Ocean Exploration may coordinate ship and submersible time for multiple Ocean Exploration-funded projects, as part of one or more larger explorations.

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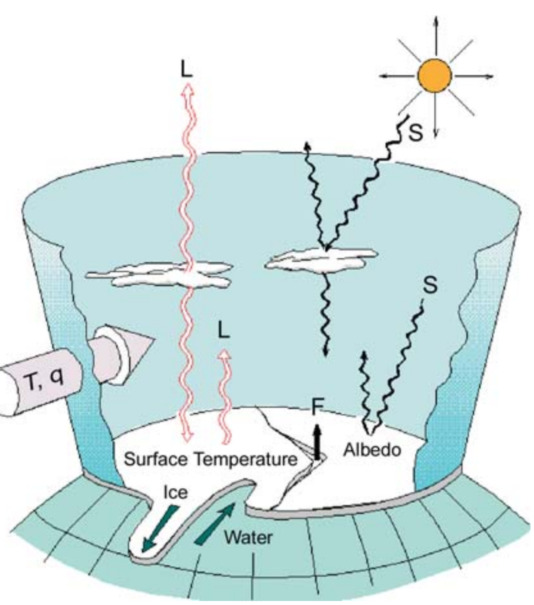
Arctic Sea Ice and Ocean Observations

This article was prepared by Ignatius G. Rigor, of the Applied Physics Laboratory (APL), University of Washington, Seattle; Jackie Richter-Menge, of the U.S. Army Cold Regions Research and Engineering Laboratory; and Craig Lee, of APL.

The Arctic and sea ice play several important roles in the global climate system, including effects on the surface heat budget and the global thermohaline circulation. Excess latent and sensible heat from the sun absorbed at lower latitudes is transported poleward by the atmosphere and ocean, where it is radiated back out to space. Sea ice over the Arctic Ocean insulates the atmosphere from the ocean, thus reducing the amount of heat lost to space. Sea ice also has a higher albedo (reflectivity) than the darker ocean, reducing the amount of sunlight absorbed by the sea-ice-covered ocean. A decrease in sea ice would increase the exposed area of the darker ocean, increasing the amount of sunlight absorbed, thus warming the ocean, melting more sea ice, and amplifying the initial perturbations (this is called ice–albedo positive feedback). However, the moisture fluxes into the atmosphere are also higher over open water than over sea ice, which may increase the areal coverage of fog and low clouds, increasing the albedo near the surface and damping the initial perturbations (this is called cloud–radiation negative feedback). These opposing feedbacks underscore the complexity of the Arctic and global climate systems.



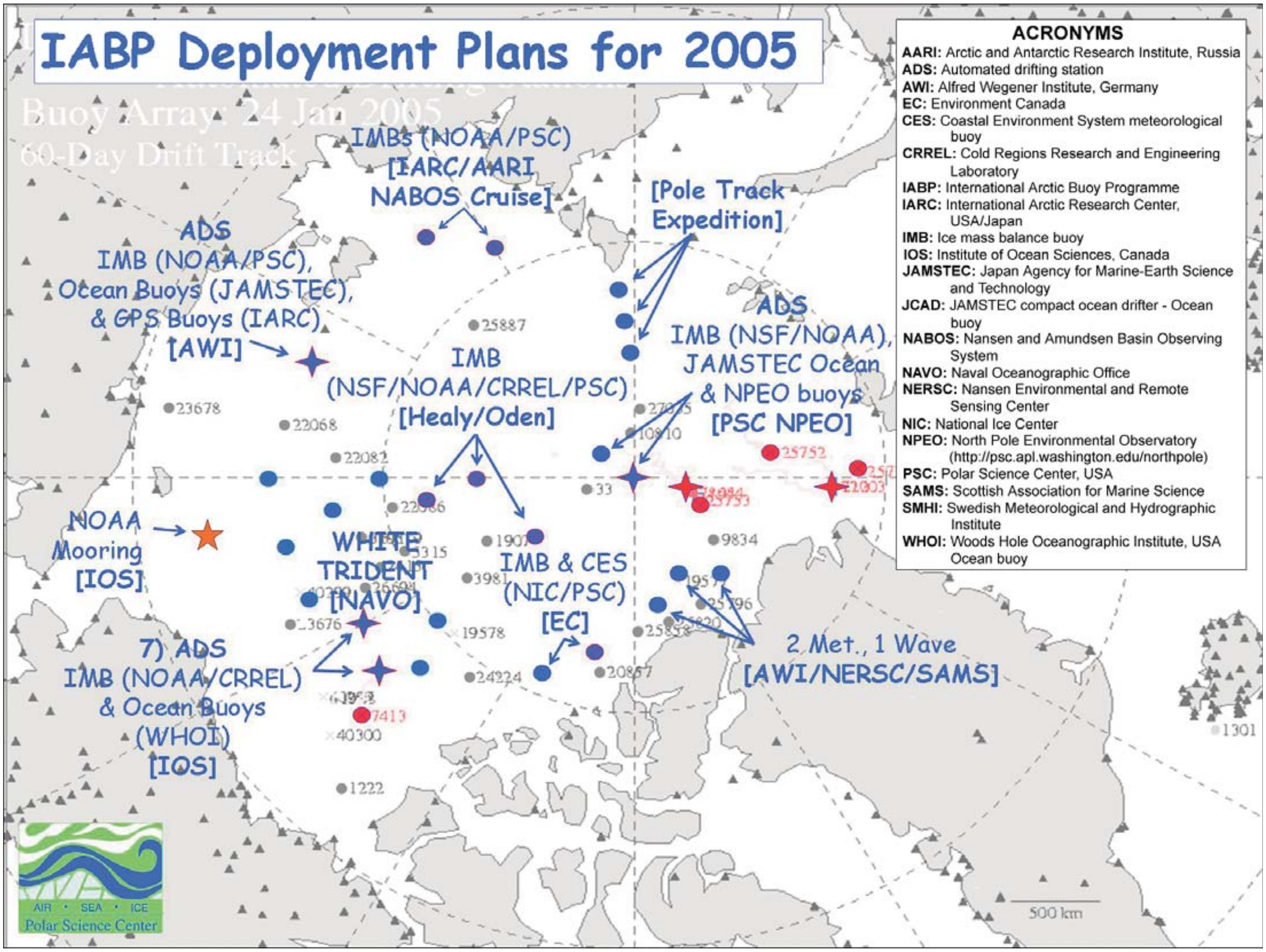
Arctic connections to global climate. Excess heat (temperature, T*, and humidity,* q*) absorbed at lower latitudes is transported poleward by the atmosphere and ocean, where it is radiated back out to space (longwave radiation,* L*). Sea ice over the Arctic Ocean insulates the atmosphere from the ocean, thus reducing the amount of heat lost to space, but it also has a higher albedo than the ocean, which reduces the amount of heat absorbed by the ice-covered ocean (shortwave radiation,* S*). Most of the heat from the ocean escapes into the atmosphere through the cracks in the sea ice (heat flux,* F*).*

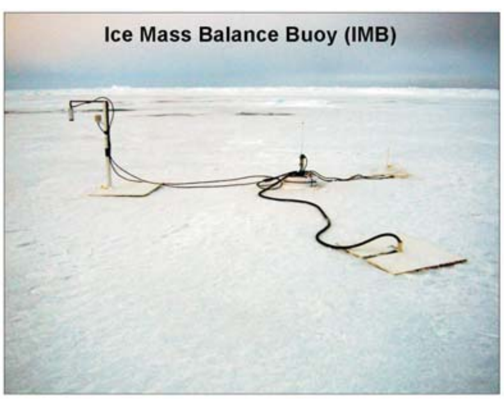
Understanding the changes in Arctic climate and sea ice is important, since these changes have significant impacts on wildlife and people. Many species and cultures depend on the sea ice for habitat and subsistence. For example, Inupiat hunt for bowhead whales, and polar bears hunt and raise their young on the sea ice. The lack of sea ice in an area along the coast may expose the coastline to ocean waves, which may threaten low-lying coastal towns and accelerate the rate of erosion. From an economic viewpoint, the extent of Arctic sea ice affects navigation from the Atlantic to the Pacific through the Arctic along the Northern Sea Route and Northwest Passage, which are as much as 60% shorter than the conventional routes from Europe to the west coast of the U.S. or Japan.

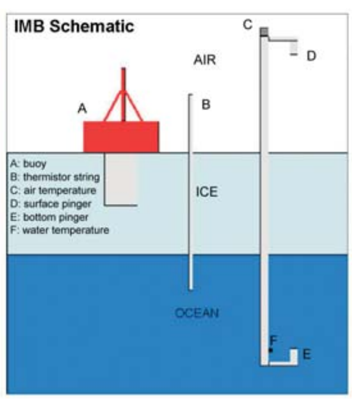
NOAA plays an important role in monitoring the Arctic and supporting research to understand and predict these changes. This article describes some of the many programs that NOAA supports to monitor Arctic sea ice and the ocean, such as the International Arctic Buoy Programme (IABP) and the Study of Environmental Arctic Change (SEARCH).

International Arctic Buoy Programme

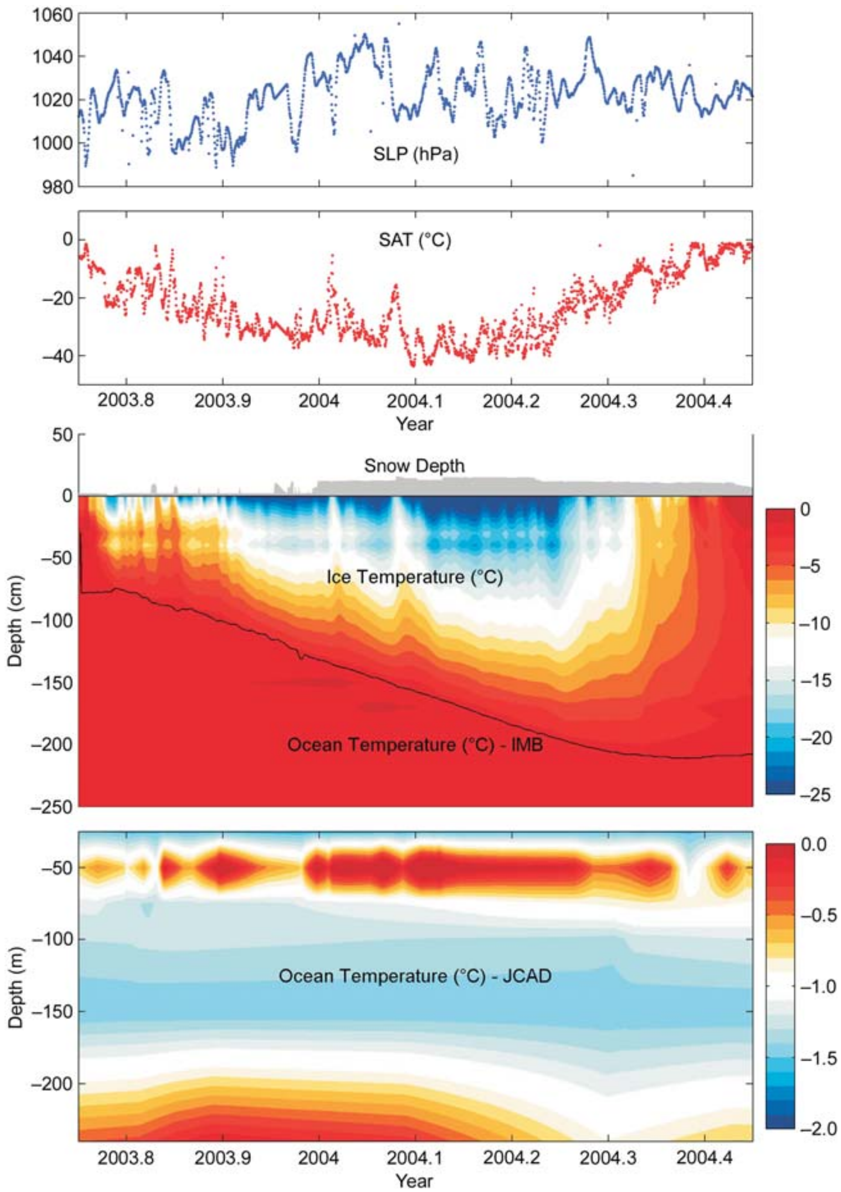
In 1974 the U.S. National Academy of Sciences recommended the establishment of a network of automatic data buoys to monitor synoptic-scale fields of sea level pressure, surface air temperature, and ice motion throughout the Arctic Ocean. As a result, the Arctic Ocean Buoy Program was established by the Polar Science Center, Applied Physics Laboratory (APL), University of Washington, in 1978 to support the Global Weather Experiment. Operations began in early 1979, and







Current locations of International Arctic Buoy Programme (IABP) buoys and the IABP deployment plans for 2005. The current locations of fundamental meteorological buoys (gray dots), ice mass balance (IMB) buoys (red dots), and automated drifting stations (ADS) (red stars) are shown. The planned deployments of buoys are shown in blue. More details can be obtained from http://iabpl.apl.washington.edu/Deploy2005/.



Observations from an IABP ice mass balance (IMB) buoy and a Japan Agency for Marine-Earth Science and Technology (JAMSTEC) compact Arctic drifter (JCAD), which were deployed together on the drifting Arctic sea ice. These buoys measure sea level pressure, surface air temperature, ice thickness and temperatures, snow depth, and ocean temperatures and salinity.

the program continued through 1990 under funding from various agencies. In 1991 the IABP succeeded the Arctic Ocean Buoy Program, but the basic objective remains: to maintain a network of drifting buoys on the Arctic Ocean to provide meteorological and oceanographic data for real-time operational requirements and research purposes, including support to the World Climate Research Programme and the World Weather Watch Programme.

The IABP currently has 33 buoys deployed on the Arctic Ocean. Most of the buoys measure sea level pressure and surface air temperature, but many buoys are enhanced to measure other geophysical variables, such as sea ice thickness, ocean temperature, and salinity. This observational array is maintained by the twenty participants from ten countries, who support the program through contributions of buoys, deployment logistics, and other services. The U.S. contributions to the IABP are coordinated by the U.S. Interagency Arctic Buoy Program (USIABP), which is managed by the NOAA/Navy National Ice Center. Of the 33 IABP buoys currently reporting, 13 buoys were purchased by the USIABP, and 18 buoys were deployed using logistics coordinated by the USIABP. The USIABP also funds the coordination and data management of the IABP by the Polar Science Center, at the University of Washington. The observations from the IABP are posted on the Global Telecommunications System for operational use, are archived at the World Data Center for Glaciology at the National Snow and Ice Data Center (http://nsidc.org), and can be obtained from the IABP web server for research (http://iabp.apl.washington.edu).

The observations from the IABP have been essential for:

- Monitoring Arctic and global climate change;
- Forecasting weather and sea ice conditions;
- Forcing, assimilating, and validating global weather and climate models; and
- Validating satellite data.

As of 2005, over 500 papers have been written using the observations collected by the IABP. The observations from IABP have been one of the cornerstones for environmental forecasting and studies of climate and climate change. Many of the changes in Arctic climate were first observed or explained using data from the IABP.

USIABP CONTRIBUTORS

U.S. Coast Guard

International Arctic Research Center, University of Alaska Fairbanks

National Aeronautics and Space Administration

National Oceanic and Atmospheric Administration (NOAA), Arctic Research Office

NOAA, National Environmental Satellite, Data and Information Service

NOAA, Office of Global Programs

Naval Oceanographic Office

Naval Research Laboratory

National Science Foundation

Office of Naval Research

The "Vision" for the SEARCH Arctic Ocean Observing System (AOOS), which includes six categories of in situ observations: ocean pathway moorings, cross shelf exchange moorings, basin moorings, gateway moorings, repeated hydrographic sections, automated drifting stations, and drifting buoys
.

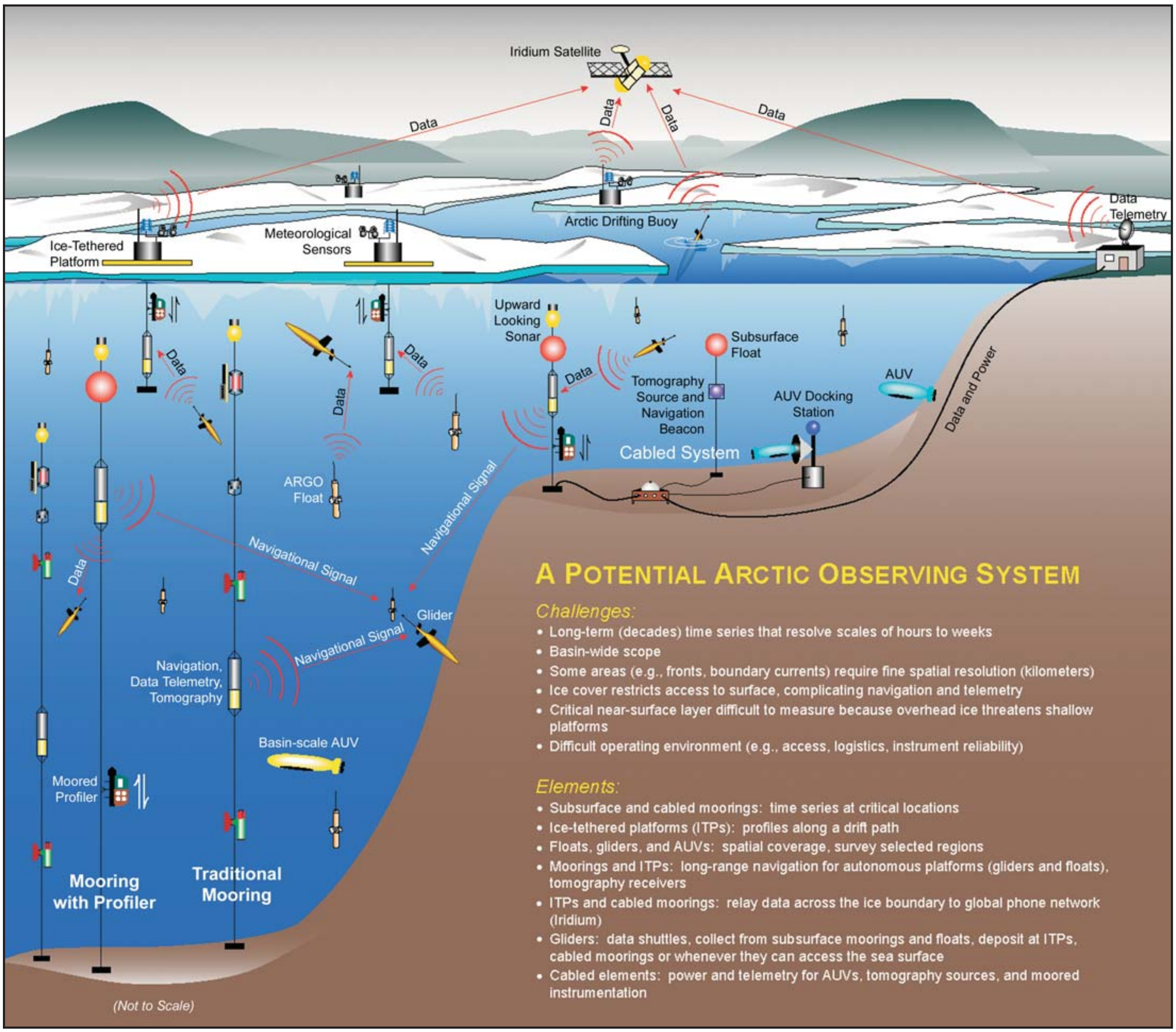
Study of Environmental Arctic Change

SEARCH is a coordinated U.S. interagency program established in recognition of the important role of the Arctic region in global climate. SEARCH's focus is to understanding the full scope of changes taking place in the Arctic and to determine if the changes indicate the start of a major climate shift in this region. NOAA has initiated its contribution to the SEARCH program with seed activities that address high-priority issues relating to the atmosphere and the cryosphere. One element of the NOAA SEARCH program is an Arctic Ocean Observing System (AOOS).

The SEARCH AOOS is envisioned to include six categories of in situ observations: ocean pathway moorings, cross-shelf exchange moorings, basin moorings, gateway moorings, repeated hydrographic sections, automated drifting stations, and drifting buoys. Enhancement of the IABP and deployment of automated drifting stations (ADSs), like the one at the North Pole Environmental Observatory (NPEO: http://psc.apl.washington.edu/northpole/), have been identified as two of the key components of the SEARCH AOOS. These enhancements and the deployment of drifting buoys have been the initial focus of NOAA's efforts. More specifically, the focus has been on establishing a network of instrumentation to monitor and understand changes in the thickness of the ice cover.

Data Collection

Central to the progress that has been made in establishing a network to monitor changes in the thickness of the ice cover has been the development and employment of autonomous ice mass balance (IMB) buoys. An IMB buoy is equipped with thermistor strings that extend through the thickness of the ice cover, acoustic sensors that monitor the position of the top and bottom surfaces of the ice, a barometer, a GPS, and a satellite transmitter. These buoys provide a time series of sea level pressure, surface air temperature, snow accumulation and ablation, ice mass balance, internal ice temperature fields, and temporally averaged estimates of ocean heat flux. Together, these data not only provide a record of changes in the ice thickness, but equally important they provide the information necessary to understand the source of these changes. This is critical to extending the results from these individual sites to other regions of the Arctic. The buoys are installed in the ice cover and, hence, drift with the ice cover. Monitoring the drift of the buoys also provides information on the circular automated drifting stations (ADSs). These sites will be established through collaboration with the Alfred Wegner Institute in Germany, the NPEO, the Japan Agency for Marine-



Components of the Arctic Ocean Observing System (AOOS).

Earth Science and Technology, and Woods Hole Oceanographic Institution's Arctic Group. These stations provide critical atmospheric, ice, and upper ocean hydrographic measurements that cannot be obtained by other means.

Since the drifting buoys move with the ice and surface currents and thus cannot reliably sample the main subsurface currents of the Arctic, these observations must also be complemented by moorings and hydrographic sections across the Arctic Ocean. In August 2003 a new mooring site was established in the northern Chukchi Sea. The mooring is equipped with an ice profiling sonar (IPS) to measure the ice draft and velocity as the ice drifts overhead, providing a measure of the ice thickness distribution. This site was located using the results from a coupled ice–ocean sea ice dynamics model. The model was used to estimate the basin-wide mean annual thickness using a 52-year window: 1948–1999. Using these estimates, a correlation analysis was applied to investigate the effectiveness of establishing a second seafloor-moored IPS to monitor changes in the annual mean thickness of the Arctic sea ice cover. The analysis recognized and was dependent on the existence of the IPS at the NPEO. The results of the analysis indicated that a moored IPS located in the northern Chukchi Sea, coupled with the results from the established NPEO site, could explain 86% of the variance of the basin-wide annual mean ice thickness. The location of a second mooring significantly improves the data collected from a single moored IPS at the North Pole, where the explained variance is estimated to be 65%. Data from the mooring sites are only available after the mooring is recovered. The first recovery of the mooring in the Chukchi Sea is scheduled for September 2004.

A potential AOOS design requires a range of complementary platforms with combined capabilities that address SEARCH requirements. The AOOS includes drifting buoys, moorings, autonomous platforms (floats, gliders, and propeller-driven autonomous underwater vehicles), and hydrographic sections occupied by ships and aircraft landings. Drifting buoys and moorings, already employed for Arctic observing, would provide sites for acoustic navigation and communications beacons and serve as data repositories and links across the ice interface for satellite communications. New autonomous platforms, especially floats and gliders, will provide unprecedented access to Arctic and subarctic regions. These platforms have seen significant successes in mid-latitude oceans and are currently being adapted for use in ice-covered environments as part of the NSF-supported Freshwater Initiative (see http://iop.apl.washington.edu for additional information). The first missions beneath the ice will investigate freshwater exchange through Davis Strait. Broader high-latitude application of autonomous platforms will require the development of long-range acoustic navigation and communications systems. An ideal system would supply long-range acoustic navigation to all platforms (Arctic underwater GPSs), allow mobile platforms to home to targets (drifting ocean buoys and moorings), and provide short-range, high-bandwidth communications for rapid data exchange. In this vision, moored platforms provide time series, data storage, and a relay through the ice to satellites; autonomous platforms provide broad spatial coverage, data shuttling, and satellite links (when in ice-free waters); and ship- and aircraft-based hydrography provide critical tracer measurements that cannot be obtained by autonomous sensors. This combination of platforms offers comprehensive coverage and creates a "store-and-forward" network to improve the timeliness and reliability of data return.

Conclusions

Recent progress has been made in establishing components of an AOOS. The initial focus is on a network of instruments to monitor and understand changes in the thickness of the ice cover and in near-surface ocean characteristics. Central to the success of this network is the coordination of these efforts with other national and international programs. The use of sea ice dynamics models has also been important, helping to optimize the location of instrumentation and the allocation of limited resources.

Data are only just beginning to be received from the recently deployed sites, but regional and interannual variability in the changes in the thickness of the ice cover and upper ocean is already apparent. This observation is consistent with other historical observations.These data will be made generally available to the scientific community for use in validating satellite-derived products; for forcing, calibration, and assimilation into numerical models; and for forecasting weather and ice conditions. Maintaining and further developing this network will provide a more consistent record of change, necessary for improving understanding of this complex and important component of the global climate system.

The establishment of the components of the AOOS discussed in this article would not have been possible without the committed collaboration among many international institutions and programs, such as the participants of the International Arctic Buoy Programme. The authors express their appreciation to the scientific participants and crew members onboard the Canadian icebreakers Louis St. Laurent *and* Sir Wilfred Laurier*, the German icebreaker* Polarstern*, the Russian icebreaker* Kapitan Dranitsin*, the Swedish icebreaker* Oden*, and the U.S. icebreaker* Healy.

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Correlated Declines in Pacific Arctic Snow and Sea Ice Cover

This article was prepared by Robert Stone, of the Cooperative Institute for Research in Environmental Sciences and NOAA's Climate Monitoring and Diagnostics Laboratory; David Douglas, of U.S. Geological Survey's Alaska Science Center; Gennady Belchansky, of the Institute of Ecology, Russian Academy of Sciences; and Sheldon Drobot, of the Colorado Center for Astrodynamics Research.

Simulations of future climate suggest that global warming will reduce Arctic snow and ice cover, resulting in decreased surface albedo (reflectivity). Lowering of the surface albedo leads to further warming by increasing solar absorption at the surface. This phenomenon is referred to as "temperature–albedo feedback." Anticipation of such a feedback is one reason why scientists look to the Arctic for early indications of global warming.

Much of the Arctic has warmed significantly. Northern Hemisphere snow cover has decreased, and sea ice has diminished in area and thickness. As reported in the Arctic Climate Impact Assessment in 2004, the trends are considered to be outside the range of natural variability, implicating global warming as an underlying cause. Changing climatic conditions in the high northern latitudes have influenced biogeochemical cycles on a broad scale. Warming has already affected the sea ice, the tundra, the plants, the animals, and the indigenous populations that depend on them.

Changing annual cycles of snow and sea ice also affect sources and sinks of important greenhouse gases (such as carbon dioxide and methane), further complicating feedbacks involving the global budgets of these important constituents. For instance, thawing permafrost increases the extent of tundra wetlands and lakes, releasing greater amounts of methane into the atmosphere. Variable sea ice cover may affect the hemispheric carbon budget by altering the ocean–atmosphere exchange of carbon dioxide. There is growing concern that amplification of global warming in the Arctic will have far-reaching effects on lower-latitude climate through these feedback mechanisms. Despite the diverse and convincing observational evidence that the Arctic environment is changing, it remains unclear whether these changes are anthropogenically forced or result from natural variations of the climate system. A better understanding of what controls the seasonal distributions of snow and ice is fundamental to the problem.

Why Be Concerned? The Temperature–Albedo Effect

Anticipation of a temperature–albedo feedback is the primary reason observers look to polar regions for early indications of global warming. This effect relates to the dramatic contrast in the reflectivity of sunlight by snow or ice compared with open tundra or seawater. Fresh snow reflects up to 90% of incoming solar radiation, while tundra and open water reflect only 15–20% and 6–8%, respectively. Changes in albedo affect the net energy balance at the surface, which in turn influences air temperature. An increase in net energy can raise temperatures, depending on how that energy is redistributed. Most of the excess energy is stored in the ground initially but is released as heat over time to warm the air above.

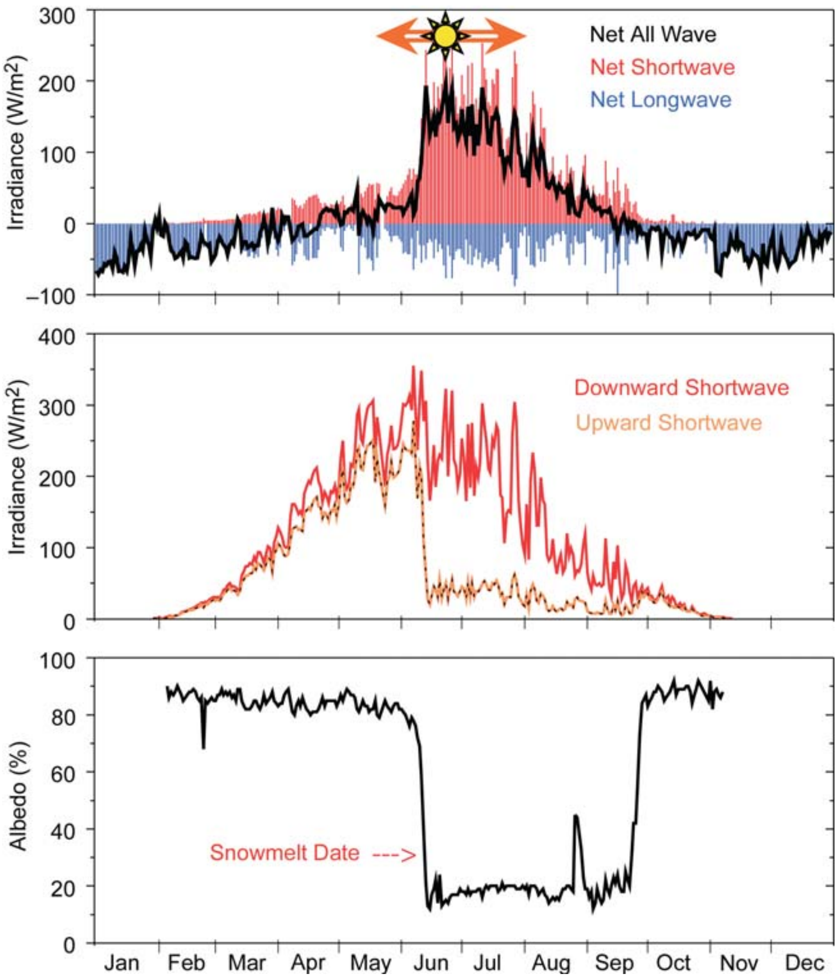
It has been rightfully stated that "the most significant factor influencing the magnitude of the yearly net radiation total is the date when snowmelt is completed."* The timing of snow and ice melt over vast regions of the Arctic can affect climate on a hemispheric scale. Thus, it is important to monitor changes in Arctic snow and sea ice cover and understand what causes them to vary.

Earlier Snowmelt in Northern Alaska

Since 1940 the spring melt at the NOAA/CMDL Barrow Observatory (BRW) has advanced by about 10 days. Most of the advance occurred after 1976, however. The break in the record coincides with regime shifts in many climatic and biological indicators of change, mainly a consequence of

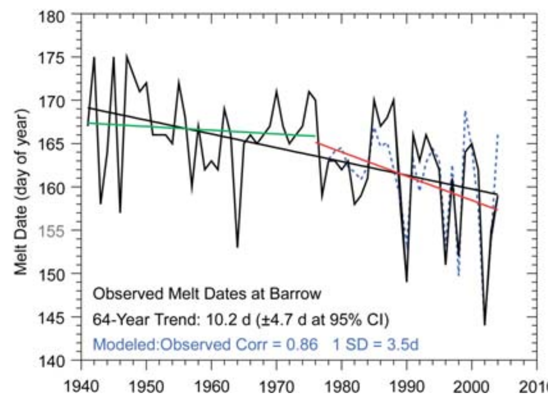
* Maykut, G.A., and P.E. Church (1973) Radiation climate of Barrow, Alaska. *Journal of Applied Meteorology*, Vol. 12, p. 620–628.

changing atmospheric circulation patterns in the North Pacific. The year 2002 had a record early melt. The 2003 melt was again early, followed by a moderately early melt in 2004. The past three years, when combined with 1990, 1996, and 1998, are unprecedented in the 64-year record. These anomalously early events statistically drive the long-term trend.



Annual cycles of daily average radiative energy at the NOAA/CMDL Barrow Observatory (BRW). The surface albedo (the bottom panel) is the ratio of the upwelling to the downwelling shortwave irradiance (middle panel), where irradiance is a measure of solar energy. Historically, a daily average albedo threshold of 30% is used to define the final day of snowmelt at BRW; i.e., when the snow cover essentially disappears. During the final week of melting, the albedo falls rapidly from about 75% to about 17%. The impact that this change has on the net all-wave radiative energy balance is illustrated in the top panel, where net all-wave radiation is simply the sum of the net shortwave and longwave components. Values of net short- and longwave irradiance are determined as downward minus upward components, indicated by red and blue spikes in the top panel. The dramatic decrease in albedo at the time of snowmelt results in a large increase in the net radiative energy (black curve) because of increased solar absorption by the surface. In this example, the rise can be likened to illuminating every square meter of the tundra by a 120-watt light bulb (net irradiance increases by about 120 W m^{-2}). Even more dramatic increases will occur over ocean areas, because seawater has a lower albedo than tundra. It is because the melt season coincides with the peak of the annual solar cycle that the albedo effect is so large.

Variations in the annual snow cycle of northern Alaska are attributable, in large part, to changes in atmospheric circulation related to the position and intensity of two pressure systems: the Aleutian Low (AL) and the Beaufort Sea Anticyclone (BSA). On this basis, an empirical model was developed to predict melt dates at BRW. About 75% of the interannual variability in snowmelt dates at BRW is explained by the model's input parameters: changes in snowfall during winter and variations in springtime temperatures and cloudiness.

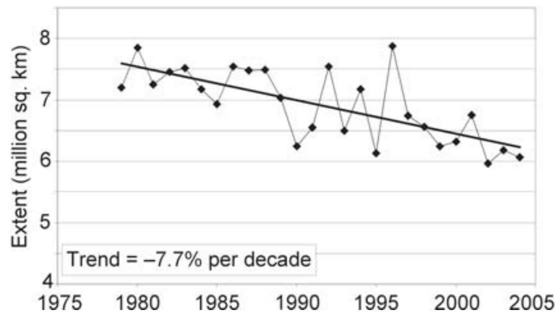


Time series of snowmelt dates (as day of year) constructed for the NOAA/CMDL Barrow Observatory. Three linear regressions are plotted: an overall fit for 1941–2004 (thin black line), one for all years prior to 1977 (green), and a third beginning in 1977 (red). The results of an empirical model are also shown (dashed blue line). The time series was compiled from direct snow depth observations, proxy estimates using daily temperature records, and, beginning in 1986, surface albedo measurements.

The timing of snowmelt perturbs the net surface energy budget through the albedo effect. Using continuous radiometric measurements made at BRW, the effect can be quantified. A 10-day advance in snowmelt results in a 14–16% increase in net surface radiative energy during the season, equivalent to more than 2 W/m^2 of thermal forcing on an annual basis. While this sounds like a small perturbation, an increase of only 1.0 W/m^2 in net surface radiation can increase the air temperature by more than 0.5°C. The additional energy is redistributed in complicated ways that involve ground storage, sensible and latent heat exchanges between the surface and atmosphere, and air flow that distributes the energy gain to other regions. In addition to contributing to warming, the recent thawing of permafrost in the region is probably attributable in large part to earlier snowmelt. Many biogeochemical cycles are also influenced by the length of the growing, or snow-free, season at high latitudes.

Diminishing Sea Ice in the Western Arctic Ocean

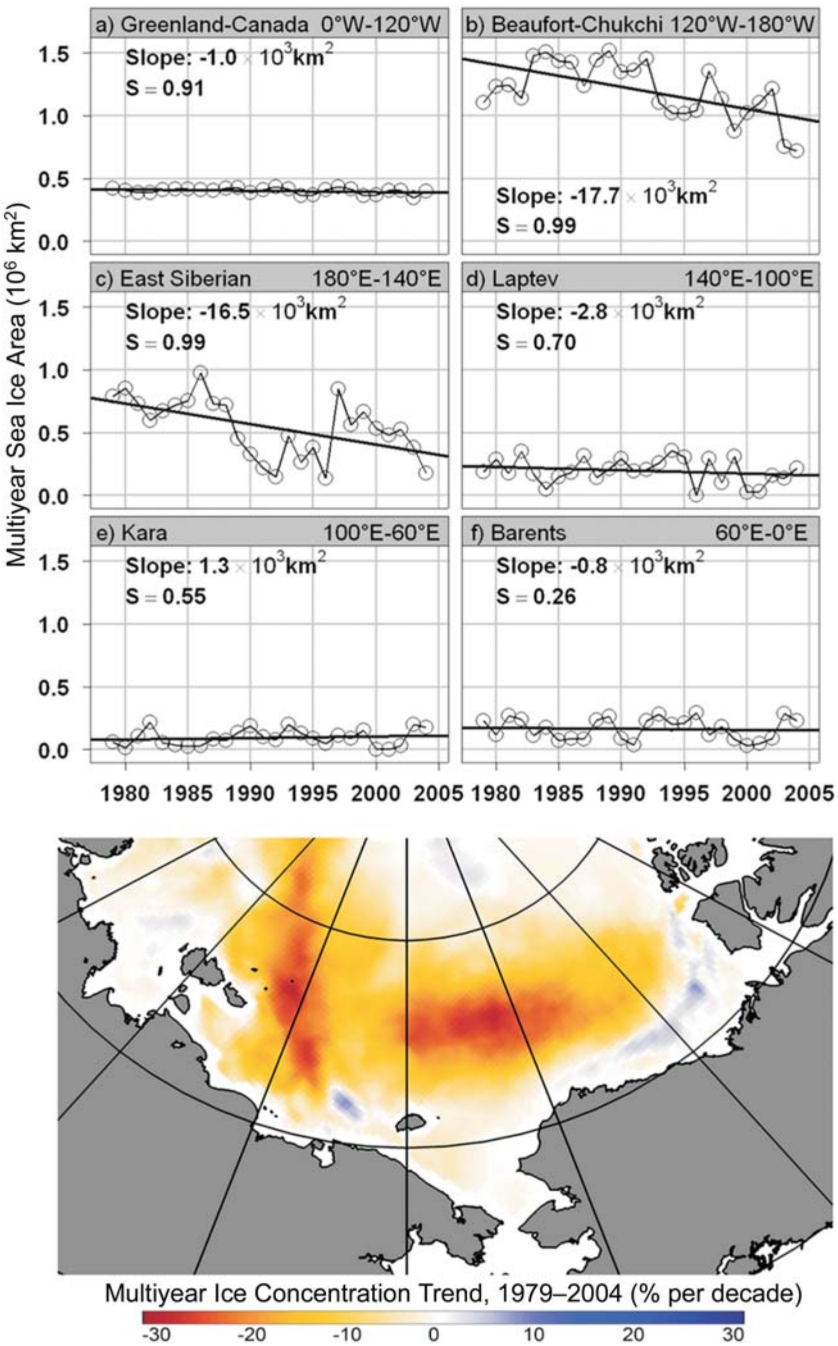
One of the most alarming indicators of global climate change is the continuing decline of Arctic sea ice. Sea ice distributions have been tracked historically by direct observations from ship and aircraft and since the late 1970s from satellite platforms. Passive microwave (PMW) satellite sensors provide daily data for evaluating sea ice conditions, including surface melt, age, ice concentration, and derived extents. From such analyses we know that the maximum retreat (or minimum extent) of ice occurs in September each year. Since the late 1970s, September sea ice extent has decreased by nearly 20%. The minimum occurred in 2002, coincident with the record early snowmelt in northern Alaska. Last year (2004) marked the third consecutive year of anomalously extreme ice retreat in the Arctic.



Time series and linear trend in September Arctic sea ice extent, 1979–2004. The calculation is made for areas having an ice concentration greater than 15.0%. The regression yields a decrease of about 7.7% per decade.

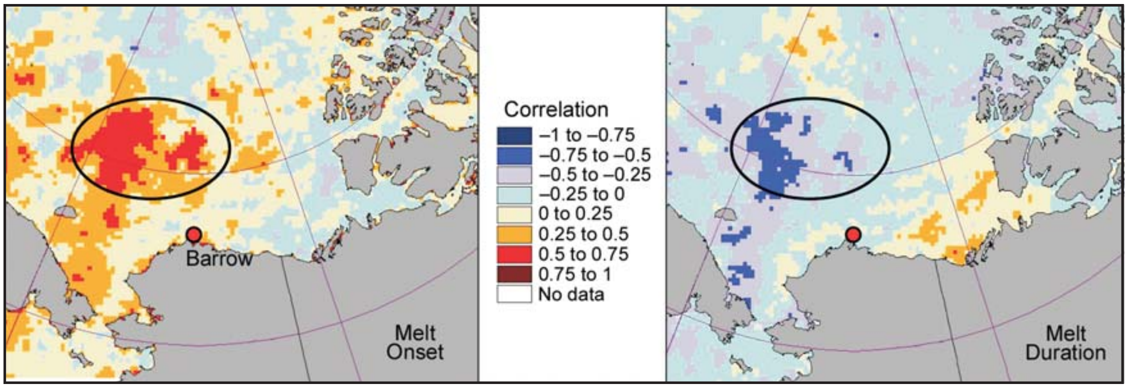
As a consequence of accelerated warming at high latitudes caused by the temperature–albedo effect, some climate simulations predict ice-free summers in the Arctic by the end of this century. Even approaching this scenario will gravely affect Arctic ecology. The zooplankton, fish, and marine mammals that depend on perennial sea ice, such as polar bears and a variety of seals, will be directly impacted.

Although differing explanations are given for the decline in Arctic sea ice, there is consensus that patterns of change derived from satellite PMW data are qualitatively reliable. As in the case of snowmelt at BRW, since 1989 several anomalous years drive the overall decline in ice extent. Changes in multiyear ice (MYI), which is sea ice that has survived at least one summer melt season, have varied geographically. Since 1979, MYI has decreased by more than 60% over large areas of the western Arctic Ocean. The most pronounced decline began in 1989 in the east Siberian region, followed a few years later by an area north of Alaska in the Beaufort–Chukchi region. After a rebound in 1997, the downward trend resumed. These dramatic declines in the Pacific Arctic dominate the trends for the entire basin.



Interannual changes and trends in January multiyear ice area within six longitudinal sectors of the Arctic Ocean (top), and 26-year (1979–2004) linear trend in January multiyear ice concentrations within the western Arctic (bottom).

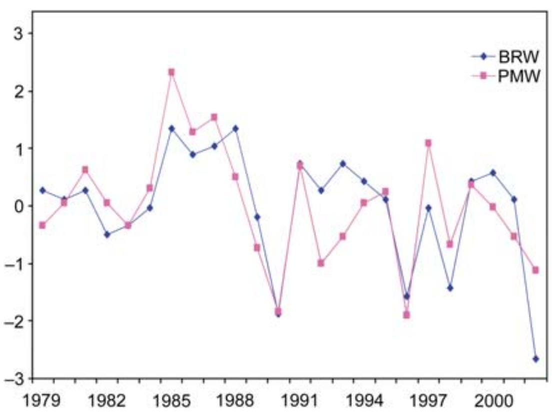
Maps contouring correlation coefficients between the date of snowmelt at the NOAA/CMDL Barrow Observatory (indicated by the red dot) and the onset date of snowmelt over sea ice (left) and the melt season duration (days) over sea ice (right). The circles indicate an area of high correlation.



Correlations of Melt at Sea and on Land

The snowmelt at BRW and the sea ice trends in the Pacific Arctic appear to be related. The relationship is made clearer through cross-correlations between time series of melt onset dates over sea ice and snowmelt dates at BRW. A large region of high positive correlation exists between melt onset over sea ice and the BRW melt record. Much of this region also experiences a longer duration of melt.

Time series of standardized anomalies of BRW melt dates (blue) and a small area of melt onset over ice (pink) located within the region of high correlation. Standardization normalizes interannual variations to a common scale to facilitate comparisons.



To better visualize these results on a scale of equal variance, standardized anomalies (normalized differences) were computed for each time series. The results demonstrate that anomalous melt onset dates over sea ice in the Chukchi–Beaufort region are reflected by similar anomalies in the snowmelt dates at BRW.

Factors that Influence Snow and Sea Ice Distribution

The fact that melt chronologies over land and at sea have co-varied for many years over a large region suggests linkages to common physical forcing mechanisms. Several processes could underlie these variations, including changes in atmospheric dynamics, synoptic-scale patterns, and related effects.

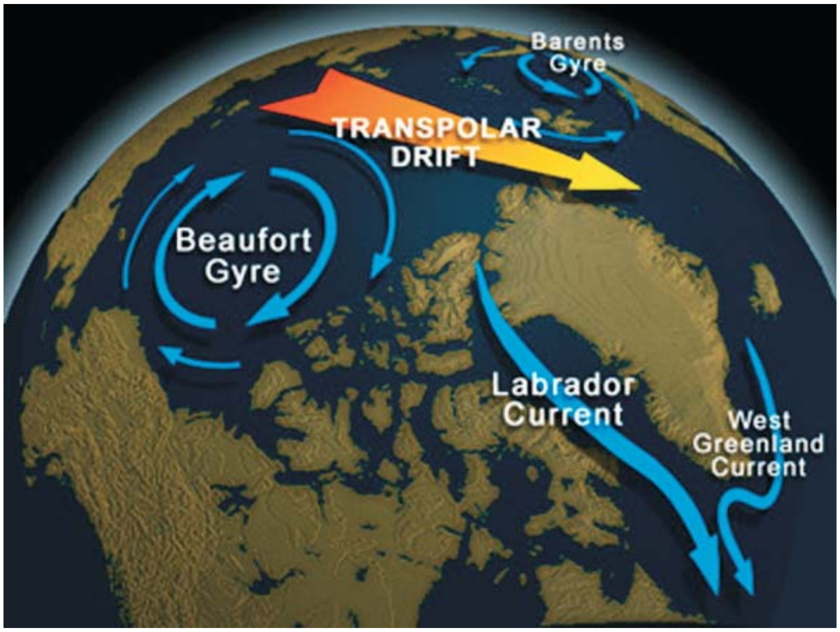
Atmospheric Dynamics

There is general consensus that the overall decline in Arctic sea ice (since the late 1970s) is due to processes associated with dynamical changes in the atmosphere. On a pan-Arctic scale, the dynamical state of the atmosphere is often expressed in terms of an Arctic Oscillation (AO) index that relates to sea-level pressure variations. High indices indicate lower-than-average sea-level pressure over the central Arctic. During a recent and predominately positive phase of the AO (1989–1995), MYI concentrations declined rapidly in a broad region of the western Arctic Ocean. It is hypothesized that during these years the Beaufort Gyre, a region of recirculating ice north of Alaska, weakened. The weakened gyre allowed more ice to become entrained in a dominant current called the Transpolar Drift Stream, which exports sea ice into the North Atlantic east of Greenland. The thick multiyear ice that was exported was replaced by younger, thinner ice that is more vulnerable to melting during the summer months. In recent years the AO index has been neutral or negative, however, and sea ice continues to decline. This suggests that factors not well represented by the phase of the AO are at play. Below, an examination of environmental conditions during years of anomalous ice retreat reveals+ how regional circulation patterns contribute to observed snow and ice variations in the Pacific Arctic.

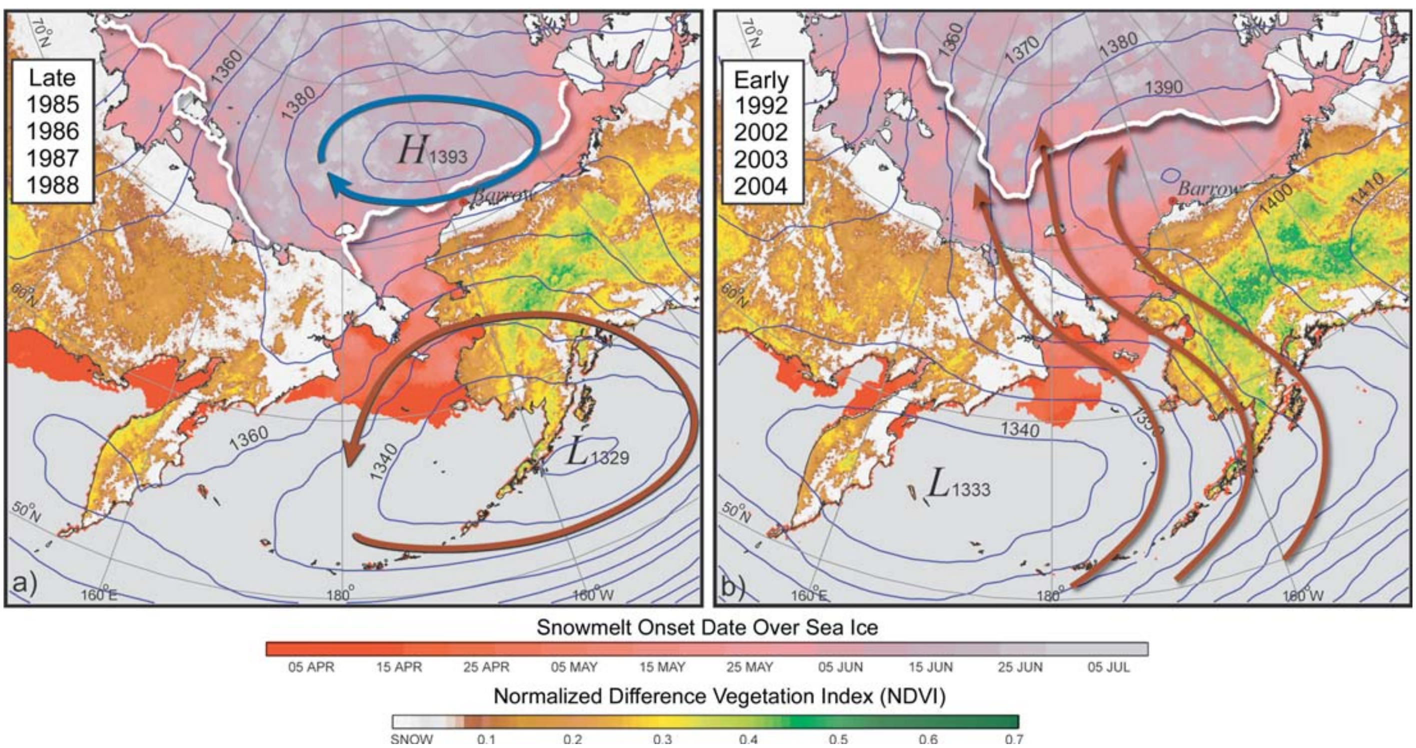
Synoptic-Scale Influences

On a more regional scale, shifts in atmospheric circulation patterns also influence the annual cycles of snow and sea ice. In the Pacific Arctic, variations in air temperatures and clouds correlate with the frequency and intensity of southwesterly winds. Airflow in this region varies with the juxtaposition of the Aleutian Low (AL) and the Beaufort Sea Anticyclone (BSA). It is the persistence of clockwise winds within the BSA that drives the Beaufort Gyre. An examination of these synoptic features provides insights on what may underlie the regional anomalies in snow and sea ice cover.

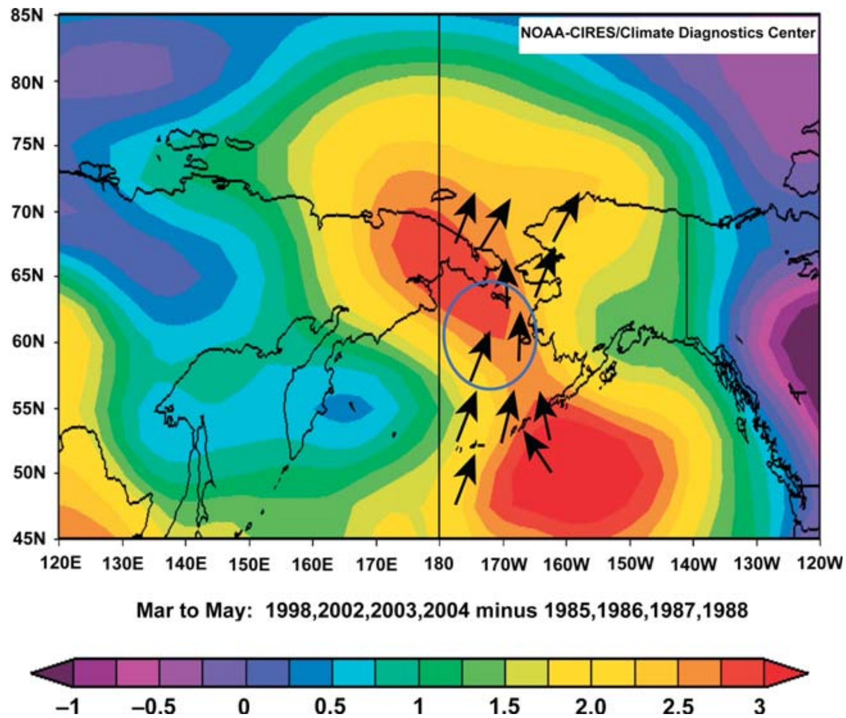
For years with minimum sea ice retreat, it is typical for the BSA and AL to be strongly coupled during March, April, and May, forming a dipole pattern. The BSA effectively blocks Pacific air from flowing into the Arctic. Such a pattern keeps northern regions cold and relatively dry and constrains the circulation of ice within the Beaufort Gyre. Climatologically, in late May the North Slope of Alaska and eastern Siberia remain covered in snow. Melt onset over sea ice does not commence until the first week in June north of Alaska and not until late June north of Siberia. Under these condi-



The main currents of the Arctic Ocean. During periods of high AO index, the Beaufort Gyre weakens, and divergent ice is entrained into the Transpolar Drift Stream, where it is exported from the Basin east of Greenland.



Environmental conditions over the Pacific Arctic averaged for years with minimum (left) and maximum (right) sea ice retreat. The extent of late summer ice retreat, defined as the southern limit of more than 50% mean ice concentration during late September, is shown as a bold white line. Thin blue lines depict 10-m contours of mean March–May 850-hPa geopotential heights from the NCEP/NCAR 40-year Reanalysis Project. These synoptic patterns for spring represent a critical transition period in the annual cycles of snow and sea ice. Geopotential is commonly used as a vertical coordinate when describing large-scale flow patterns, where larger values at a prescribed pressure level (e.g., 850 mb) indicate higher atmospheric pressure.Generalized circulation patterns are shown with bold vectors. Mean melt onset dates over sea ice are color-shaded for areas where ice concentrations averaged more than 50% during the second half of May. Vegetation greenness is depicted by the mean maximum NDVI (Normalized Difference Vegetation Index), also during the last two weeks in May, derived from GIMMS NDVI-d and NDVI-n16 data sets.



Mean March–May difference field of 850-mb temperatures for (1998, 2002–2004) minus (1985–1988). A jet of air transports anomalously warm air from the North Pacific into the Arctic Basin during years of early snowmelt and large ice retreat. The southerly winds within the circle are more than 3.5 m s^{-1} more intense during years of early melt onset than for years of late onset. Temperatures aloft, over a broad region, are warmer by more than 2°C during years of early melt onset. The results are derived from the NCEP/NCAR 40-year Reanalysis Project.

tions the pack does not retreat very far north of the coastlines in September, leaving stretches of the Siberian coast ice bound.

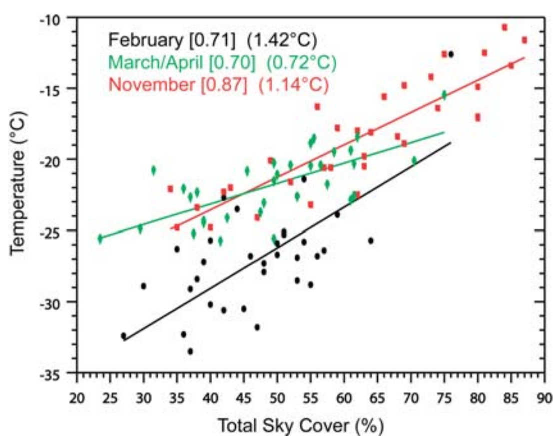
In contrast, for four recent years of extreme minimum ice extent, the spring BSA is poorly defined. Instead, a ridge of high pressure persists over eastern Alaska, and the AL is shifted westward. This pattern sets up a strong west-to-east gradient in the pressure field that favors the transport of warm, Pacific air northward. From the large, anomalously warm pool south of the Aleutian Islands, a "jet" transports warm, moist air well into the Arctic Basin. A region of intense southerly winds coincides with large pressure gradients south of the Bering Strait. This incursion of warm air accelerates snowmelt over Alaska and eastern Siberia and ice melt over adjacent ocean areas. By late May, Pacific air is further warmed as it flows over bare tundra (with a low albedo) being irradiated continuously by intense sunlight. This further contributes to an early onset of melt over sea ice. An early, and thus prolonged, melt season amplifies late-summer ice retreat, especially in the Pacific Arctic, where the ice pack has become younger and thinner.

Other Factors

The Role of Clouds

During years with minimum ice extent, the influx of moist air associated with the circulation pattern described above increase spring cloudiness. The presence of clouds have a profound impact on the surface temperatures in polar regions, where paradoxically, they warm rather than cool the surface. The warming is due to net cloud-radiative forcing whereby infrared (thermal) emissions from clouds exceed their cooling effects caused by increased solar reflectivity. Snow and ice surfaces absorb about 99% of this energy and reradiate much of it back into the atmosphere, which raises air temperature. Although the effect is greatest during winter, significant warming during March and April is associated with enhanced cloudiness. Empirically, a 5% increase in cloud cover leads to about 1.0°C of warming over the course of the season, with a range from about 0.7°C in spring to more than 1.4°C in winter. In summer, net cloud radiative forcing is slightly negative at BRW but is not statistically significant.

Prolonged effects of warm air incursions, augmented by cloud radiative forcing during early spring, are thought to modify the microphysical structure of the overlying snow. This "ripening" may precondition the snow so that melting accelerates during May and June, when solar insolation reaches its annual peak.



Empirical relationships of air temperature and total sky cover at Barrow, Alaska, averaged over 33 years, illustrating how the presence of clouds tends to warm the surface. Regressions for monthly mean values show correlations, given in brackets, and temperature sensitivity to a 5% increase in sky cover, given in parentheses.

Effects of Snowfall Variations

The depth of snow prior to the onset of melt is also important. Over land, for average conditions, if there is less snow on the ground when the melt begins, the snowpack will melt more quickly. And significant sea ice melt cannot begin until the

An August sun casting a warm glow over the northern coastline of Ellsmere Island, northeastern Canada. Rocky ridges of the United States Range rise above low-lying stratus clouds. There is a glint of sunlight from exposed areas of broken sea ice. The image illustrates the complexity of the dynamic and thermodynamic processes that modulate snow and sea ice cover in the Arctic. We face a great challenge to gain sufficient understanding of this system in order to forecast the ecological and sociological changes that will accompany rising global temperatures.

insulating surface layer of snow melts first. If less snow accumulates on sea ice in winter and conditions favor an earlier ripening of the snowpack, the snow cover will melt more rapidly, advancing the onset of ice melt.

Historically, direct observations of snowfall over sea ice have been made at Russian drift stations. Analyses of these data indicate reductions in winter snowfall up until the early 1990s, when, unfortunately, measurements were indefinitely suspended. Even over the terrestrial Arctic, snow depth observations are sparse and difficult to interpret because of wind-induced measurement biases.

Despite these limitations, an analysis of Arctic snow cover variations made in 2000 showed that the Northern Hemisphere snow cover had decreased by about 10% since the mid-1980s. At BRW, a 36% decrease in October–February snowfall from 1966 to 2000 was identified as a major factor in the trend toward earlier snowmelt. Because BRW has been shown to be regionally representative, it is likely that the western Arctic Ocean has experienced recent declines in snowfall as well, a condition that would exacerbate the early onset of summer ice melt.

The Albedo Effect Revisited

Finally, as a consequence of early melt onset and the longer duration of the melt season, a temperature–albedo feedback occurs that further accelerates ice melt. The albedo effect is very significant over land areas when surface reflectivity decreases rapidly at the time of snowmelt. Measurements indicate that a two-week advance in the date of snowmelt can lead to an increase of more than 1.0°C in air temperature. Because open water has a significantly lower albedo than tundra, it will absorb 7–12% more solar energy under equal illumination. The resultant increase in solar absorption by seawater warms the water column as well as the air above. Higher air temperatures feed back immediately to enhance melting, while higher water temperatures increase lateral and subsurface ice melt and extend the melt season by delaying the onset of autumn freeze. Ultimately, the ice pack will become thinner if the duration of melt becomes longer and the period of freeze shorter. Without winter recruitment of ice that is thick enough to survive the subsequent melt season, the MYI fraction will continue to decline.

Summary

Factors that influence the distributions of snow and sea ice are many and complex. Both dynamic and thermodynamic processes have contributed to the earlier onset of snowmelt and reductions of ice concentration in the Arctic. These mechanisms occur naturally but may be exacerbated by increasing global temperatures caused by greenhouse forcing. Significant regional and temporal variations in snow and ice cover are observed because forcing mechanisms interact through complicated pathways.

Recent trends appear to be related to shifts in planetary wave patterns, either on a hemispheric scale as in the case of the Arctic Oscillation or on more regional scales. The dramatic decrease in MYI in the Pacific Arctic dominates the trend observed for the entire basin. In the Pacific Arctic, the juxtaposition of the BSA and AL during spring affects the dynamic and thermodynamic processes that ultimately dictate the distributions of snow and ice.

In summary, factors contributing to the loss of snow and ice in the Pacific Arctic include the following:

- A breakdown of the BSA diminishes the strength of the Beaufort Gyre. Older ice is more readily entrained into the Transpolar Drift Stream and exported through the Fram Strait, reducing the overall age and thickness of the icepack and its resilience to summer melt.

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- A westward displacement of the AL, coupled with a high-pressure ridge over Alaska during spring, favors incursions of warm, moist Pacific air into the Arctic, promoting earlier and more rapid melt because of thermodynamic and radiative preconditioning of the snowpack. These involve sensible and latent heat exchanges at the surface through enhanced turbulence and net cloud-radiative heating caused by increased cloudiness.
- Earlier melt prolongs the melt season by enhancing the temperature–albedo feedback, exacerbating summer sea ice retreat and delaying the onset of freezing in autumn. Reductions in the mean sea ice thickness result as this cycle repeats.
- Under conditions of reduced snowfall, snowmelt and subsequent icemelt occur more rapidly and the albedo feedback is further prolonged, enhancing processes described above. Snowfall variations are also a function of varying modes of atmospheric circulation (now under investigation).

The question arises as to whether the recent retreat of Arctic sea ice is a manifestation of natural, low-frequency climate oscillations or an early signal of anthropogenic forcing. Are these mechanisms now self-propagating as a consequence of increasing global temperatures? Stroeve et al. (2005) questioned whether "the extreme ice minima of 2002–2004 represent the crossing of a threshold," in which case thinner ice cannot survive longer summer melt seasons. Lindsay and Zhang (2005) suggested the system may have already "tipped" into a new equilibrium state, in which summers will be characterized by vast regions of open water. The mechanisms underlying major shifts in planetary circulation and their influence on regional-scale dynamic and thermodynamic processes must be better understood to determine the likelihoods of future scenarios.

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Acidifying Pollutants, Arctic Haze, and Acidification in the Arctic

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The Arctic Haze Phenomenon

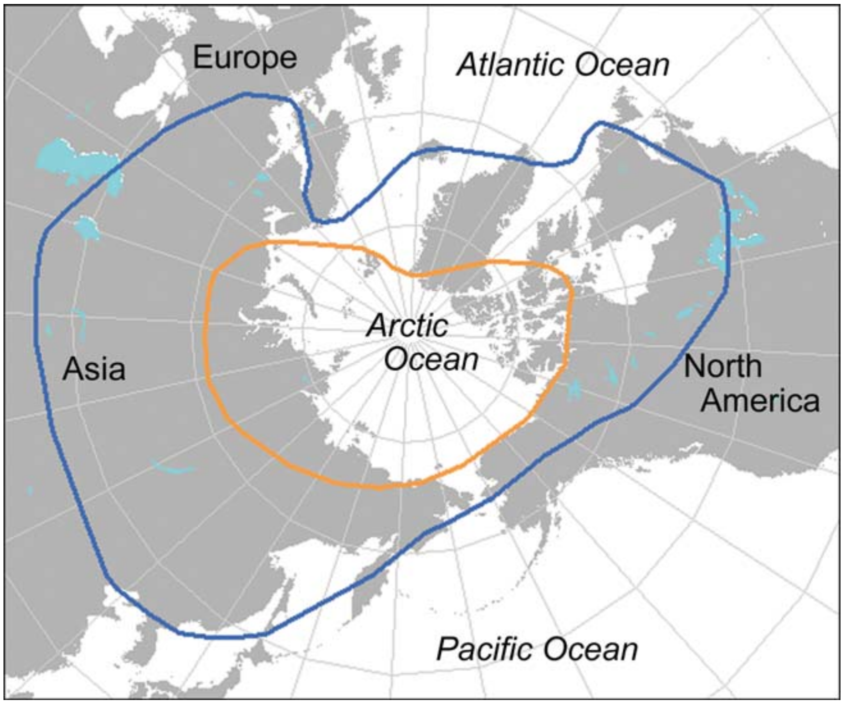
It has been more than 50 years since observations of a strange atmospheric haze, of unknown origin, were reported by pilots flying in the Canadian and Alaskan Arctic. Based on measurements at McCall Glacier in Alaska, Shaw and Wendler (1972) noted that the turbidity in the air reached its peak in spring. The first measurements of the vertical structure of the haze were made using an Alaskan "bush" airplane with a hand-held sunphotometer.

At that time the origin of the haze was uncertain and was attributed to ice crystals seeded by open leads in the ice or blowing dust from riverbeds. It was only through "chemical fingerprinting" of the haze that its primary anthropogenic (man-made) source in Eurasia was revealed. By the late 1970s the anthropogenic origin was clear but surprising, since it was widely believed that aerosols were generally not transported more than a few hundred kilometers from their source regions. Experts from Europe and America convened at the first Arctic Air Chemistry Symposium at Lillestrom, Norway, in 1978, and an informal measurement network was agreed upon. Data soon showed the direction of flow and the anthropogenic cloud of pollution. A combination of intensive field programs and long-term measurements extending over the past thirty years confirmed the early conclusions that the haze is anthropogenic and originated from Eurasia. It also became known that these atmospheric contaminants were transported to and trapped in the Arctic air mass during the winter and early spring.

Soot covering a statue in Krakow, Poland, one of the source regions of Arctic Haze.

Arctic Haze has been the subject of more than three decades of study because of its potential to change the solar radiation balance of the Arctic, affect visibility, and provide a source of contaminants to Arctic ecosystems. The near-surface concentration of aerosols at most places in the Arctic is about an order of magnitude lower than those found at more polluted and industrialized locations. At the same time, however, the affected areas are much larger, and the affected ecosystems in the high Arctic are thought to be quite sensitive to gaseous and aerosol contamination.

The haze is composed of a varying mixture of sulfate, particulate organic matter (POM), and, to a lesser extent, ammonium, nitrate, dust, black carbon, and heavy metals. The identification of particular heavy metals allowed industrial sources to be identified. Particles within the haze are well aged, with a mass median diameter of 0.2 microns or less. This particle size range is very efficient at scattering solar radiation because the peak in the particle surface–area size distribution is near the maximum efficiency for Mie scattering. The haze also is weakly absorbing because of the presence of black carbon. These scattering and absorption effects lead to the well-documented reduction in Arctic atmospheric visibility (sometimes down to only a few kilometers or less). During transport from Eurasia to the Arctic, the pollutant-containing air masses have a high probability of reaching saturation and nucleating and precipitating clouds. Both the clouds and the Arctic Haze may also significantly affect climate because the haze weakens the reflectivity of the white snow and ice, lowering the albedo of the earth in the process.



Range of the Arctic air mass in winter (January, blue) and summer (July, orange).

Several seasonally dependent mechanisms are thought to contribute to the formation of Arctic Haze:

- Strong surface-based temperature inversions form in the polar night, causing the atmosphere to stabilize.
- This cold and stable atmosphere inhibits turbulent transfer between atmospheric layers, and it also inhibits the formation of cloud systems and precipitation, the major removal pathway for particulates from the atmosphere.
- In addition, transport from the mid-latitudes to the Arctic intensifies during the winter and spring.

The combination of these factors results in the transport of precursor gases and particulates to the Arctic and the trapping of the pollutant haze for up to 15–30 days.

Aircraft and lidar measurements collected throughout the 1980s and 1990s revealed that the haze occurs primarily in the lowest 5 km of the atmosphere and peaks in the lowest 2 km. Throughout the haze season, the pollution layers are highly inhomogeneous, both vertically (tens of meters to 1 km thick) and spatially (20–200 km in horizontal extent).

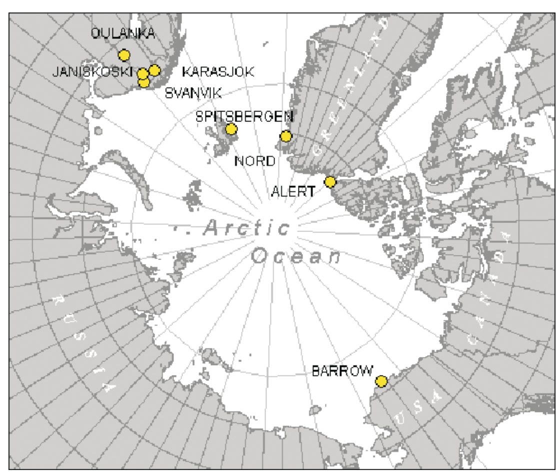
Recent aircraft measurements of sulfate aerosol revealed how the haze develops its vertical structure between February and May (Scheuer et al. 2003). During early February, atmospheric sulfate aerosol is transported from cold regions in northern Eurasia and accumulates in a 2-km-thick layer on the land and ocean surface. As the haze season progresses, transport from warmer regions in Eurasia (the source region of the haze) occurs at higher altitudes (up to at least 8 km). Since vertical mixing is prevented by the persistent Arctic low-level inversion, the haze layers remain stratified until spring. During early April, sulfate layers below 3 km begin to dissipate because of the beginning of solar heating and the resulting mixing near the surface. However, more stable isentropic transport (transport that follows constant temperature lines) continues at higher altitudes. By the end of May, both the lower- and higher-altitude sulfate enhancements are significantly decreased because of the continued break-up of the inversion and the return of rain and wet snow, which removes the haze from the atmosphere and deposits it to the ground.

Occurrence and Trends of Arctic Haze

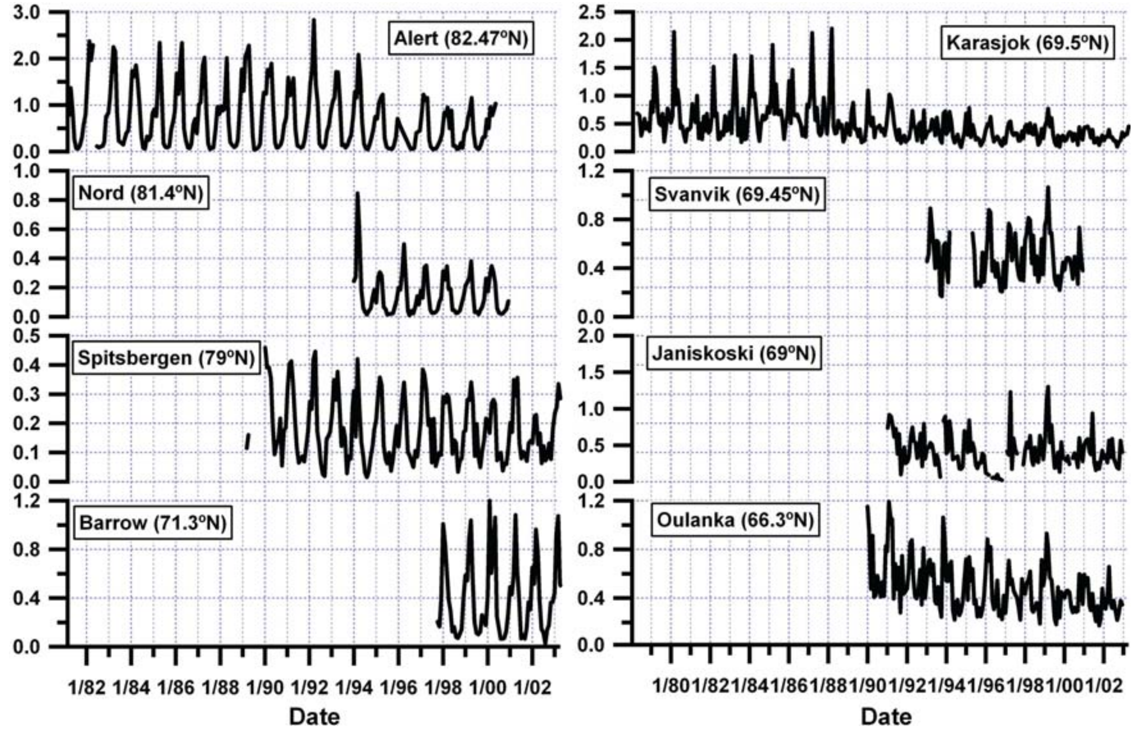
Trends in Chemical Composition

Arctic Haze is marked by a dramatic increase in the concentrations of several key particulate pollutants during winter. Stations where Arctic Haze is monitored include Alert in the Canadian Arctic (82.46°N), Station Nord in Greenland (81.4°N), Spitsbergen on the island of Svalbard (79°N), Barrow, Alaska (71.3°N), Karasjok (69.5°N) and Svanvik (69.45°N) in northern Norway, Oulanka in northern Finland (66.3°N), and Janiskoski (69°N) in western Russia.

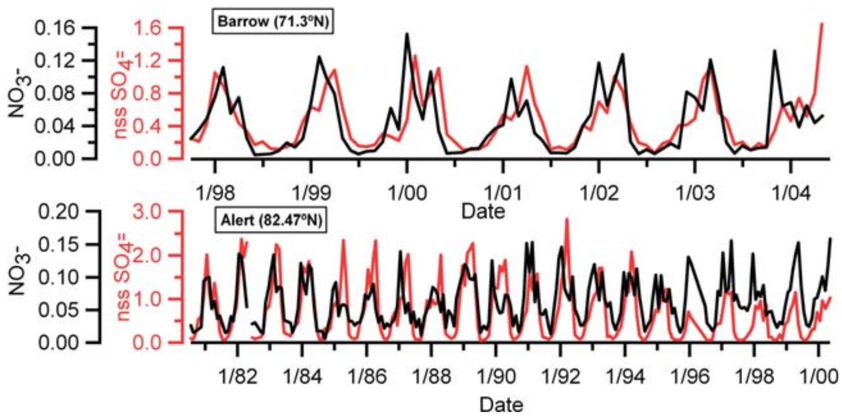
Each site undergoes a similar winter/early spring increase in sulfate, with maximum concen-



Arctic Haze sampling station locations.



Time series of monthly averaged particulate sulfate concentrations in μg/m³ for eight Arctic monitoring sites. The data were made available for Alert by the Canadian National Atmospheric Chemistry (NAtChem) Database and Analysis System, for Barrow by NOAA PMEL (Pacific Marine Environmental Laboratory; https://saga.pmel.noaa.gov/data/), and for the other stations by EMEP (Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe; http://www.emep.int/).



Time series of monthly averaged particulate sulfate and nitrate concentrations in μg/m³ for Barrow, Alaska, and Alert, Canada. The data were made available for Alert by the Canadian National Atmospheric Chemistry (NAtChem) Database and Analysis System and for Barrow by NOAA PMEL (https://saga.pmel.noaa.gov/data/).

trations reaching up to 2.5 μg/m³. Summertime monthly average concentrations are generally less than 0.1 μg/m³. Nss (non-sea-salt) sulfate makes up about 30% of the submicron mass during the haze season. The time series of particulate nitrate at Alert and Barrow show clear seasonal patterns for this chemical species. Maximum concentrations approach 0.15 μg/m³.

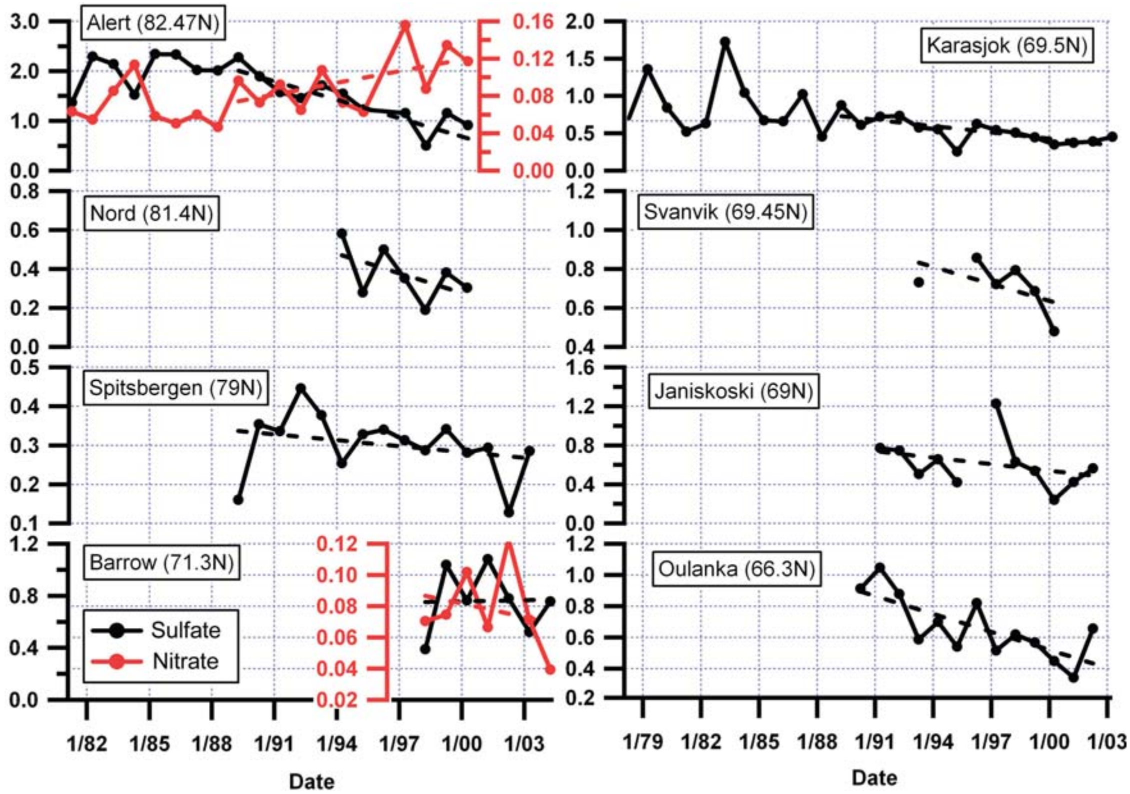
Other species sampled in the haze have their origins from biomass burning and dust from Eurasia (ammonium and nss potassium from biomass burning and magnesium and calcium from dust). The concentration of these particles in the haze reaches a maximum in the winter and spring.

Natural aerosol chemical components have seasonal cycles that are quite different from anthropogenic components. Sea salt is a natural aerosol component that is transported to the North American Arctic from the North Pacific and the North Atlantic Oceans between November through February.

Another natural aerosol component is methanesulfonic acid (MSA). Concentrations of MSA begin to increase in late June as the ice melts and recedes from the shoreline and phytoplankton productivity in surface waters begins. Dimethylsulfide that has been trapped under the ice is released to the atmosphere, where it oxidizes to form MSA.

A third aerosol component that has a natural source is particulate organic matter (POM), which makes up, on average, 22% of the total fine aerosol mass. POM reaches a maximum in the atmosphere during the summer, probably because of summer biogenic emissions and/or enhanced oxidation processes. There is a small increase in organic acids as early as February and March that may be an indication of photooxidation at polar sunrise.

The longest record of sulfate concentrations in the Arctic (1980 to present at Alert, Canada) revealed no change in sulfate concentrations during the 1980s. These stable concentrations are attributed to little change in emissions in the former Soviet Union between 1985 and 1990. Beginning in 1991, sulfate and other measured anthropogenic constituents (lead, zinc, copper,



Monthly averaged concentrations of sulfate and nitrate in µg/m³ for April. The dashed lines are linear fits to the data. The data were made available for Alert by the Canadian National Atmospheric Chemistry (NAtChem) Database and Analysis System, for Barrow by NOAA PMEL (https://saga.pmel.noaa.gov/data/), and for the other stations by EMEP (http://www.emep.int/).

excess vanadium and manganese, ammonium, and nitrate) began to decline, suggesting that the reduction of industry in the early years of the new Eurasian republics had an effect in the Arctic. In fact, sulfate concentrations measured at Station Nord in northern Greenland and at several other sites in the Arctic decreased significantly throughout the 1990s, coinciding with a reduction in emissions from the former Soviet Union.

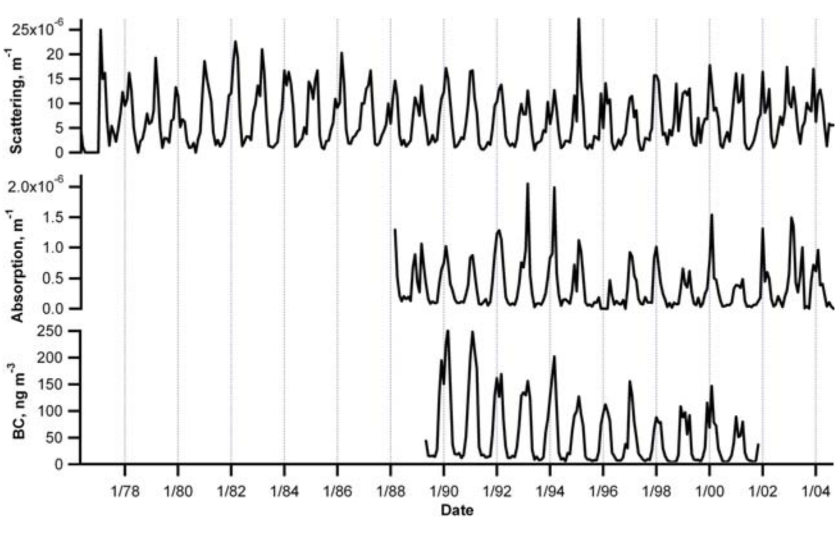
Based on a linear fit to monthly averaged April concentrations, the decrease ranges from 0.1 to 0.5% per year. In contrast, nitrate appears to be increasing at Alert at the rate of about 0.3% per year. The decoupling of the trends of nitrate and sulfate also are evident. Nitrate concentrations peak in early winter and then again in spring in Barrow, while sulfate concentrations do not.

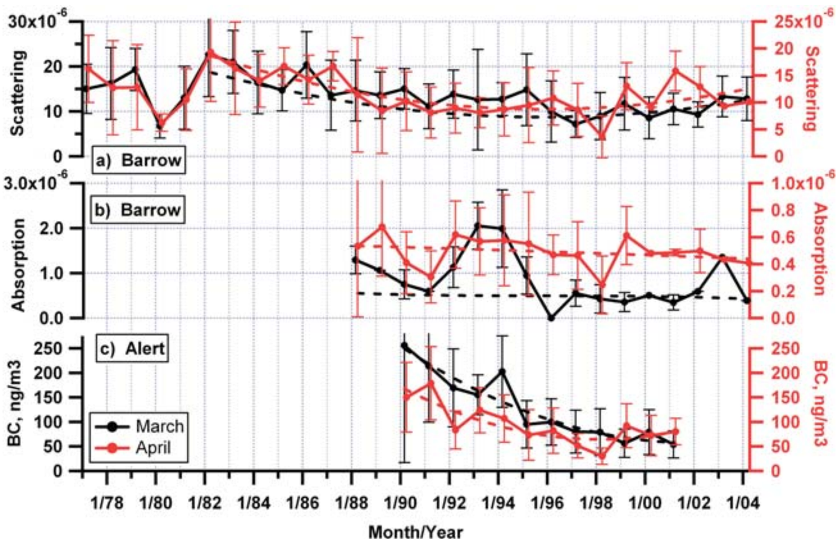
Trends in Optical Properties

The seasonality and trends of Arctic Haze are clearly seen in time series data of light absorption and scattering by aerosols measured at the surface and in total column aerosol optical depth measurements.

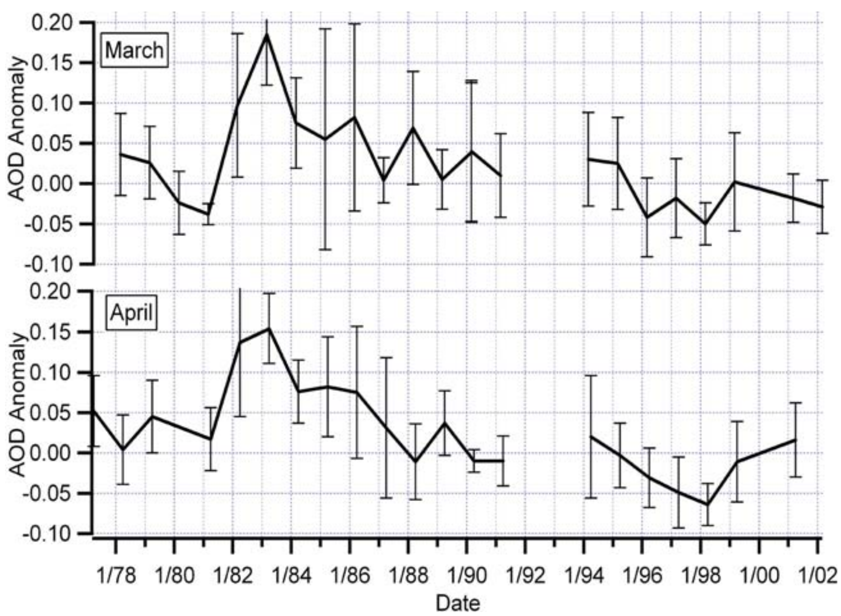
Bodhaine and Dutton (1993) reported that aerosol scattering, optical depth measurements, and sulfate concentrations at Barrow and Alert were at a maximum in 1982, reducing twofold by 1992. The decrease was apparent during March and April, the usual maximum haze period. They suggested that the reduction in the output of pollution aerosols by Eurasia and stricter pollution controls in Western Europe caused the decrease in the haze. The decreases in aerosol scattering and optical depth at Barrow during this ten-year period are not equal to the known reductions of sulfate emissions, however, indicating that other factors such as changes in transport could have played a role.

Monthly averaged light scattering and light absorption at 550 nm by sub-10-µm aerosols at Barrow, Alaska, and black carbon mass concentration at Alert, Canada. The data were made available for Barrow by NOAA CMDL (Climate Monitoring and Diagnostics Laboratory) and for Alert by the Canadian National Atmospheric Chemistry (NAtChem) Database and Analysis System.





Monthly averaged concentrations of light scattering and light absorption at 550 nm for sub-10-μm aerosol at Barrow, Alaska, and black carbon for Alert. The averages for March and April are shown. The dashed lines are third-order polynomial fits to the data. The vertical lines represent one standard deviation of the monthly mean. The data were made available for Barrow by NOAA CMDL and for Alert by the Canadian National Atmospheric Chemistry (NAtChem) Database and Analysis System.



Monthly averaged aerosol optical depth anomalies at Barrow, Alaska, for March and April. The anomalies are relative to a base of non-volcanic years. The data from 1992 and 1993 were removed because of stratospheric aerosol influx from the Mount Pinatubo eruption in 1991. The vertical lines represent one standard deviation of the monthly mean. The data were made available by NOAA CMDL.

From 1992 through the late 1990s, light scattering at Barrow continued to decrease.

An update of the monthly averaged light scattering data analysis shows that, for the months of March and April, scattering increased from the late 1990s to 2004. This increase is not apparent in the March and April monthly averaged values of light absorption at Barrow. Sharma et al. (2004) reported a decrease of 56% in black carbon (the main light absorber in the Arctic atmosphere) during the winter and spring from 1989 to 2002 at Alert, Canada. A monthly average of the data for April suggests an increase in black carbon since 1998 at Alert.

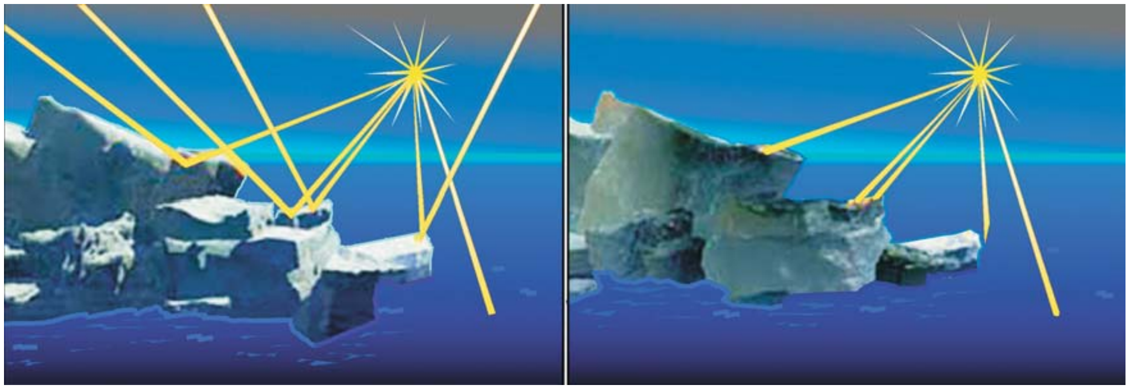
An extension of the Barrow aerosol optical depth (AOD) data through 2002 shows a continued decrease through the late 1990s. Monthly averaged values of AOD anomalies (relative to a base of non-volcanic years) for March show a continued decline through 2002. However, the AOD anomalies for April indicate an increase between 1998 and 2001, where the currently available data record ends. In contrast to the Barrow trend through the 1990s, Herber et al. (2002) reported a slightly increasing trend in AOD (1% per year) at Koldewey station in Ny-Alesund, Spitzbergen, between 1991 and 1999.

Effects of Aerosols on the Climate System in the Arctic

Direct Effect

The direct effect of aerosols on the radiation balance in the Arctic is due to the absorption and scattering of radiation by the aerosol. The Arctic is thought to be particularly sensitive to changes in radiative fluxes imposed by aerosols because of the small amount of solar energy normally absorbed in the polar regions. Arctic Haze is present as a layer of light-absorbing material over a highly reflective ice and snow surface.

Shaw and Stamnes (1980) first realized that the absorbing nature of Arctic Haze would have a significant impact on the energy balance of the Arctic. Several early calculations estimated that the diurnally averaged atmospheric warming due to the layer ranged between 2 and 20 W/m^2. These estimates agreed with direct measurements from wideband sun photometers. Valero et al. (1989) measured heating rates of about 0.1–0.2 K/day during AGASP (Arctic Gas and Aerosol Sampling Program) II. The AASE (Airborne Arctic Stratospheric Expedition) II flights in the winter of 1992



Impact of soot deposited on snow and ice surfaces in the Arctic. Polar ice reflects light from the sun back to space (left panel). As the ice begins to melt, less light is reflected and more is absorbed by the oceans and surrounding land, leading to an increase in overall temperature and further melting. Darker, soot-covered ice reflects even less light and, thus, enhances the warming (right panel).

revealed soot-contaminated Arctic aerosols at altitudes of 1.5 km. Pueschel and Kinne (1995) calculated that this layer of aerosols could heat the earth–atmosphere system above surfaces of high solar albedo (ice and snow), even for single scattering albedos as high as 0.98. Hence, a modest amount of black carbon in the haze layers can result in a measurable contribution to diabatic heating.

MacCracken et al. (1986) estimated that the cooling of the surface because of absorption of solar radiation by the haze layers would be balanced by infrared emission from the atmosphere to the surface. The large reflection from the high-albedo ice and snow surface may enhance aerosol solar absorption. This aerosol-induced atmospheric heating would result in increased infrared emission from the atmosphere to the surface, producing surface cooling. During the dark winter, infrared emissions from the haze may heat the surface, but this amount of heating is expected to be small because the haze particles are predominantly in the submicron size range and therefore are an order of magnitude smaller than the characteristic wavelength of infrared radiation. Deliquescent sulfate salts, however, may cause the particles to grow and become cloud droplets or ice crystals, thereby enhancing their impact in the longwave. In addition, since the haze is present throughout the Arctic night, the integrated effect may modify the radiative budget. The vertical distribution of the absorbing haze layers does not affect the radiation budget at the top and bottom of the atmosphere but may impact atmospheric circulation and climate feedback processes.

Indirect Effects

The indirect effect of aerosols on radiative fluxes in the Arctic results from the impact aerosols have on the microphysical properties of clouds. Aerosols modify cloud optical properties by changing the concentration, size, and phase of cloud droplets. An increase in the number of pollution aerosol particles that act as cloud condensation nuclei (CCN) will affect Arctic stratus and stratocumulus clouds by increasing the cloud droplet number concentration, which results in more radiation being reflected back to space. At the same time, cloud droplet size will decrease, reducing drizzle formation and increasing cloud coverage and lifetime. Garrett et al. (2004) showed that low-level Arctic clouds are highly sensitive to particles that undergo long-range transport during the winter and early spring. The sensitivity was detected as higher cloud droplet number concentrations and smaller cloud droplet effective radii compared to summertime clouds exposed to particles nucleated in the Arctic from local biogenic sources. In addition, Arctic stratus clouds appear to be more sensitive to pollutant particles than clouds outside of the Arctic. The most significant effect of the change in cloud properties caused by Arctic Haze may be on cloud emissivity. A decrease in droplet effective radius in these optically thin clouds will increase the infrared optical depth and thus the infrared emissivity. The result is expected to be an increase in downwelling infrared fluxes from the cloud and an increase in the rate of springtime snowpack melting.

Pollution aerosol within Arctic Haze also is thought to impact ice nucleation. Anthropogenic sulfate is a large component of the haze. Models estimate that aerosols containing sulfuric acid produce fewer ice nuclei than nearly insoluble aerosols. Measurements corroborate this finding. Borys (1989) reported that Arctic Haze aerosols had lower ice nuclei concentrations, a lower ice-nuclei-to-total-aerosol fraction, and slower ice nucleation rates than aerosols from the remote unpolluted troposphere. The reduction in ice nuclei leads to a decrease in the ice crystal number concentration and an increase in the mean size of ice crystals. As a result, the sedimentation and precipitation rates of ice crystals increase, leading to an increase in the lower troposphere dehydration rate and a decrease in the downwelling infrared fluxes from the cloud. Girard et al. (2005) found that a cloud radiative forcing of –9 W/m^2 at Alert may occur locally as a result of the enhanced dehydration rate produced by sulfate aerosol. If this applies to much of the Arctic, it could explain the cooling tendency in the eastern high Arctic during winter.

Because of the combination of the static stability of the Arctic atmosphere, the persistence of low-level clouds, and the relatively long lifetime of aerosols during the haze season, the impact of aerosols on cloud microphysical and optical properties may be larger in the Arctic than elsewhere on earth.

Surface Albedo

Surface albedo affects the magnitude and sign of climate forcing by aerosols. Absorbing soot deposited on the surface via wet and dry deposition impacts the surface radiation budget by enhancing absorption of solar radiation at the ground and reducing the surface albedo. Hansen and Nazarenko (2004) have estimated that soot contamination of snow in the Arctic and the corresponding decrease in surface albedo yields a positive hemispheric radiative forcing of +0.3 W/m^2. The resulting warming may lead to the melting of ice and may be contributing to earlier snowmelts on tundra in Siberia, Alaska, Canada, and Scandinavia.

Clearly, the radiative impacts of pollutant aerosols in the Arctic are complex. Complex feedbacks between aerosols, clouds, radiation, sea ice, and vertical and horizontal transport processes complicate the impact, as do potentially competing effects of direct and indirect forcing. As a result, the magnitude and sign of the forcing are not yet well understood for the Arctic.

Summary

Measurements of sulfate aerosol—a main constituent of Arctic Haze—and light scattering and extinction show that the amount of the haze impacting the Arctic was either nearly constant or decreasing between the 1980s and early 1990s. The updated trends in light scattering presented here show indications of an increase in the haze at Barrow, Alaska, since the late 1990s. There also is evidence, although not as strong, of an increasing trend in light absorption during this same period at Barrow and in black carbon at Alert, Canada. Sulfate appears to still be declining at all sites except Barrow, where the trend is unclear. On the other hand, nitrate appears to be increasing at Alert and Barrow. Continued measurements coupled with chemical transport models are required to better define emerging trends and assess their causes.

Arctic Haze is generally understood to consist of anthropogenically generated material and has often been attributed to sources in central Eurasia. There may be, however, increasing amounts of material entering the Arctic from growing natural and anthropogenic sources in eastern Eurasia, particularily from China. Examples of Asian dust entering the Alaskan sector of the Arctic were documented as long ago as the mid-1970s. The rapid industrialization of China and increasing amounts of pollution being transported over long distances are likely to impact the Arctic. More research is required to document the contribution of this increasing source to Arctic Haze and to determine its impact on the Arctic.

Other key atmospheric species have a distinct seasonality in the Arctic. There is evidence of the enrichment of halogens in Arctic air masses in late winter and spring. Since these compounds tend to peak later in the year, it is thought that they are produced photochemically. More research is required to determine their sources (for example, anthropogenic, especially coal combustion, vs. marine), to investigate their numerous and complex chemical pathways, and to assess their environmental impacts. Of special note is iodine, which shows a bimodal seasonal behavior, peaking in both spring and autumn.

The direct radiative effect of Arctic Haze has been estimated with one-dimensional radiative transfer models, which find a warming in the atmosphere because of absorption of solar radiation and a concurrent cooling at the surface. These estimates are highly sensitive to the assumed properties of the aerosol in the haze. Despite the many research activities devoted to the characterization of Arctic Haze since the 1970s, measurements of Arctic aerosols are not extensive or well distributed in space or time, which limits the accuracy of the estimates of both the direct and indirect radiative forcing. Treffeisen et al. (2004) have designed an approach based on cluster analysis for integrating aircraft, ground-based, and long-term data sets for use in three-dimensional climate models. The accurate evaluation of climate forcing by Arctic Haze requires such data sets coupled with three-dimensional climate models that consider both direct and indirect effects. In particular, three-dimensional models are required to assess the complex feedbacks between aerosols, clouds, radiation, sea ice, and dynamic transport and to quantify climate forcing caused by Arctic Haze.

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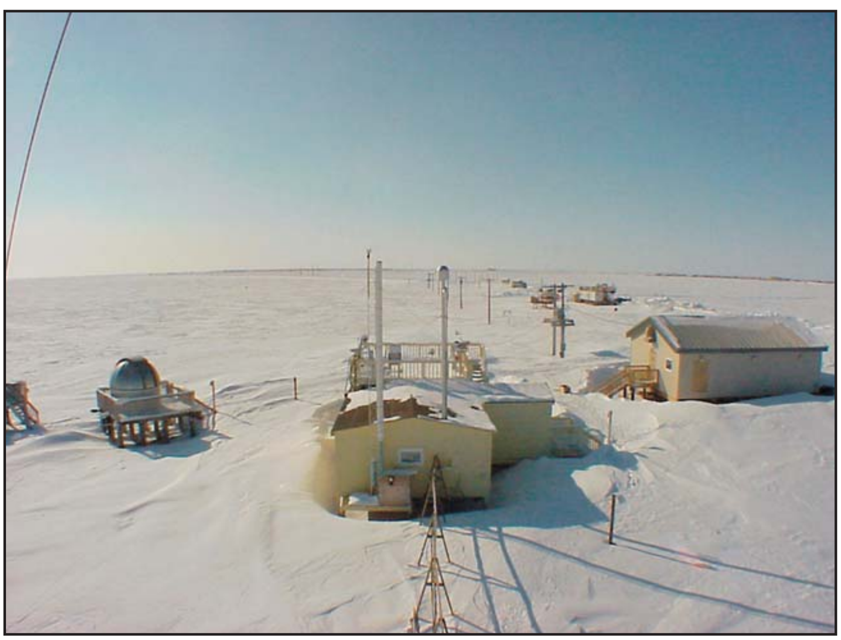
The Barrow Atmospheric Baseline Observatory

This article was prepared by Russ C. Schnell and David J. Hofmann, of NOAA's Climate Monitoring and Diagnostics Laboratory, Boulder, Colorado.

NOAA's Climate Monitoring and Diagnostics Laboratory (CMDL) operates the manned Atmospheric Baseline Observatory six miles east of Barrow, Alaska (71.3°N; 156.6°W). The observatory measures changes in atmospheric climate forcing agents such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), climate-forcing and stratospheric-ozone-depleting chlorofluorocarbons, air pollution from Eurasia known as Arctic Haze, and solar radiation, to name only a few of the more than 200 measurements conducted at the facility. NOAA established the observatory in 1973 in an 800-ft^2 building in use today. In recent times the observatory has taken on the support of 16 cooperative research projects from other agencies and universities, with a concentration of projects from the University of Alaska. Two permanent CMDL staff operate the facility.



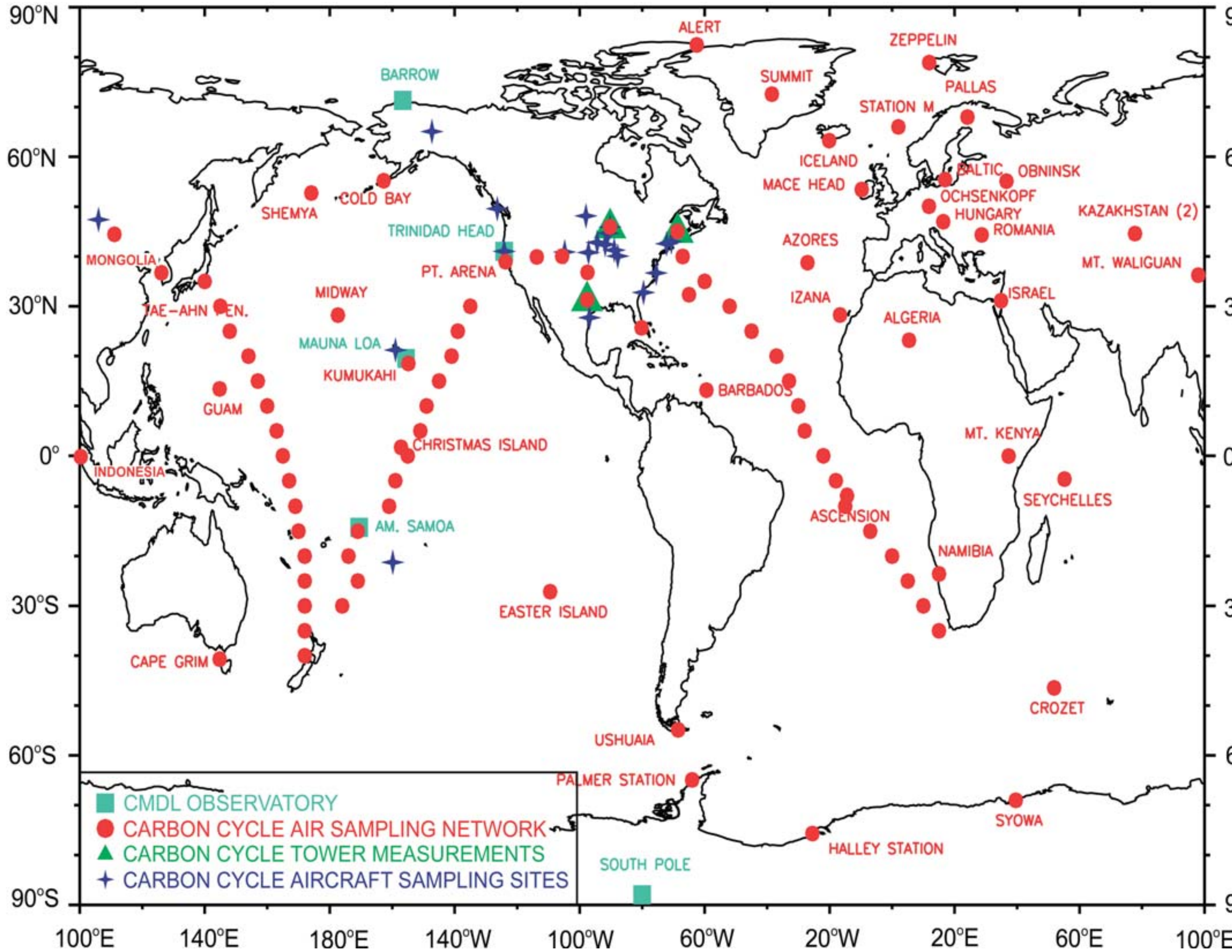
NOAA/CMDL Barrow Atmospheric Baseline Observatory, viewed from the east near the base of the 20-m sampling tower. The former Naval Arctic Research Laboratory is on the upper right horizon. The DOE ARM facilities are above and to the left of the garage (center right), with the USGS Magnetic Observatory above and to the left of the white DOE building. The Barrow Atmospheric Baseline Observatory is in the center of the view, and the Dobson ozone spectrophotometer dome is at center left. Winds persistently blow from the point of the photograph towards the main observatory building.

The observatory is situated near the center of an 80-acre parcel of Federal land one mile south of a DOD radar facility, through which the observatory access road passes. The CMDL acreage is bounded on the west by an 80-acre parcel of Federal land that is home to the U.S. Geological Survey's Barrow Magnetic Observatory and on the south and east by the 7,500-acre Barrow Environmental Observatory (BEO), land preserved for scientific research. Adjacent to the main building is a two-vehicle garage with gas cylinder storage space. Additional facilities consist of a 60-ft-tall walk-up sampling tower, three elevated platforms for instrument support, and a number of smaller towers and instrument installations on the tundra. The observatory site is host to a Department of Energy Atmospheric Radiation and Monitoring (ARM) facility, two NOAA National Environmental Satellite, Data, and Information Service (NESDIS) polar-orbiting satellite downlink antennas, and a NOAA Climate Reference Network (CRN) station.

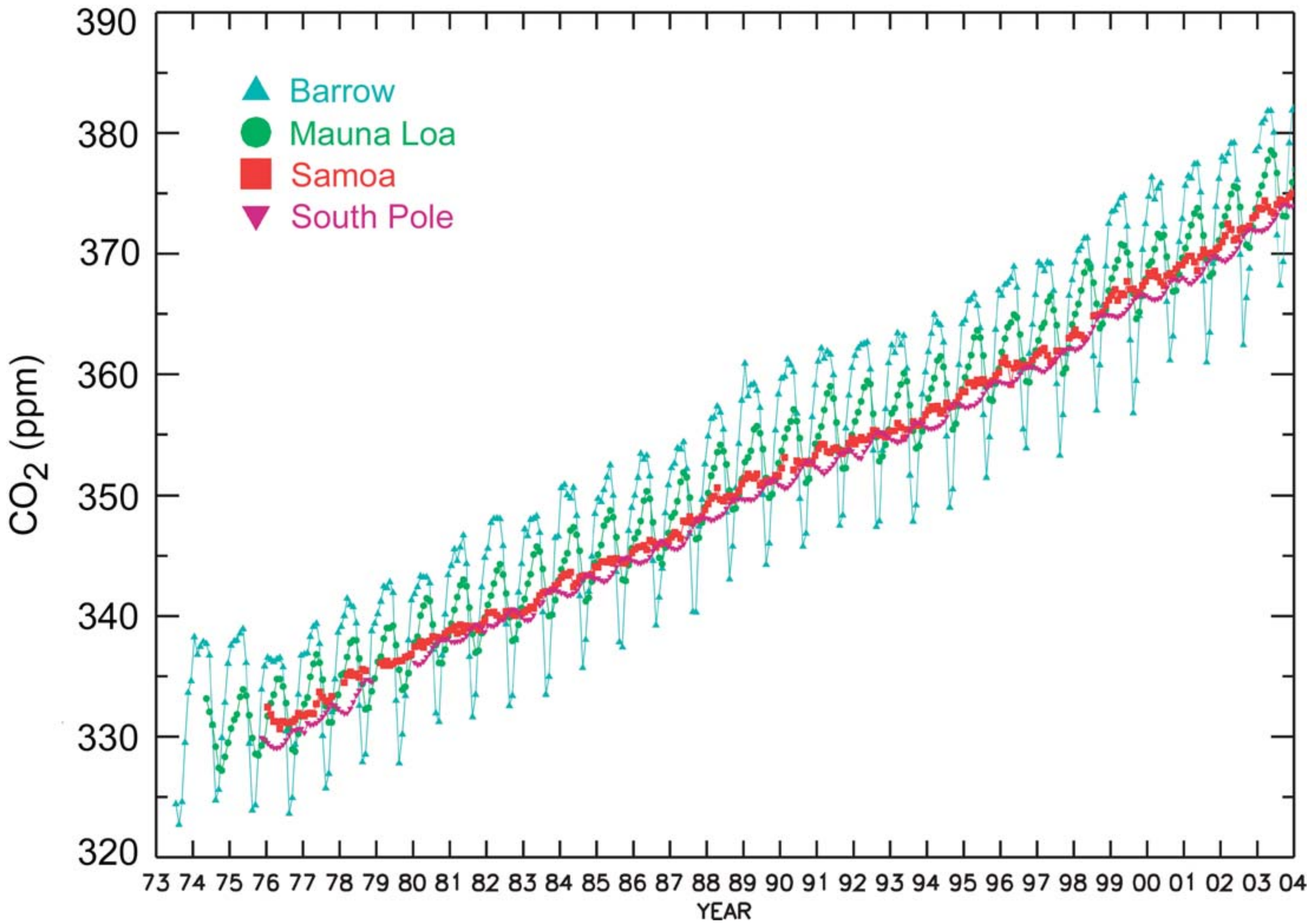
The observatory facility does not have any internal combustion sources or volatile chemicals that might contaminate the trace gas measurements conducted within the facility. Vehicle traffic near the station is controlled, and there are no roads upwind of the observatory. Some observatory measurements require a view of the natural surface that is unaffected by anthropogenic influences and will be maintained in such a state for at least a century or more. The upwind clean-air sector (45° through 100°) is expected to remain a clean-air sector in perpetuity unless oil production facilities are installed in the Arctic Ocean within a 100-mile radius upwind of Barrow.

The Barrow Atmospheric Baseline Observatory is the farthest north of the five manned observato-

NOAA National Environmental Satellite, Data, and Information Service (NESDIS) 3-m (left) and 4-m (right) High Resolution Picture Transmission (HRPT) downlink antennas for the NOAA Polar Operational Environmental Satellite (POES) at the observatory site. These antennas allow for near-real-time downloads of ice and cloud conditions over the Arctic Ocean.



The NOAA/CMDL global Carbon Cycle Greenhouse Gas monitoring network. Carbon dioxide is measured continuously at the observatories shown by the blue squares, and weekly, paired glass flask samples of air are collected at the sites represented by the red dots. The marine samples are taken at 5°-latitude intervals from regularly scheduled ships. Weekly to biweekly vertical profiles of trace gases are sampled with light aircraft at the blue- starred locations.



Monthly mean carbon dioxide concentrations determined from continuous analyzers at four NOAA/CMDL baseline stations. Note the large relative amplitude of the CO_2 cycle at Barrow, which is a combination of transport of fossil fuel combustion effluents from lower latitudes and high primary productivity in the northern hemisphere and mid-latitude forests and agricultural regions.

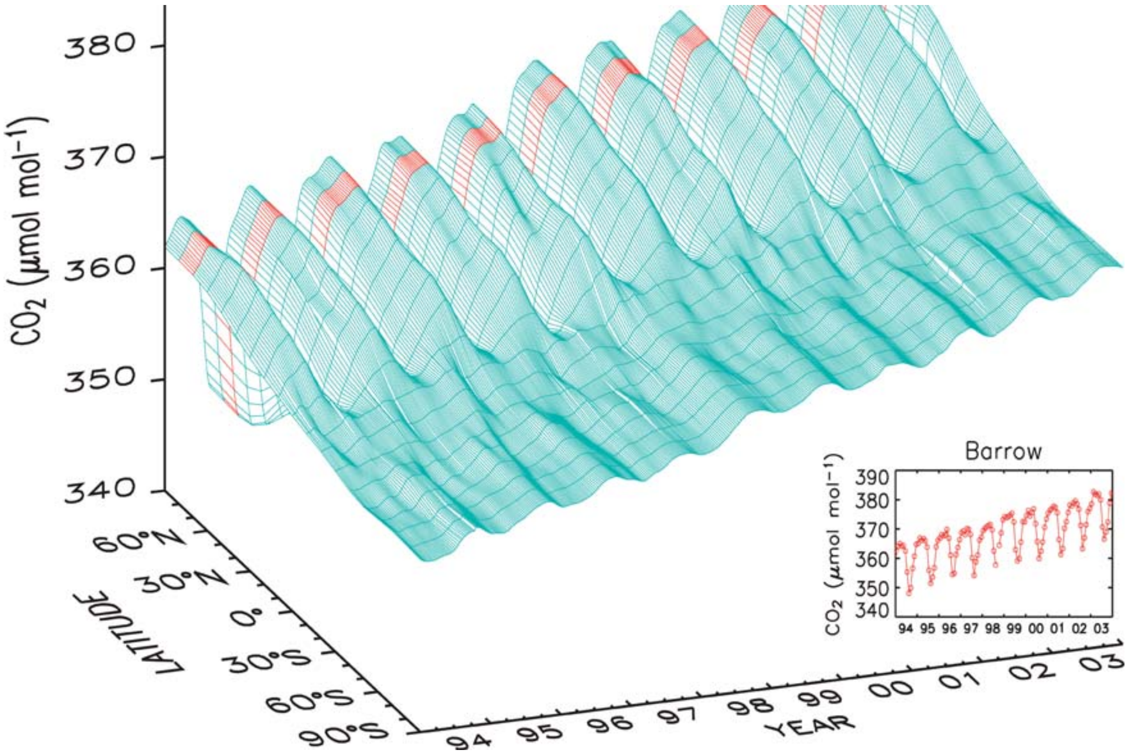
ries operated by CMDL; the others are at Trinidad Head, California; Mauna Loa, Hawaii; American Samoa; and South Pole. Carbon dioxide has the largest total cumulative direct radiative climate forcing in the atmosphere—about three times greater than CH_4, six times greater than the CFCs, and 15 times greater than N_2O. Sulfur hexafluoride (SF_6), although a strong greenhouse gas and increasing in the atmosphere, is present in low concentrations and has a much smaller net effect on total radiative forcing than the other greenhouse gases.

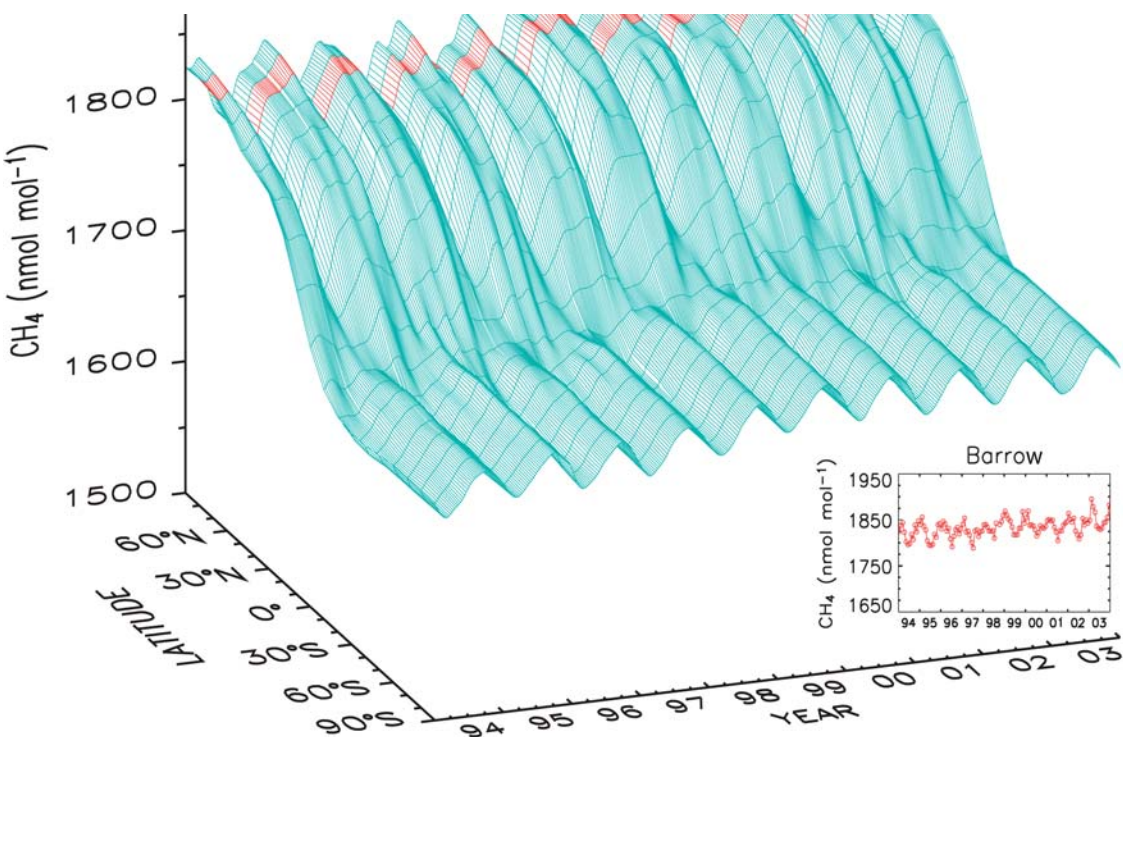
Carbon Dioxide and Methane Measurements

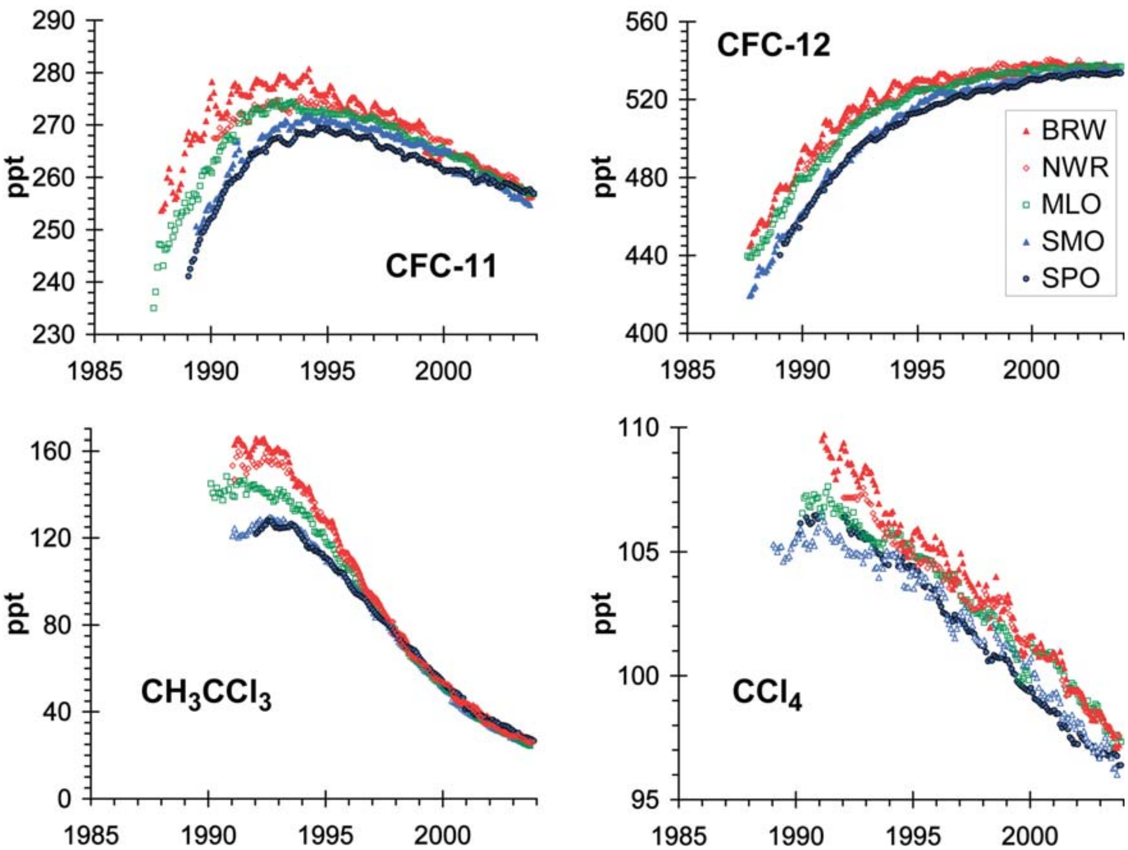
Most of the landmass on earth is in the northern hemisphere, as is vegetation and the human population. Anthropogenic activities at lower latitudes produce combustion effluents that result in high background CO_2 concentrations at Barrow and other locations in the Arctic thousands of kilometers north of the sources because of northward transport of the gases. Similarly, even though Barrow has very low annual plant growth, forests and agriculture in regions such as in Russia and Canada, well south of the latitude of Barrow, dominate the summer CO_2 drawdown in the high Arctic. Combined, these factors produce the largest annual background CO_2 cycle on earth.

Methane measurements at Barrow show that the Arctic also has the highest annual CH_4 cycle amplitude on earth, as well as the highest winter concentrations of the gas compared to lower northern latitudes and the southern hemisphere. This is caused by complex interactions between CH_4 sources and sinks and transport of mid-latitude air into the Arctic. Global average atmospheric CH_4 concentrations increased from 1625 ppb during 1984 to 1751 ppb during 1999 and then have remained essentially constant for the past five years. This is a large decrease in the methane growth rates compared to 1983, when the growth

Three-dimensional views of the global distribution of carbon dioxide (top) and methane (bottom) over time, showing the large amplitude of both cycles in the northern hemisphere. The 10°-latitude band that encompasses the Barrow data is indicated in red on the three-dimensional graph.







Concentrations in tropospheric mixing ratios of the chlorofluorocarbons (CFCs) controlled by the Montreal Protocol and measured at five CMDL measurement sites from Barrow, Alaska, in the Arctic to South Pole, Antarctica. Note that the Barrow concentrations, shown in red, are for the most part higher than measurements at lower latitudes.

rate was 13.5 ppb. It is not yet known if this change in the atmospheric methane growth rate is a temporary pause or a new, and as yet unexplained, steady state.

CFCs, Nitrous Oxide, and Sulfur Hexafluoride

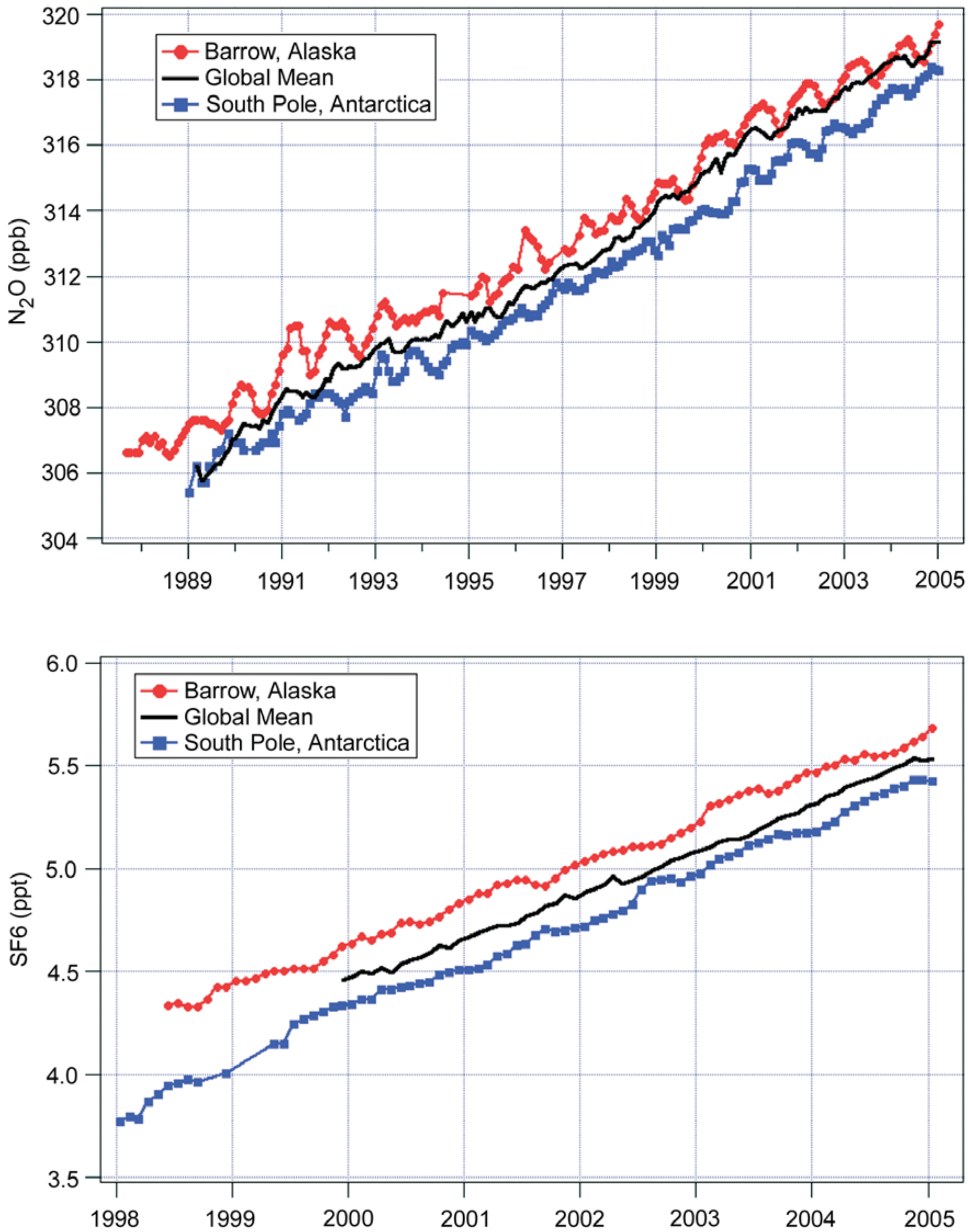
Concentrations of anthropogenic chlorofluorocarbon-11 (CFC-11), CFC-12, methyl chloroform (CH_3CCl_3), and carbon tetrachloride (CCl_4) in the atmosphere have decreased since 1991 in response to the international treaty known as the Montreal Protocol to Reduce Chemicals that Deplete the Ozone Layer and its subsequent amendments. The amount of the decrease for each compound, after production was reduced or ceased, is related to how quickly the compound is naturally destroyed in the atmosphere; methyl chloroform has an atmospheric lifetime of 5.5 years and is decreasing fast compared to CFC-11, which has a lifetime of 45 years, and CFC-12, with a lifetime of about 100 years. The Arctic typically has higher levels of these anthropogenic gases than at lower latitudes, as atmospheric transport moves air pollution from heavily populated northern mid-latitudes into the Arctic, where the gas concentrations build up, especially in winter.

The concentrations of nitrous oxide and sulfur hexafluoride at Barrow continue to grow. Nitrous oxide is produced in conjunction with fossil fuel combustion and oxidation of agricultural fertilizers, whereas sulfur hexafluoride is produced by a limited number of manufacturers mainly supplying the electricity transmission industry. N_2O has a seasonal cycle at Barrow, with a clear wintertime peak in February. SF_6 is steadily increasing in the atmosphere at a rate of 5% per year, and its sources are in the northern hemisphere.

Advance of Snowmelt Date and Springtime

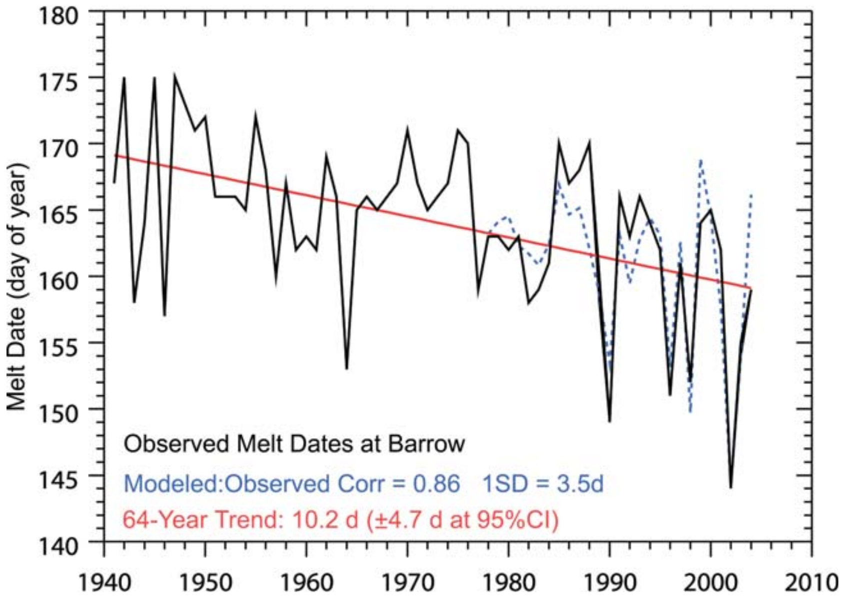
The date on which the last snow melts in the Barrow area, defined as the last day when one inch of snow can no longer be measured, has been monitored by the National Weather Service (NWS) since 1940 and by CMDL since 1986. The snowmelt date at the Barrow Atmospheric Baseline Observatory has advanced by 10.2 days in 64

Global tropospheric mixing ratios for N_2O (top) and SF_6 (bottom). Global means were determined from measurements made by on-site instrumentation and from air collected in flasks in the NOAA cooperative sampling network that were subsequently analyzed by NOAA/CMDL in Boulder, Colorado.



years. This is a significant advance at the beginning of the snow-free period, which is in the range of 85–135 days in Barrow. The causes for this increase in snowmelt date are believed to be a combination of decreased snowfall in winter and higher spring temperatures brought on by changes in both winter and spring Arctic air-flow patterns.

Whatever the causes of the advancing snowmelt date, one species of bird that nests on the observatory property is taking advantage of the earlier spring. In the summer of 2002, snow buntings raised two clutches of chicks in the Barrow area, the first time this has ever been observed, according to the local Inupiat hunters and elders.



Observed dates of snowmelt at Barrow, showing an advancing trend over the past 64 years.

Baby snow bunting (top) hatched near the Barrow observatory and a parent (bottom) looking for insects to feed this second-hatch chick. In 2002 the early spring and consequent longer summer allowed snow buntings to successfully raise two sets of fledglings on the North Slope tundra, the first time this has been observed in Barrow in living memory.

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NOAA and the Alaska Ocean Observing System

Contributions to the National Backbone and Regional Needs

This article was prepared by Allen Macklin, of NOAA's Office of Oceanic and Atmospheric Research; Gary Hufford, of NOAA's National Weather Service; Bernard Megrey, of NOAA's National Marine Fisheries Service; Rebecca Smyth, of NOAA's National Ocean Service; and Molly McCammon, Executive Director, Alaska Ocean Observing System.

The Alaska Ocean Observing System (AOOS) will improve Alaska's ability to detect changes in marine ecosystems and living resources, predict future changes and their consequences for the public, and enable stakeholders to make better decisions about use of the marine environment. AOOS partners include:

- Federal agencies, such as the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey, the Minerals Management Service, and the U.S. Coast Guard;
- Federal–State agencies, such as the *Exxon Valdez* Oil Spill Trustee Council;
- State agencies, such as the Alaska Department of Fish and Game, and state academic institutions, including the University of Alaska;
- Research organizations, such as the North Pacific Research Board, the Alaska SeaLife Center, the Prince William Sound Science Center, the Arctic Research Commission, and the Barrow Arctic Science Consortium; and
- Industry groups, including fisheries and marine navigation associations.

AOOS is one of 11 regional associations developing across the country to ensure that observing systems meet regional needs as part of the U.S. Integrated Ocean Observing System (IOOS). Nationally, the effort to establish IOOS is led by the Ocean.US Office under the National Oceanographic Partnership Program. Legislation creating the national system and associated regional systems, such as AOOS, is currently pending in the U.S. Congress. IOOS, in turn, is part of the Global Ocean Observing System and ultimately will be the U.S. ocean contribution to the Global Earth Observing System of Systems.

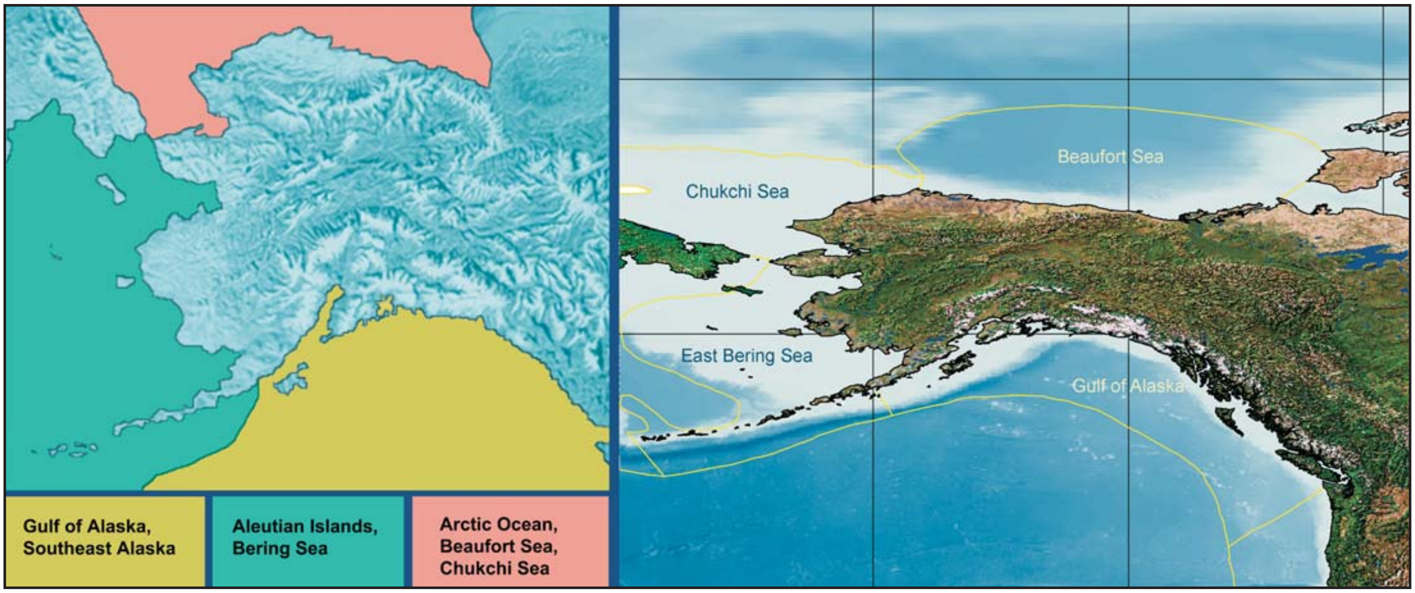
Implementation of AOOS started in 2002. A pilot project, employing elements of the Prince William Sound Ocean Observing System that includes NOAA platforms, will be the first on-line operational element, delivering information this year. When fully developed, AOOS will:

- Serve as the Alaska regional node for the national network of observing systems (IOOS);
- Systematically deliver real-time information and long-term trends about Alaska's ocean conditions and marine life;
- Provide public Internet access to cost-free data and information on coastal conditions; and
- Supply tailored products to meet the needs of mariners, scientists, industry, resource managers, educators, and other users of marine resources.

Implementing AOOS presents an enormous challenge because of the vastness of the region. Alaska's nearly 44,000 miles of coastline constitute about two-thirds of the total U.S. coastline and support a wide variety of habitats and user communities. NOAA, with a strong statewide presence in research, monitoring, and forecasting, is well positioned to help establish AOOS.

To make the challenge of implementation more tractable, AOOS's first approach is to organize along three large marine ecosystem boundaries: Arctic, Bering Sea/Aleutian Islands, and Gulf of Alaska. These regional classifications tend to be natural divisions that are differentiated by physical and biological characteristics, management schemes, and use by stakeholders. Even the size of these three regions, however, poses challenges.

Because of Alaska's remoteness and extreme weather conditions (frigid temperatures, precipitation, storms, high sea state, and sea ice), designing, installing, and operating an ocean observing system throughout the three Alaska regions is more difficult than in any other shelf area in U.S. waters. The extremely long distances render any plan for periodic servicing or unscheduled maintenance and repairs of observing arrays very costly and logistically often impractical. The dearth of nearby infrastructure, such as villages or other semipermanent settlements, makes power availability,



AOOS's three regions (left), which are similar to the Large Marine Ecosystems of the area (right).

real-time data retrieval, and routine equipment maintenance extremely demanding for almost every installation. Winter conditions challenge instrument capabilities because of the extreme temperature changes and the high winds and seas, ice, snow, and fog that accompany them. Extensive cloud cover associated with frequent passage of storms also contributes to the lack of ocean color, AVHRR, and other visible remote sensing products that are typically available in other coastal areas.

In spite of the challenges of establishing an integrated ocean observing system in Alaska, the opportunities and needs warrant national attention. Presently, the Alaska fisheries provide more than 40% of the U.S. and about 5% of the world harvest of fish and shellfish; Bristol Bay supports the world's largest sockeye salmon fishery; and the snow crab fishery is currently the largest crustacean fishery (by weight) in the U.S. In addition to supporting a large portion of the nation's fishery production, Alaska waters also support more than 80% of the U.S. seabird population. Another crucial point for implementing AOOS is that greenhouse-gas-related global warming is thought to be amplified in polar regions, making Alaska conditions a harbinger for climate change.

NOAA's Mission

NOAA also shares many of Alaska's concerns. NOAA envisions an informed society that uses a comprehensive understanding of the role of the oceans, coasts, and atmosphere in the global ecosystem to make the best social and economic decisions. NOAA's mission is to understand and predict changes in the earth's environment and conserve and manage coastal and marine resources to meet our nation's economic, social, and environmental needs.

To achieve its mission, NOAA's focus through 2010 will be on four mission goals and a mission support goal:

- Protect, restore, and manage the use of coastal and ocean resources through an ecosystem approach to management;
- Understand climate variability and change to enhance society's ability to plan and respond;
- Serve society's needs for weather and water information;
- Support the nation's commerce with information for safe, efficient, and environmentally sound transportation; and
- Provide critical support for NOAA's mission.

In an effort to build specific core strengths, NOAA has selected five cross-cutting priorities for the 21st century that it recognizes as essential to support its mission goals. Three that pertain particularly to efforts to develop AOOS are:

- Integrating global environmental observations and data management;
- Ensuring sound, state-of-the-art research; and
- Promoting environmental literacy.

Stakeholders

By partnering, NOAA and AOOS can address common themes and provide benefits to their stakeholders. The stakeholders cover a broad range of subsistence, commercial, cultural, and economic interests. User groups include a wide array of commercial and recreational fishers; subsistence hunters and fishers; marine transportation interests such as barges, ferries, cruise ships, and oil/gas tankers; oil and gas developers; coastal communities and their residents; and resource managers, including the U.S. Coast Guard performing its full range of regulatory, safety, and security missions.

The user groups have a wide range of needs for data and information products. For example, some of these groups require precise navigation and real-time information, yet others need only rudimentary knowledge of currents and water masses. While these needs exist today, others lie in the future, such as possible Northwest Passage transits under reduced Arctic ice cover. Increased surveillance, security, and safety of transportation and commercial shipping activities (offshore, in ports, and in sea lines of communication between Alaska and the continental U.S.) are recent and emerging areas of concern for the U.S. that will be addressed by many of the proposed AOOS activities. All of the above information needs are closely tied to forecasting weather and oceanographic conditions, as most weather systems, including extreme events, transit across marine waters before entering Alaska.

The use of AOOS observations and products for science applications is also important, especially for developing a better understanding of the variability of Alaska's ocean waters and the diverse ecosystem dynamics that produce the nation's most abundant fish and shellfish harvests, as well as important bird and marine mammal populations. Many of the science applications are directed toward the sustainability of commercial and subsistence fishing, especially in the Bering Sea/Aleutian Islands and Gulf of Alaska regions. Other examples of how AOOS products will contribute to scientific understanding include addressing the need to better understand the biophysical processes (for example, wind mixing, upwelling, and eddy formation) that contribute to the sustained high productivity of the shelf and continental slope waters, as well as improved assessment of biota. Weather and climate forecasts will benefit greatly from a much larger set of real-time observations in coastal areas where they are presently missing. Modeling long time series data would result in an improved and more comprehensive understanding of icing phenomena, shelf currents, shoreline erosion, tsunami hazards, and the evolution of catastrophic spill trajectories. In addition, longer-term climate change scenarios will become more "testable" given a more comprehensive and complete set of observations.

Statewide Priority Needs

There is a need throughout Alaskan waters for a system to acquire, process, integrate, and present remote sensing products, some of NOAA origin, that incorporate wind, sea surface height, sea ice cover, ocean color, wave height and direction, water column current, water column salinity, and water column temperature data. An immediate requirement that NOAA will address is the need to obtain a density of data buoys comparable to at least half that along the rest of the U.S. coast.

Additionally, Alaska needs data management and communications systems that provide real-time data for use by Alaska stakeholders. The systems must include the assimilation of data into models that provide information products such as ocean circulation patterns (taking into account waves, eddies, and fronts) and improved near-shore forecasts to minimize impacts of coastal erosion on development. These data systems also must store the data and metadata from the observing network in formats that provide ready access to researchers, regulators, educators, and public and commercial users.

Finally, Alaska must develop:

- Models that assimilate data to simulate circulation, predict wave heights and storm surges, and nowcast/forecast changing sea ice conditions;
- Systems that connect marine data and models with terrestrial data, especially given the importance both of freshwater input into the marine system and anadromous fish such as salmon that rely on both freshwater and marine waters;
- Comprehensive coastal and offshore mapping and charting; and
- Shore-side capabilities to develop, stage, deploy, operate, and maintain observing systems, including AUVs, cabled and moored systems, and ground- and air-based remote sensors throughout Alaska.

Besides these statewide needs, AOOS also will address specific requirements of the Arctic, Bering Sea, and Gulf of Alaska regions. These are documented on the AOOS web site (www.aoos.org).

A NOAA Polar Operational Environmental Satellite (POES), which collects global data on cloud cover; surface conditions such as ice, snow, and vegetation; atmospheric temperatures; and moisture, aerosol, and ozone distributions. They also collect and relay information from fixed and moving data platforms.

NOAA's Role in AOOS

Because of NOAA's long-term involvement in Alaska, NOAA is already a major contributor to the development of AOOS. NOAA efforts range from service on the Governance and the Data Management and Communications committees to provision of funds, observations, and products. Existing and planned activities by NOAA components are detailed in the subsections below.

National Environmental, Satellite and Data Information Service

To properly understand the Arctic environment, an observing system must consist of both space-based and in situ observations. The backbone of present space-based observations is the operational system of polar-orbiting satellites, such as NESDIS's Polar Operational Environmental Satellite (POES) series. The five AVHRR satellite-borne sensors offer a cost-effective means of gaining large-scale information from the synoptic to mesoscale in a systematic, repetitive manner over remote, data-sparse, polar regions. With two operating POES satellites, a pass over a portion of the Arctic can be obtained about every two hours. The POES series of satellites provides a long-term (more than 30 years), consistent database to detect and monitor spatial and temporal variability, necessary for distinguishing climate trends from natural "noise." The POES series will continue until 2012, when a new generation of satellites called the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) will be launched.

NPOESS will consist of a number of advanced sensor arrays to provide higher resolution and

Contributions of NOAA's major line organizations to the Alaska Ocean Observing System. Early, direct contributions are designated by a check. With ongoing commitment, all boxes will eventually be checked.

	AOOS Activity					
NOAA Line Organization	Observations	Modeling and Analysis	Data Management and Communications	Education and Outreach	Governance and Planning	Funding
NESDIS	√					
NMFS	√	√	√		√	√
NOS	√	√	√	√	√	√
NWS	√	√	√		√	
OAR	√	√	√		√	√

more accurate measurements of the atmosphere, clouds, aerosols, the earth radiation budget, clear-air land/water/ice surfaces, sea surface temperature, ocean color, ocean surface wind speed and direction, ocean surface topography, and temperature and moisture profiles. (See htpp://npoess.noaa.gov/index.html for detailed information on sensor type and expected performance.) The major challenge will be to integrate the satellite sensor information with the in situ observations, including calibration and verification of sensor data to the surface observations.

Another area in which NESDIS is committed to AOOS is the implementation of Climate Reference Network (CRN) observing stations across Alaska, including coastal sites. The CRN stations will reduce the uncertainty in the observed climate signal for surface temperature to less than 0.1°C per century and precipitation to less than 1% per century on regional scales. Approximately 29 CRN sites will be located in Alaska, with about 10 sites along the coast. Two sites, at Fairbanks and Barrow, are already operating. Four more sites will be installed during the summer of 2005, and it is anticipated that four sites will be installed each summer until the installation is complete. The coastal CRN sites will provide an important tie to the ocean–land system.

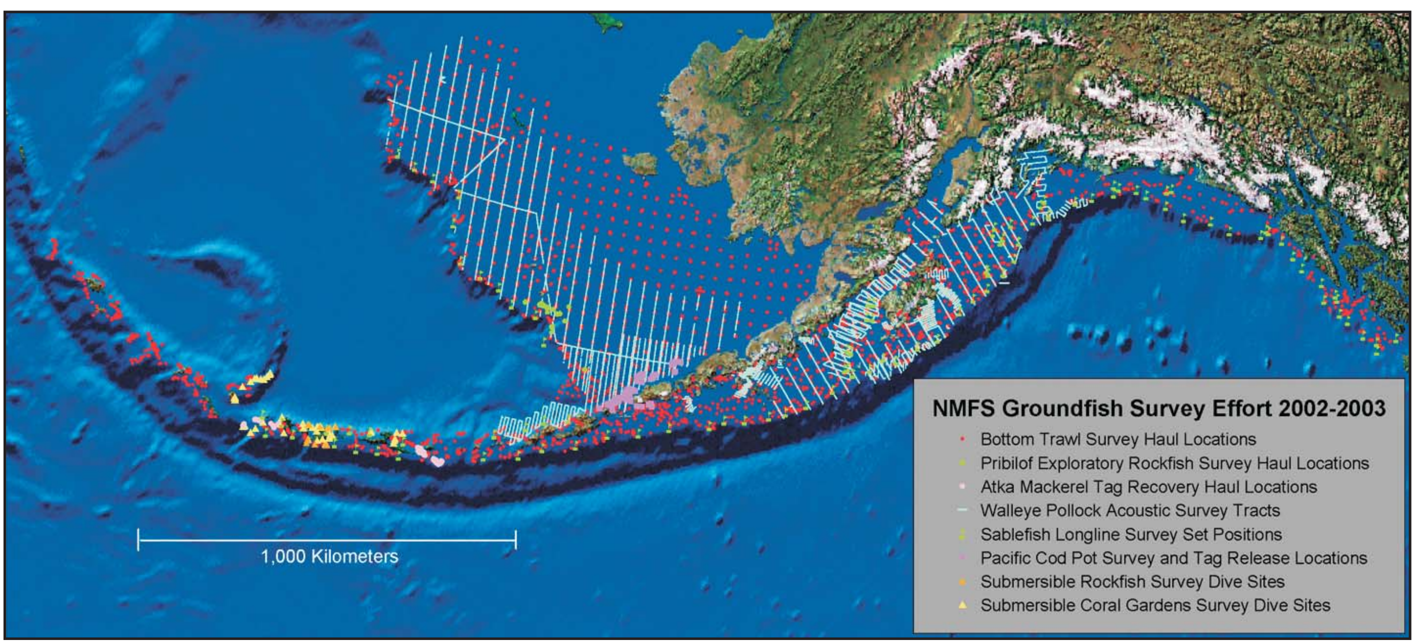
National Marine Fisheries Service

NOAA's National Marine Fisheries Service (NMFS) conducts biological, ecological, and economic research to provide information for the needs of regional fishery management councils, interstate and international fishery commissions, fishery development foundations, government agencies, and the general public.

NMFS, through its research and monitoring activities, seeks to understand and predict changes to marine ecosystems and their subsystems affecting living marine resources, fisheries, habitats, ecosystem condition, productivity, aquaculture, and the generation of net national benefits. NMFS develops the scientific information base required for fishery resource conservation, fishery development and utilization, habitat conservation, protection of marine mammals and endangered species, and the impact analyses and environmental assessments for management plans and international negotiations. It also pursues fisheries oceanographic research from a marine ecosystem standpoint to answer specific needs in the subject areas of population dynamics, fishery economics, fishery engineering, food science, and fishery biology.

The Alaska Fisheries Science Center (AFSC) conducts ecosystem-based research and assessments of living marine resources, with a focus on the North Pacific, to promote the recovery and long-term sustainability of these resources and to generate social and economic opportunities and benefits from their use. Since the early 1970s, the AFSC has conducted annual scientific fishery surveys to measure the distribution and abundance of approximately forty commercially important fish

National Marine Fisheries Service survey of commercially valuable and associated fish, shellfish, and marine mammals in the Gulf of Alaska, eastern Bering Sea, and Aleutian Islands.



and crab stocks in the Gulf of Alaska, eastern Bering Sea, and Aleutian Islands. Surveys in the Bering Sea are conducted annually on a regular sampling grid, while surveys in the Gulf of Alaska occur every other year using a stratified random sampling approach to estimating abundance.

The research surveys utilize a wide range of sampling techniques, mensuration equipment, and fishing gear, including underwater video systems, autonomous submersibles, hydroacoustic technology, and midwater, bottom trawl, ichthyoplankton, longline, crab pot, and pot sampling gear, as well as tagging studies. Often physical oceanographic measurements are taken concurrently with biological samples.

Data derived from these surveys and other sampling programs are analyzed by AFSC scientists, and the results and outcomes from these activities are supplied to fishery management agencies and to the commercial fishing industry, where they are used in making resource management decisions.

National Ocean Service water level observing station at Valdez. Stations such as this one are located at 18 sites in Alaska, and six new stations are planned.

NMFS and the AFSC, through their regular execution of large-scale fisheries surveys, will be an important source of biological information for AOOS. In turn, AOOS will provide much of the physical and chemical information needed by NMFS for ecosystem-based fisheries management.

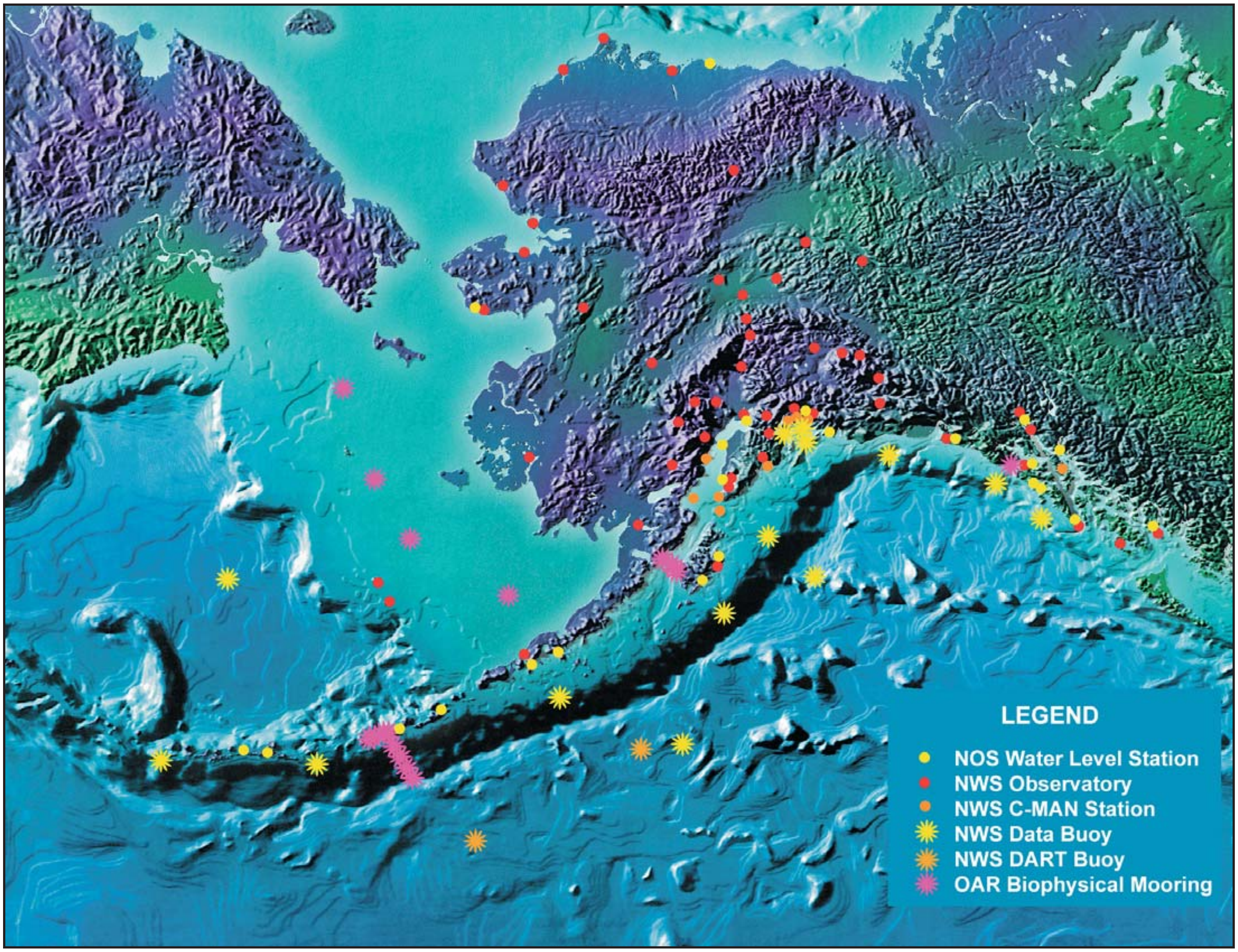
Besides the valuable survey information that NMFS will provide to AOOS, NMFS is a major partner in the development of AOOS, providing funds and personnel who serve in governance and data management capacities.

National Ocean Service

NOAA's National Ocean Service (NOS) works to balance people's use of the coast with conservation of the nation's coastal and ocean resources. Thus, NOS's mission is to manage society's uses of coastal ecosystems to sustain their natural resources and services. This mission is undertaken in a variety of ways: supporting commerce and marine transportation navigation; protecting, restoring, and managing coastal and marine resources; and building the capacity of regional, state, and local partners to undertake both these activities. A key component of these activities is to observe coastal and ocean conditions and resources, either directly or by building the capacity of regional, state, and local partners.

NOS is conducting or has planned a number of activities that will expand or enhance IOOS-related activities in Alaska. NOS will expand the multi-mission National Water Level Observation Network (NWLON) in Alaska (18 existing locations) with six new NWLON stations, primarily to help strengthen the U.S. Tsunami Warning System. NOS will continue to conduct tidal current surveys in Cook Inlet and southeast Alaska to update tidal current predictions, as well as hydrographic surveys using in-house and contract capabilities. NOS also will deploy a high-frequency surface current mapper during the summer of 2005 to complete its data collection requirements in the Cook Inlet area.

NOS also provides financial and technical assistance to Alaskan partners to aid in the development of regional observing capabilities. Grants to AOOS have helped fund the development of the regional governance needed to establish the regional association, including outreach and data management. Additional grants starting this fall will aid the Alaska region in implementing data management, visualization, and pilot observing systems around the state and in developing edu-



Locations of nearly 115 land and marine stations operated by NOS, NWS, and OAR. The observations from these stations represent NOAA's primary contribution to AOOS. In addition, about 150 more stations (not shown) operated by the Federal Aviation Administration, the Department of Defense, and commercial interests report through the NWS network.

cation, outreach, and business plans. Over the past two years, NOAA has provided resources to aid in developing coastal observations along the Gulf of Alaska. The system-wide monitoring program of the National Estuarine Research Reserves, part of the national backbone, which includes long-term data on water quality and weather at frequent time intervals, provides resources for the Kachemak Bay Reserve to participate in the system-wide program and the regional efforts. In addition, NOS is working with other parts of NOAA and with their partners, including AOOS, to coordinate and provide technical assistance for data management.

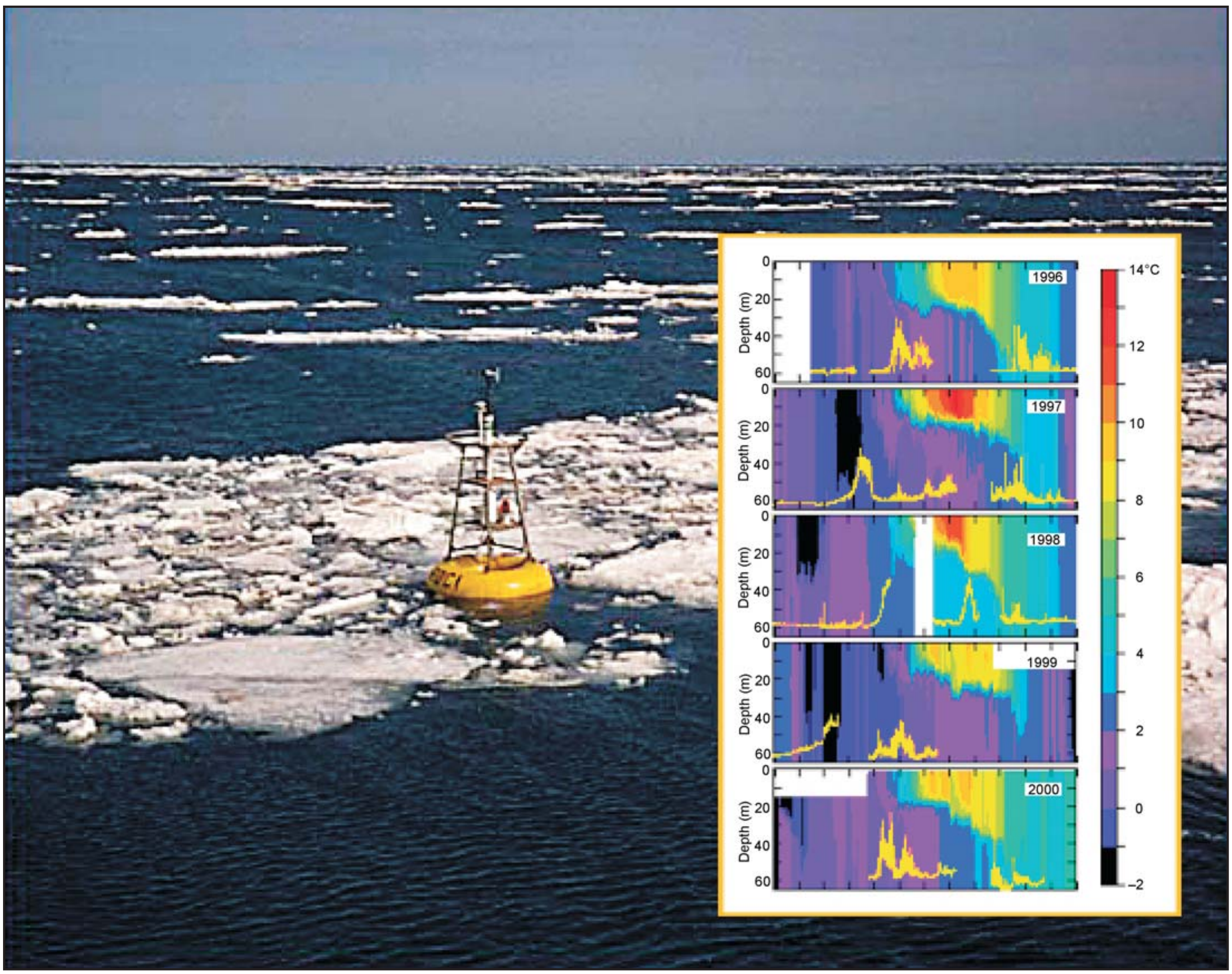
National Weather Service

The National Weather Service (NWS) has nearly 100 land observation stations across Alaska that report hourly. NWS also has over 150 cooperative observation sites (many near the coast) that provide daily minimum and maximum temperatures and total precipitation. In addition, Coastal-Marine Automated Network (C-MAN) stations are being installed along the coast, especially in the Gulf of Alaska. C-MAN was established by the NWS in the early 1980s to continue meteorological observations previously made by the U.S. Coast Guard until automation of many Coast Guard navigational aids ended that practice. Over the last few years, the number of fixed ocean data buoys has increased from 3 to 13, providing new information in data-sparse areas. Several of these buoys will be instrumented with subsurface ocean instruments in the coming year as part of a national effort to increase the data generated by this system. The data from all these sites form the backbone for the long-term surface observations in Alaska.

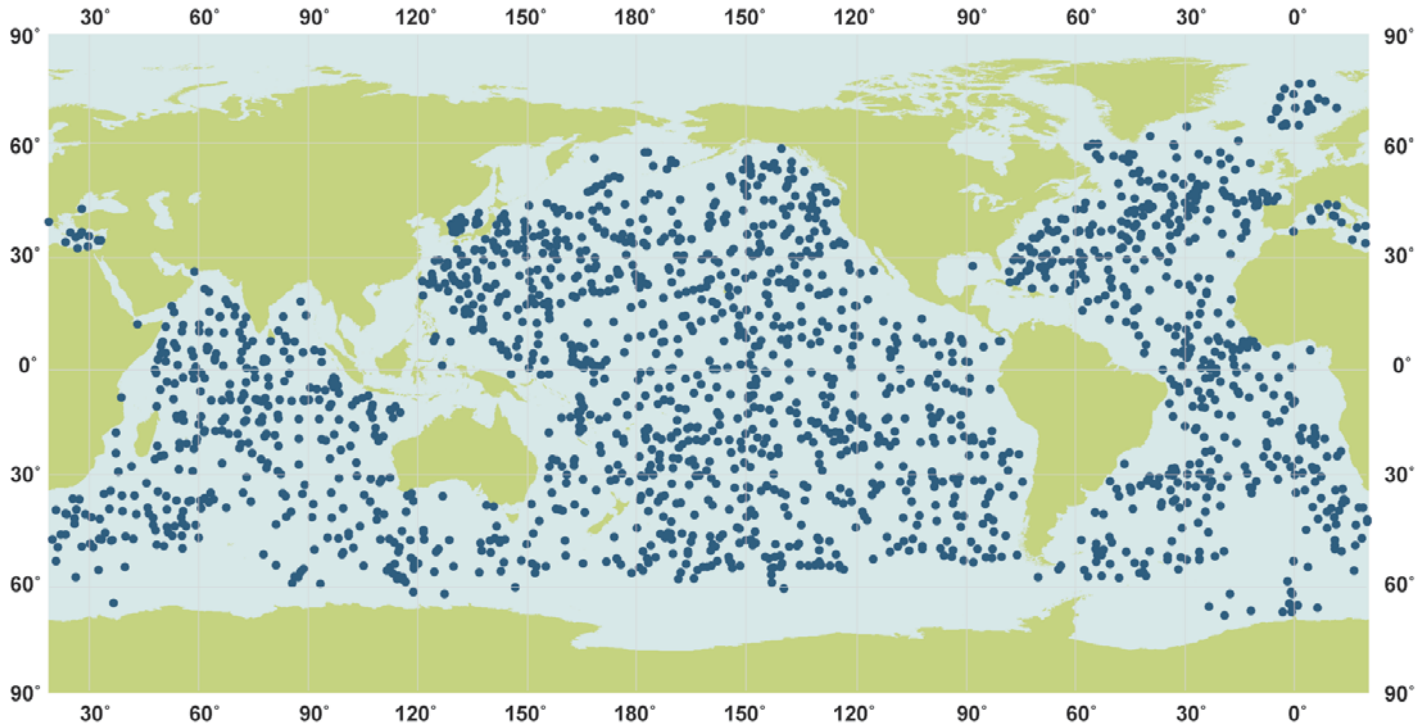
As funding becomes available, NWS will continue its efforts to expand marine observational sites, especially for the northern waters of the Bering and Chukchi Seas and the Arctic coast, as technology provides a buoy that can withstand sea ice conditions. With climate change occurring around Alaska, forecasters are observing increasing frequencies and intensities of ocean storms, shifts in storm track, and more formation of storms in the Arctic. The recession in sea ice cover is producing larger areas of open water, which is resulting in greater air–sea interaction. Large waves from these storms are not only affecting vessels at sea, but they are also creating increased coastal erosion and coastal flooding. In addition, subsistence activities are being disrupted. Longer lead times are required for short-term forecasts and warnings so that affected towns and villages can prepare the best they can. There is a need for more and better Arctic atmospheric and oceanic observations, both in situ and remotely sensed, and improved numerical weather and ocean prediction models that will incorporate the observations and better handle advances in high-latitude meteorology and oceanography.

Office of Oceanic and Atmospheric Research

The major contributors to AOOS from NOAA's Office of Oceanic and Atmospheric Research (OAR) are the Pacific Marine Environmental Laboratory (PMEL) in Seattle and the Arctic Research Office. PMEL helped fund early planning for AOOS and has provided representation and leadership to the AOOS Data Management and Com-



Biophysical mooring, operated jointly by OAR and NMFS, that measures a suite of environmental variables (pressure, wind, radiation, humidity, air and sea temperature, current, salinity, nutrients, and indicators of primary and secondary productivity), some of which are reported in real time.



Locations of Argo floats, which provide a new source of data from the top 2 km of the ocean. There were 1894 active floats as of June 13, 2005. The robotic floats spend most of their lives at depth but surface regularly to make temperature and salinity profile measurements. Many countries contribute the floats, and all data are freely available. A challenge for the Argo program will be the deployment of floats in Arctic waters. NOAA funds the U.S. Argo component.

munications Committee. The Arctic Research Office also has been instrumental in planning AOOS and is represented on the Governance Committee. OAR marine observations and products will come largely from PMEL. PMEL, together with the Alaska Fisheries Science Center, is a leader in the deployment of biophysical moorings in continental shelf and slope waters of the Arctic and subarctic. Several of these are planned for AOOS, including moorings in Cross Sound (southeastern Alaska), Shelikof Strait (western Gulf of Alaska), across the Alaska Stream south of the Aleutian Islands, in passes of the Aleutian Islands, and in the eastern Bering Sea. Biophysical moorings measure a suite of environmental variables (pressure, wind, radiation, humidity, air and sea temperature, current, salinity, nutrients, and indicators of plankton biomass), some of which are reported in real time. These observations may be reported directly by AOOS or incorporated into marine products that are disseminated through AOOS. PMEL also is working cooperatively with AOOS to plan and produce ocean circulation models of coastal Alaska.

NOAA funds the U.S. portion of the Argo Project. The Argo Project is building an array of 3,000 profiling CTD floats that, when completed, will measure the temperature and salinity of the upper 2 km at a spacing of roughly 3° latitude by 3° longitude and at 10-day intervals. The U.S. is presently contributing about half of the floats for the array, which was over 60% complete as of mid-June 2005. North of 45°N and east of 180°W in the Pacific at that date, there were about 49 Argo floats, and about 15 of these were U.S. floats. No floats have been deployed in the Pacific Arctic region. OAR's PMEL and Atlantic Oceanographic and Meteorological Laboratory are key contributors to the U.S. Argo effort.

Summary

NOAA and AOOS is a strong partnership. NOAA's line organizations are present and operating in each of the three AOOS regions, offering a rich mixture of marine and atmospheric measurements. AOOS and its constituents benefit from the information and services that NOAA supplies. Many of these will now be delivered to and disseminated by AOOS, as well as through existing NOAA channels. NOAA benefits from AOOS through the enriched flow of Alaska marine information that NOAA scientists and managers will have at hand for formulating analyses and decisions concerning regional marine issues. Moreover, discussions and exchanges between NOAA and AOOS foster an increased understanding of mutual problems and aspirations that can further improve cooperation between the organizations. Because of ongoing cooperation, NOAA and AOOS will be stronger and better able to serve the region and nation.

Marine Mammals in the Bering/Chukchi Sea

This article was prepared by Sue Moore, of the Alaska Fisheries Science Center, NOAA.

The National Marine Mammal Laboratory (NMML), Alaska Regional Office, and the Protected Resources Management Division are responsible for research on and management of 22 species of marine mammals that commonly occur in Alaska, including five endangered cetacean species (bowhead, fin, humpback, North Pacific right, and sperm whales); one pinniped species (Steller sea lion), which is threatened in one portion and endangered in another portion of its range; and two depleted species (Cook Inlet beluga whale and northern fur seal). Field research by the NMML staff on marine mammals off central and northern Alaska focused on two pinniped and six cetacean species during 2002 and 2003: Steller sea lions, harbor seals, Cook Inlet beluga whales, killer whales, and large cetaceans (fin, blue, humpback, and North Pacific right whales) in the Bering Sea.

Steller Sea Lions

NOAA is the lead agency responsible for the management and recovery of the endangered western and threatened eastern populations of Steller sea lions. The western population has declined by more than 80% in the last two decades, but it may have stabilized over much of its range during the last two years. Conversely the eastern population appears to be recovering from severely reduced levels in the early part of this century and has exhibited consistent growth over the past three decades. Factors hypothesized for the dramatic decline in the western population include reduced prey availability leading to nutritional stress, poor juvenile survival, and decreased reproduction; disease; pollution; predation by killer whales; incidental mortality in groundfish fisheries; and

Fin whale.

Feeding gray whale.

legal and illegal shooting. The Steller sea lion research program at the NMML conducts scientific research on each of the potential factors that could have contributed to the decline of the western population. The core research program includes vessel and aerial surveys to quantify abundance, molecular and genetic studies to elucidate stock structure, assessment of predator–prey dynamics and foraging distributions to determine foraging ecology, and individual identification and tracking to provide the foundation of mortality and life history.

Killer Whales

To investigate the potential role of killer whales in the decline of the western population of Steller sea lions, a vessel-based survey extending from the Kenai Fjords to the central Aleutian Islands was initiated in 2001. The DART (Distribution and Abundance of Residents and Transients) surveys are designed to estimate the abundance of killer whales by ecotype. Three killer whale ecotypes have been identified in Alaskan waters: the piscivorous (resident) ecotype; the mammal-eating (transient) ecotype; and the "offshore" ecotype, which apparently preys mostly on fish. Biopsy samples are taken whenever possible, to provide data for molecular genetic, prey isotopic, and fatty acid and contaminant analyses. When conditions permit, photographs and biopsies of sperm, fin, humpback, and Baird's beaked whales are also taken. These data augment sighting and biopsy sampling conducted in collaboration with the Alaska Fisheries Science Center's Resource Assessment and Conservation Engineering groundfish surveys.

Cetaceans

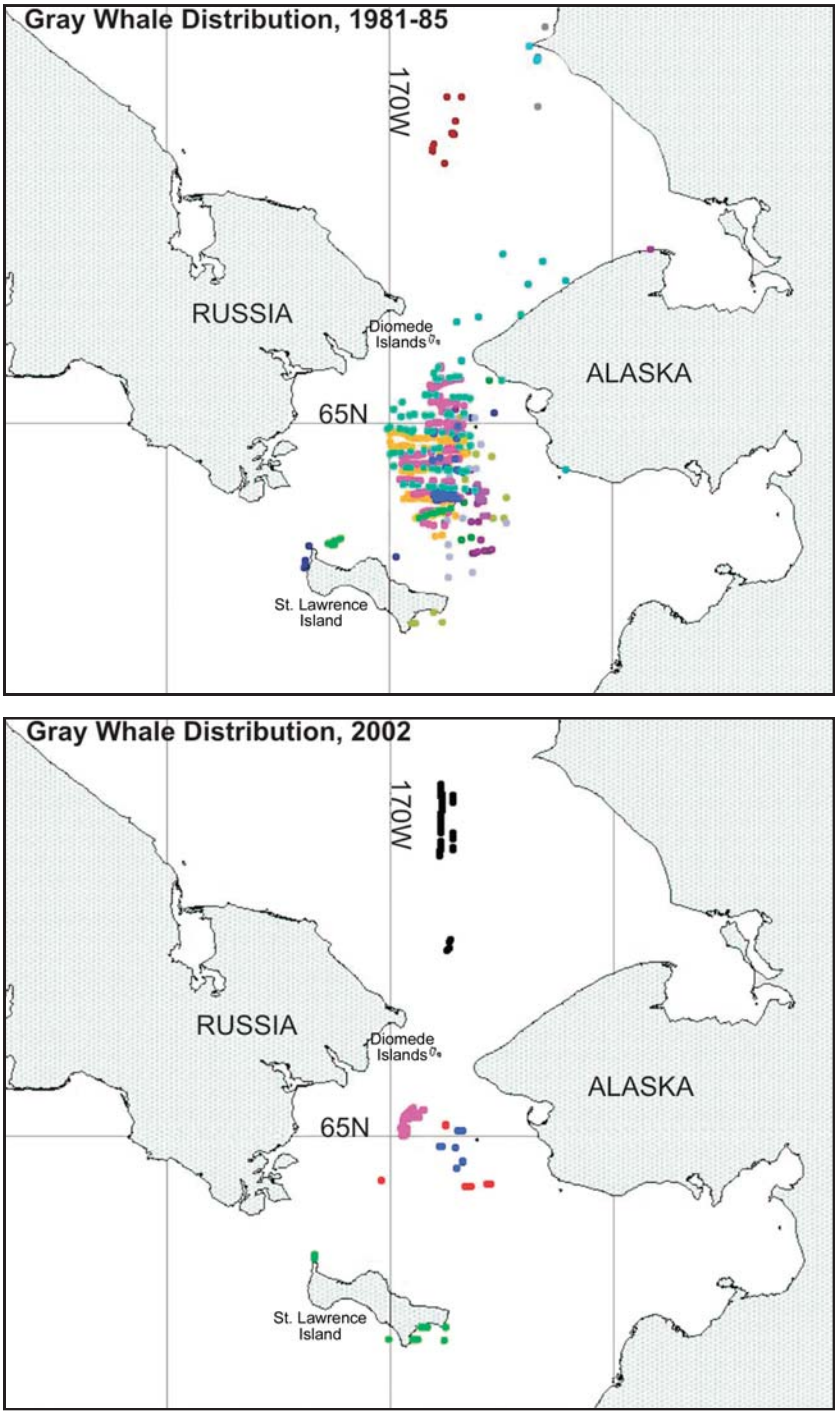
Research on the Cook Inlet beluga whale stock has been conducted annually since 1993. This stock was designated as depleted under the Marine Mammal Protection Act in 2000. Scientists from NMML, in cooperation with the Alaska Beluga Whale Committee, the Cook Inlet Marine Mammal Council, the Alaska Native Marine Mammal Native Hunters Committee, the Alaska Department of Fish and Game, and NMFS's Alaska Regional Office, have estimated the abundance of this relatively small and isolated population each year since 1994. Analysis of sighting data from aerial surveys indicated that the abundance of Cook Inlet beluga whales declined by nearly 50% between 1994 and 1998. Distribution and abundance estimates from annual aerial surveys in 2002 and 2003 indicated that the population was stable but low in number. In 2002, research was directed toward catching whales and outfitting them with radio and satellite tags to determine seasonal movement patterns and correction factors for aerial surveys. A Cook Inlet beluga habitat model, which is in development, is based on satellite tracking data and fatty acids analyses of blubber samples used to determine diet and contaminant burdens.

Since 1999, line-transect surveys for cetaceans have been conducted periodically in the southeast Bering Sea in association with the AFSC/RACE groundfish stock assessment survey. Provisional estimates indicate that fin whales are the most common large whale and that Dall's porpoises are the most common small cetacean in these waters. Fin whales are common on the Middle Shelf (50–100 m) and Outer Shelf (100–200 m) domains of the southeastern Bering Sea, with large feeding aggregations noted near canyons along the Bering Sea slope. Dall's porpoises, too, are most abundant along the Bering Sea slope. Cetaceans are generally good indicators of oceanographic productivity because to feed efficiently they must locate dense prey aggregations. Thus, baleen whale harvests during the commercial whaling era have been used to document hydrographic patterns associated with areas of zooplankton and forage fish abundance. Alternatively, odontocete distribution likely reflects patterns of higher-order productivity associated with nektonic prey. Overall, the distribution and abundance estimates available from the line-transect surveys in the southeastern Bering Sea suggest that baleen whales are reoccupying productive hydrographic zones in patterns similar to those depicted in summaries of commercial whaling harvests. Observations of cetacean distribution and estimates of cetacean abundance from surveys completed to date offer a beginning for the incorporation of whales and porpoises in ecosystem-based research plans for the Bering Sea.

Patterns of habitat change in the northern Bering and Chukchi seas have been investigated for gray and bowhead whales. In the 1980s the Chirikov Basin north of Saint Lawrence Island in the northern Bering Sea was considered a prime gray whale feeding area, but an unusual mortality event in this species in 1999–2000 precipitated concern that this area no longer supported a viable benthic forage community. In 2002 a provisional five-day survey for gray whales revealed restricted distribution in the basin and a 3- to 17-fold decline in sight rates. To put these data in context, a retrospective summary of gray whale and benthic fauna distribution was undertaken. Available measures of biomass suggest a downturn in productivity from 1983 to 2000, when estimates of gray whale population size suggested that the population began to expand. Sighting rates for gray whales were highest north of Bering Strait during the 2002 survey, suggesting the whales may simply be moving north following prey availability.

Bowhead whales are ice-adapted baleen whales, the only species endemic to Arctic waters. To examine how sea ice changes may be affecting bowhead whale habitat, trends in sea ice cover were examined over a 24-year period (1979–2002) in habitats identified as important to migration, feeding, and over-wintering. Significant increases in open-water areas were identified for small regions associated with feeding opportunities but not in areas used during migration and over-wintering. High interannual variability, together with consistent shifts to earlier and longer (i.e., June to November) ice-free or light-ice conditions, may alter foraging opportunities or prey availability. The evaluation of sea ice cover at spatial and temporal scales linked to bowhead whale natural history provides a first step towards developing conservation insights regarding the potential effects of climate change on this pagophilic species.

Gray whale distribution in the northern Bering and Chukchi Seas in the early 1980s and in 2002. The colors indicate different days and years of aerial surveys.



Pinnipeds

Five species of pinnipeds are associated with sea ice in Alaskan waters, including walruses and four species of "ice seals"—bearded, ringed, spotted, and ribbon. NOAA has management responsibility for the ice seals, each species of which depends at least in part on sea ice to rest, give birth, and molt. Ribbon and spotted seals are thought to prefer the loose ice in the Marginal Ice Zone (MIZ), which occurs between nearly solid floes and open sea water. Conversely, bearded seals, ringed seals, and walruses are commonly found in zones where ice covers over 50% of the sea surface.

Bowhead whales.

Results of aerial surveys conducted south of St. Lawrence Island found that both ringed seals and walruses preferred large ice floes (larger than 48 m in diameter), while spotted seals were found on smaller ice floes (smaller than 20 m in diameter) near the MIZ. Ringed seals were found in areas with more than 90% sea ice cover and bearded seals preferred 70–90% ice cover. All species, except spotted seals, were associated with a region where benthic biomass was especially high.

Bearded seal.

In recent decades, Alaska harbor seals have declined dramatically in some regions, while their numbers have increased in some other regions. The primary objectives of NMML's research on this species are to obtain data on the abundance of the species throughout Alaska and to collect information on haulout patterns that can be used to better interpret abundance information. In 2002 and 2003 the NMML produced peer-reviewed papers describing the abundance of harbor seals in the Gulf of Alaska and the stability of harbor seal haul-out patterns. In addition, research was undertaken to determine the response of harbor seals to cruise ships and to determine the genetic relatedness of harbor seals via molecular genetic techniques. Obtaining information on Alaska harbor seals is critical, as they are an important component of the Alaska Native subsistence harvest. A co-management agreement, signed by the Alaska Native Harbor Seal Commission and NMFS, has charged the Harbor Seal Co-management Committee to prepare an Annual Action Plan for this culturally important species.

Ocean Climate Changes and the Steller Sea Lion Decline

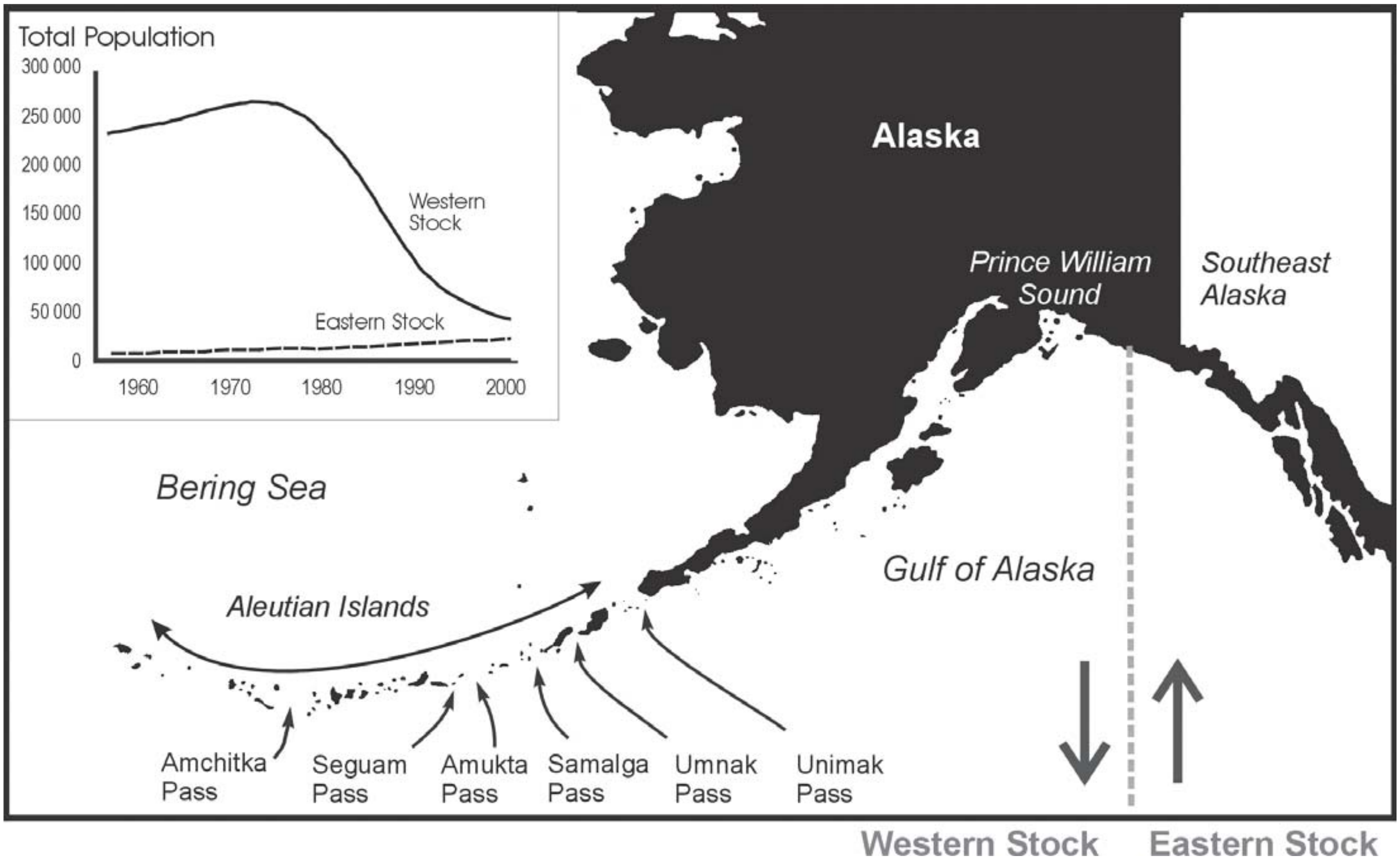
This article was prepared by Arthur J. Miller, of the Scripps Institution of Oceanography; Andrew W. Trites, of the University of British Columbia; and Herbert D.G. Maschner, of Idaho State University.

Steller sea lion populations declined by over 80% between the late 1970s and early 1990s in the western Gulf of Alaska and the Aleutian Islands. Concurrent declines also occurred farther west in the Russian coastal waters. Yet population trends were reversed along the coasts of southeast Alaska, British Columbia, Washington, and Oregon, where sea lions increased through the 1980s and 1990s. The cause or causes of these population changes have not been resolved and have been the subject of considerable debate and research because their preferred prey often coincides with economically important fisheries.

Much of the search for an explanation of the Steller sea lion decline in western Alaska has focused on trying to identify a single cause, rather than recognizing that many of the proposed theories are interrelated. The leading hypotheses of epidemic diseases, predation by killer whales, ocean climate change (regime shifts), and nutritional shifts in types of prey available to sea lions (the junk food hypothesis) may all be linked through bottom-up processes. Conceptually, changes in water temperatures, ocean currents, and other oceanographic variables can influence the survival and distribution of assemblages of species that are consumed by predators such as sea lions. This in turn will affect the quantity, quality, and accessibility of the prey that sea lions consume. Individuals that consume sufficient energy are typically fat and large and experience reduced levels of oxidative stress at a cellular level. In contrast, inadequate nutrition can increase oxidative stress (and susceptibility to disease), reduce body fat (and pregnancy rates), and increase rates of predation (as a function of reduced body size or increased vulnerability while spending longer times searching for prey). Such changes to the health of individuals ultimately translate into changes in numbers at a population level through decreased birth rates and increased death rates.

A major change in both the physical state and the ecology of the North Pacific Ocean occurred

Steller sea lions.



Habitats of the western and eastern stocks of the Steller sea lion. The graph shows the estimated numbers of Steller sea lions (all ages) in Alaska from 1956 to 2000. The dashed line shows the division between the declining (western) and increasing (eastern) populations.

during the mid-1970s, with basin-wide changes in temperature, mixed layer depth, primary productivity, fisheries, and other variables. This linkage between the physical climate and the oceanic ecosystem provided the impetus for the Cooperative Institute for Arctic Research (CIFAR) to fund a suite of studies that addressed the hypothesis that large-scale changes in the physical environment of the North Pacific Ocean influenced Steller sea lion populations directly or indirectly. The investigations covered a variety of topics, including physical and biological oceanographic data analysis, ocean modeling experiments, and archaeological evidence.

CIFAR also sponsored a synthesis workshop in December 2004 that resulted in a detailed publication in *Fisheries Oceanography*, which is briefly summarized here. It had two primary goals. The first was to determine whether any spatial and temporal patterns in the physical and biological oceanographic data corresponded with observed differences in the diets and numbers of sea lions since the late 1950s. The second was to put the recent decline in context with similar changes that may have occurred over the past 4000 years.

Characteristics of Steller Sea Lions

Steller sea lions are restricted to the North Pacific Ocean and range along the Pacific Rim from California to northern Japan. Genetically there are two distinct population segments that are split at 144°W near Prince William Sound, Alaska. The sharp decline of the larger western population through the 1980s was mirrored by population growth in the smaller eastern populations in southeast Alaska, British Columbia, and Oregon.

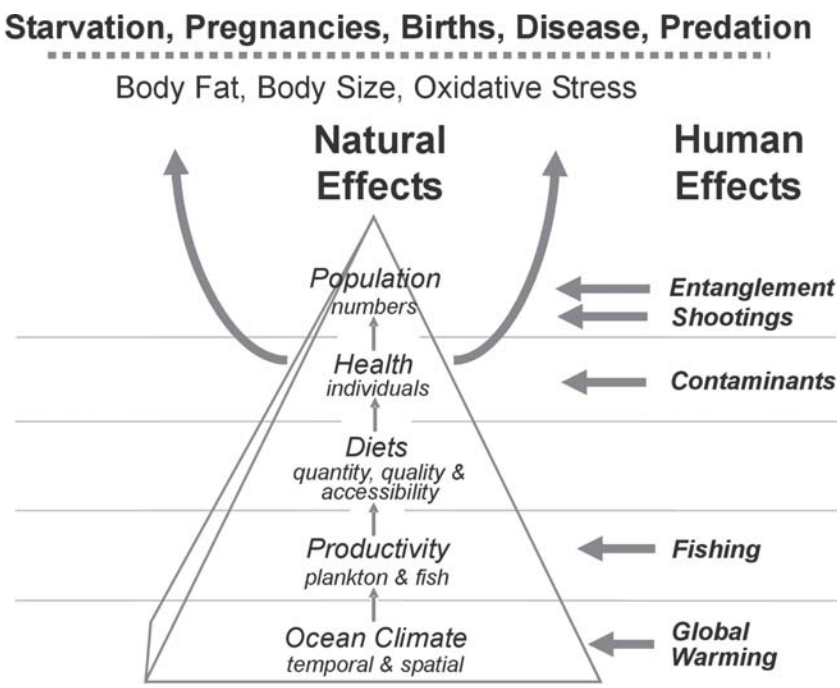
Counts of Steller sea lions in Alaska began in 1956 and continued sporadically through the 1960s and 1970s. They suggest that sea lion numbers were relatively high and increased slightly through the 1960s and 1970s. Trouble was not noted until the mid-1970s, and it appeared to spread east and west from the eastern Aleutian Islands in following years. The frequency and thoroughness of sea lion censuses increased through the 1980s and 1990s and showed an overall rapid decline of sea lions through the 1980s, with an inflection point and slowing of the decline around 1989. Recent counts

(2002) suggest the possibility that some breeding populations in the eastern Aleutian Islands and Gulf of Alaska may have increased slightly since 1999.

Steller sea lions regularly haul out on shore at breeding (rookeries) and nonbreeding (haulout) sites. They typically spend one to two days at sea followed by one day resting on shore. Principal prey species include Atka mackerel, walleye pollock, Pacific cod, squid, octopus, salmon, Pacific herring, sand lance, and arrowtooth flounder. The most complete set of dietary information for sea lions was collected during the 1990s. It also suggests distinct geographic clusterings, with the split points centered on major Aleutian passes (Samalga Pass and Unimak Pass during summer and Umnak Pass during winter).

Significant correlations between rates of population decline and the diversity of diets suggest that a relationship may exist between what sea lions eat and how their populations have fared. Sea lions living in regions with the highest rates of declines, such as the western Aleutian Islands, consumed the least diverse diets with the lowest energy prey. In contrast, the increasing populations of sea lions in southeast Alaska had the most energy-rich diet and the highest diversity of prey species of all regions studied during summer. During the 1990s, sea lion diets were dominated by Atka mackerel in the Aleutian Islands and by walleye pollock in the Gulf of Alaska. Little is known about what sea lions ate prior to their population decline.

Conceptual model showing how sea lion numbers might be affected by ocean climate through bottom-up processes. This hypothesis suggests that water temperatures, ocean currents, and other climatic factors determine the relative abundances of fish available to eat, which in turn affects sea lion health, as measured by the proportion of body fat, rates of growth, and, at a cellular level, oxidative stress. These three primary measures of individual health ultimately determine pregnancy rates, birth rates, and death rates (through disease and predation). Also shown are the effects of human activities that could have directly or indirectly affected sea lion numbers.



The National Research Council review of the causes of the Steller sea lion decline noted that "levels of groundfish biomass during the 1990s were large relative to the reduced numbers of sea lions, suggesting that there has been no overall decrease in prey available to sea lions." They also concluded that "existing data on the more recent period of decline (1990–present) with regard to the bottom-up and top-down hypotheses indicate that bottom-up hypotheses invoking nutritional stress are unlikely to represent the primary threat to recovery" of sea lions.

The available data support the National Research Council's conclusion that gadid populations were indeed abundant during the population decline and that Steller sea lions did not starve and incur "acute" nutritional stress. However, historic data and more recent studies do not support a conclusion that no form of nutritional stress occurred. Instead it appears that sea lions may have experienced "chronic" nutritional stress associated with the high abundances of low-quality species of prey that were present during the 1980s and 1990s. This conclusion is based on a growing body of research that includes blood chemistry comparisons, dietary analyses, population modeling, and captive feeding studies.

Shifting from a high-energy diet (dominated by fatty fishes) to one dominated by lower-energy fish (such as walleye pollock) may have significantly affected young sea lions by increasing the amount of food they would have had to consume to meet their daily energy needs. Bioenergetic models indicate that a yearling sea lion requires about twice the relative energy compared to an adult. Recent feeding experiments with captive sea lions suggest that it may be physically impossible for young sea lions to meet their daily energy requirements if low-energy prey species dominate their diet. Adults who have finished growing and have lower metabolic needs than young animals are not similarly constrained and have the stomach capacity to consume sufficient quantities of prey to meet their daily needs.

The overall abundance of Steller sea lion prey may have changed in the mid-1970s because of changes in ocean productivity, fishery removals, and/or other ecosystem interactions. Decreased prey availability could potentially have increased foraging times and thus the risk of predation. Similarly, abundant prey located farther from shore could also increase foraging times and exposure to killer whales, which are the principal predators of sea lions. Survival and reproduction would have ultimately been compromised if sea lions were unable to efficiently acquire sufficient prey to maintain normal growth and body condition. A dietary shift to low-energy prey could have further exacerbated any effects of decreased prey availability by increasing food requirements.

Differences in diet and relative prey abundance appear to be associated with pronounced changes in Steller sea lion numbers. The ocean climate could account for these geographic and temporal patterns. However, the spatial and temporal patterns associated with the available ocean climate data have not been previously explored in the context of Steller sea lion dynamics and food webs. The following section therefore begins evaluating the ocean climate hypothesis by considering the changes that occurred in the oceanic habitats of sea lions in Alaska.

Physical Oceanographic Data

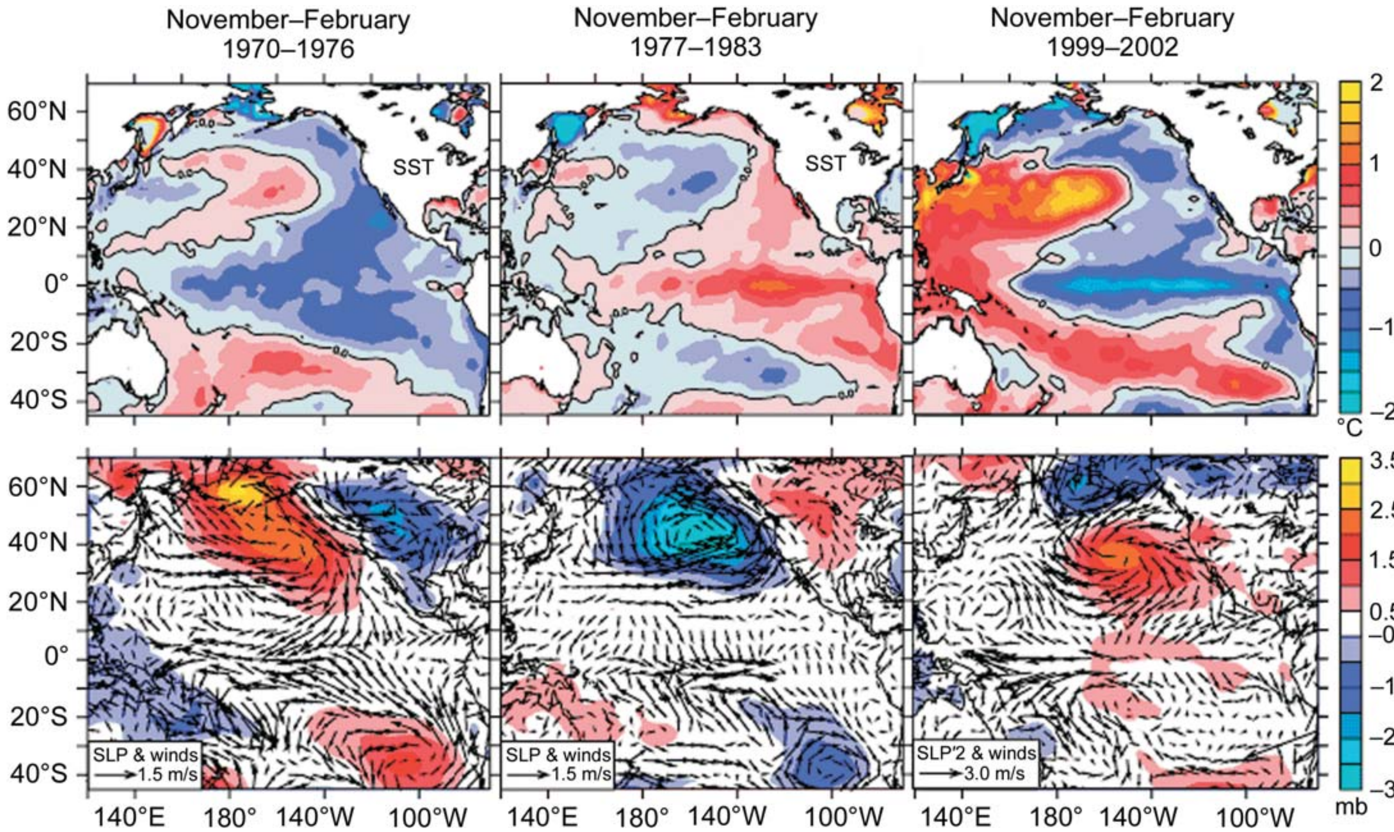
Physical oceanographic data for the North Pacific are generally sparse in time and space, and this is especially true in the Gulf of Alaska. Broad-scale changes over recent decades have been identified in sea surface temperature (SST), which is the most complete set of oceanographic data available. The Gulf of Alaska was predominantly cool in the early 1970s and warmed in the late 1970s and throughout the 1980s. There is substantial evidence that this was part of a basin-wide regime shift of the North Pacific that commenced during the winter of 1976-77. These physical changes have been linked to a number of responses within the ecosystem of the Gulf. For some variables, especially biological ones, the mid-70s transition was not a sharp change, and the duration of the stable time periods before and after the shift may have ranged from six years to more than twenty years.

Besides the issue of detecting significant regime changes from short time series, a greater problem lies in identifying the mechanisms by which the large-scale physical environmental changes drive associated biological regime shifts, which are highly uncertain. Some detailed mechanisms have been proposed, but none have yet been truly tested and validated with field studies. The large-scale, surface-derived indices such as the Pacific Decadal Oscillation (PDO), the first principal component of SST north of 20°N in the North Pacific, provide little information on how large-scale climate affects local populations. The regional dynamics of climate regimes and the transitions between them need to be understood before ecologically relevant, mechanistic-based indicators of climate state can be developed.

Regional and depth-dependent differences in the timing and amplitude of important ocean climate events in the eastern subarctic Pacific could have caused local differences in ecosystem response. Statistical patterns in SST reflect important large-scale climate impacts in the Gulf of Alaska associated both with El Niño events and the 1976 regime shift. Moreover, the patterns were of sufficient magnitude and duration to potentially foster changes in lower trophic productivity and structure. But there is also significant spatial heterogeneity in long-term SST patterns across the region. An analysis of SST time series reveals five distinct regions, with common variability within the eastern Gulf of Alaska and the western Gulf of Alaska, as well as the transitional zone to the south. Other analyses also revealed this robust east–west asymmetry.

The ocean temperature data show temporal and spatial patterns that are visually correlated with some of the observed differences in sea lion numbers and diets. Changes in the seasonality (phase and amplitude of the seasonal cycle) of important environmental processes may have a large ecosystem impact by leading to mismatches in biophysical coupling. Unfortunately, the available temperature data are on a much coarser spatial scale than the fine scales over which sea lions forage, making it difficult to draw firmer conclusions in the context of the Steller sea lion decline.

Important changes were observed across the unique mid-70s temporal boundary for winter SST, sea level pressure, and surface wind anomalies before and after 1976-77. The timing of this major regime shift corresponds to the start of the sea lion decline. Comparing ocean climate conditions across the 1999 temporal boundary also shows similarities between the latest period of sea lion stability (and possibly recovery) and the earlier cool regime (before 1977). This is noteworthy, given some of the early indications that positive changes in sea lion diets and numbers in the Gulf of Alaska may have begun with the start of the 1999 regime shift. However, the 1999 regime shift may not be a reversal to earlier conditions. Significant differences between regimes (1970–1976 and 1999–2002) are evident, such as a strong, displaced Aleutian Low with a strengthened North Pacific High. This suggests that more than two stable



Sea surface temperature anomalies (top panels) and sea level pressure anomalies and surface wind anomalies (bottom panels) for winter periods (November–February) before and after the 1976-77 regime shift and for the most recent period.

climate states may exist, and it adds support to the arguments that a second SST pattern has become more important than the PDO in recent years.

The east–west patterns of sea lion population dynamics are therefore associated with the east–west asymmetries in key physical oceanographic observations, such as SST and thermocline depth. Atmospherically controlled oceanic forcing functions, such as Ekman pumping patterns and streamflow discharge into the Alaska Current, also indicate that basin-scale ocean changes may have occurred after the 1976-77 climate shift when the populations decreased significantly in the western Gulf. These results imply a linkage between the distinct observed climate changes and sea lion populations, but the specific physical forcing mechanisms affecting the animals are unclear. Numerical simulations can be used to gain further insight into how these physical changes may have influenced the sea lions and other species.

Ocean Modeling

Because of the sparseness of oceanographic observations in space and time (especially before the 1976-77 climate shift), a number of modeling studies were designed to decipher the physical processes that may have led to changes in the sea lion food web. These studies included hindcasts forced by observed atmospheric variations to determine the magnitude of phasing of oceanic events in the water column. They also involved process studies in which the effects of eddies, such as eddy interactions with topography and mean conditions, were explored. Coarse-resolution models allow a broad-scale perspective of the physical oceanographic changes induced by climate forcing, while eddy-permitting models can suggest roles for eddies in altering the mean background states of the ocean and driving fluxes of nutrients across the shelf–slope system.

A coarse-resolution hindcast of the Gulf of Alaska over the period 1958–1997 showed a shoaling of the pycnocline in the central part of the Gulf of Alaska after the mid-1970s and a deepening in a broad band that follows the coast. The deepening was particularly pronounced in the northern and western part of the Gulf of Alaska, to the southwest of Kodiak Island, where the pycnocline deepened by 25–30 m after 1976. The surface forcing responsible for these changes was the local Ekman pumping, which can account for a large fraction of the pycnocline depth changes as a local response.

Changes in the distribution of mesoscale eddies in the Gulf of Alaska after the 1976-77 regime shift were studied in a regional eddy-permitting ocean model over the 1950–1999 time period. After the shift, mesoscale eddy variance changed dramatically in the western Gulf of Alaska. The consequences of this change included altering the cross-shelf/slope mixing of water masses of the open-ocean and shelf regions. Since mesoscale eddies provide a mechanism for transporting nutrient-rich open-ocean waters to the productive near-shore shelf region, the fundamental flow of energy through the food web may have been altered by this physical oceanographic change. This mechanism may have altered the relatively abundances of key prey species available to Steller sea lions prior to and following the 1977 regime shift.

In contrast to the western Gulf of Alaska, the model surface velocity variance in the eastern Gulf was only weakly altered. Hence, an east–west asymmetry occurred in the Gulf of Alaska circulation response to the strengthened Aleutian Low. This is consistent with eastern populations of Steller sea lions in southeast Alaska continuing their steady increase across the temporal boundary of the 1976-77 climate shift.

Basin-scale models designed to study oceanic processes are not of sufficient resolution to investigate coastal ecosystem dynamics. Instead, limited-domain models of ocean circulation with higher resolution allow focused, regional studies of critical processes and circulation. Such an approach allows for proper representation of the complex flow–topography interactions and their influence on exchanges between adjacent water masses and through the Aleutian Island passes.

A pan-Arctic coupled sea ice–ocean model provides insight into the circulation and exchanges between the subarctic and Arctic basins, particularly on the exchange between the North Pacific Ocean and the Bering Sea through the passes of the Aleutians, which can influence biological productivity along the Aleutian Island chain. Model-simulated eddies along the Alaskan Stream have significant influence on both the circulation and the water mass properties across the eastern and central Aleutian Island passes. Eddy-related upwelling of salty water along the southern slope affects the water column down to about 1000 m. Given the high correlation between salinity and nutrient content at depths, the increased salinity in the upper ocean over the pass can represent nutrient input for enhanced and/or prolonged primary productivity. Since modeled eddies along the Alaskan Stream occur throughout a year, their contribution to high surface nutrient concentrations within the Aleutian Island passes could be especially significant during otherwise low primary productivity seasons. This effect would be most important during years in which mesoscale eddies frequently propagate along the Alaskan Stream.

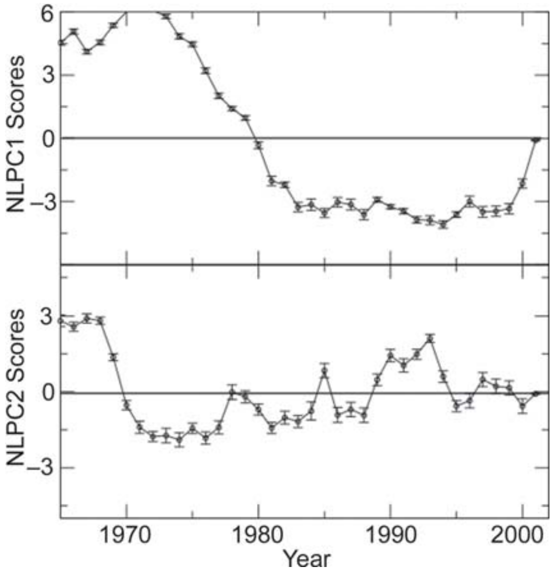
There is therefore evidence that climate-forced changes occurred in both the strength of the mean currents of the Alaskan Stream and the spatial distribution of the mesoscale eddy field of the Alaskan Stream after the mid-70s climate regime shift. These changes are strongest in the western Gulf, where sea lion populations experienced precipitous declines during the same period. Ocean models also demonstrate that mesoscale eddies provide an important mechanism for mixing nutrient-rich waters with nutrient-depleted waters along the Alaskan Stream and across the Aleutian Island passes. Hence, the flow of energy through the ecosystem in the Gulf may have been fundamentally altered by changes in these basic physical oceanographic changes. There are also other indications that the broad suite of concurrent food web changes that occurred at basin and regional scales were influenced by the effects of physical oceanography.

Ecosystem and Biogeographic Links

The oceanographic studies described thus far provide evidence of medium- and long-term changes in the physical dynamics in the northern Gulf of Alaska and Aleutian Islands. It is therefore reasonable to expect these changes to be reflected in observations of the broad-scale ecosystem and the biogeography of the regional fauna. Several studies have addressed these issues.

A nonlinear analysis of a multivariate data set also captures the pattern of decline of Steller sea lions. The data contained time series for such variables as annual salmon landings for five species and three regions in Alaska, rockfish and herring recruitment indices, herring biomass, and zooplankton biomass estimates for subregions of the Gulf of Alaska and Bering Sea. The main result is a pattern with all positive scores from 1965–1979 and all negative scores from 1980–2000.

Research cruises to the passes of the eastern and central Aleutian Islands revealed a number of



Nonlinear principal component (NLPC) analysis results from a multivariate data set of 45 biotic indices (fishery and survey records) that span broad regions over the Bering Sea, Gulf of Alaska, and North Pacific Ocean from 1965 to 2001. The top panel shows the first (and dominant) characteristic time series that emulates the pattern of sea lion decline and the 1976-77 climate shift. The bottom panel shows the second characteristic time series that exhibits interannual variability.

intriguing biogeographic features of the region that correspond to the population and dietary divisions of sea lions. Sharp fronts in surface salinity were found at Unimak and Samalga Passes that coincided with demarcation points for sea lion diets and population dynamics. Samalga Pass appears to be a boundary between shelf waters to the east and open-ocean waters to the west, with the Alaska Coastal Current influencing the waters east of the pass and the Alaskan Stream water influencing the waters farther west. The difference in source waters in the two regions likely affects the distributions of nutrients and biota around the different passes.

Changes in the abundance and composition of zooplankton species are associated with seasonal changes in water mass and other physical properties along the island chain. Declines in the abundance of *Neocalanus plumchrus* and *N. flemingeri* at Akutan and Unimak Passes in June resulted as these species left the surface waters and migrated down to depths over 300 m. Elevated abundances of *Calanus marshallae* and *Acartia* spp. at Umnak, Akutan, and Unimak Passes were due to their preference for warmer neretic conditions. Abundances of two species of euphausiid along the islands showed a preference by *Thysanoessa inermis* for the neretic waters of Akutan, Unimak, and Samalga Passes and a preference by *Euphausia pacifica* for the open-ocean conditions of the passes west of Samalga Pass.

In addition to zooplankton and fish, the western extent of the Alaska Coastal Current also operates as a biogeographical "boundary" for seabirds around Samalga Pass. Seabirds depending on coastal food webs (shearwaters and puffins) are more abundant east of Samalga, whereas seabirds depending on oceanic food webs (fulmars and auklets) are more abundant west of Samalga. Fulmars and shearwaters consume oceanic copepods and shelf-break species of euphausiids west of Samalga, while both of these seabirds consume shelf species of euphausiids east of Samalga.

At-sea surveys of seabirds during cruises in 2001 and 2002 showed large-scale patterns of avifauna that suggest that the central and western Aleutian Islands support the vast majority of breeding seabirds dependent on oceanic zooplankton, whereas the eastern Aleutian Islands support the majority of piscivorous seabirds. These data support the premise that the eastern Aleutians provide a very different habitat than regions of the archipelago west of Samalga Pass. At smaller spatial scales, the passes of the Aleutian Islands are the focal points of much seabird foraging activity.

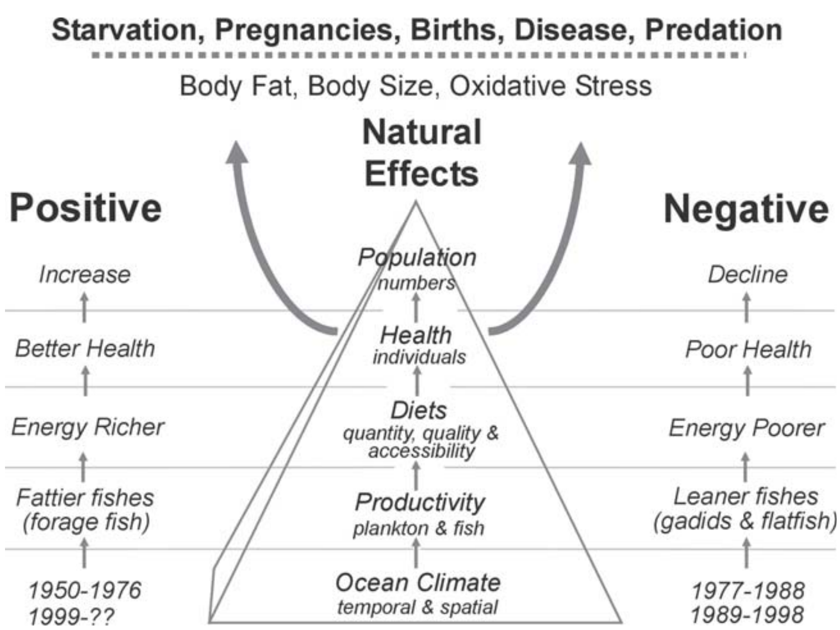
Changes in the benthic and pelagic fish communities within the Gulf of Alaska and Aleutian Islands in response to the regime shift of 1976 were dramatic. Population increases occurred in flatfish, gadids, and salmonids as a result of an increase in the frequency of strong year classes after 1976. At around the same time, decreases occurred in shrimp and crab stocks. Small-mesh trawl surveys conducted near Kodiak Island between 1953 and 1997 documented the "community reorganization" in the Gulf of Alaska. The catch composition of the trawl catches in this survey prior to 1977 was dominated by forage species such as capelin and shrimp. Following the regime shift, the catches were primarily high-trophic-level groundfish.

Further up the food chain, concurrent changes were also noted in the few populations of marine mammals that have been counted since the 1960s and 1970s. At Tugidak Island, for example, the largest population of harbor seals in Alaska began an unexplained decline in the mid-1970s, falling to less than 20% of its peak abundance by the mid-1980s. Steller sea lions numbers at the nearby rookery on Chowiet Island also fell rapidly through the 1980s. Similarly the Pribilof Islands population of northern fur seals, which accounts for about 80% of the world population, also declined unexpectedly from the late 1970s to mid-1980s. All three populations of pinniped species appear to have declined at about the same time, coincidental with the 1976-77 regime shift.

These broad-scale ecological changes across all trophic levels are generally coincident in time and are widely believed to be driven by differences and changes in the oceanic environment. This is not to say that the other primary force affecting fish populations (fishing) is without impact. Fishing can, and does, affect community dynamics. The effect of fishing is added to natural sources of variability. Archaeological studies have repeatedly demonstrated wide swings in the abundance of fish species long before the development of large-scale fisheries. Generally, fishing impacts the adult portion of fish populations. An important link between climate and population size occurs at the larval and juvenile stages for many marine animals. Making the transition from egg (marine fishes) or smolt (salmon) to successful recruit requires oceanic and ecological conditions conducive to survival. Under the regime-shift hypothesis, certain species are favored under one set of ocean conditions while other species flourish when conditions change abruptly.

The effects of broad-scale changes in ocean climate on Steller sea lion habitat appear to be moderated through a number of indirect mechanisms. For example, increased storm activity might have reduced the suitability of certain haulouts and rookeries, while bottom-up effects mediated through at least three trophic levels (such as phytoplankton, zooplankton, and forage fish) have the potential to affect the distribution of Steller sea lion prey species. In light of the spatial distributions of different species in the food web, and the potential foraging distances of individual sea lions, further range-wide studies encompassing areas of both decreased and increased habitat suitability will be required to fully elucidate the effects that changing climate can have on apex predators.

Conceptual model showing how regime shifts might have positively or negatively affected sea lion numbers through bottom-up processes that influenced suites of species and subsequently affected sea lion health and numbers.



In summary, a suite of changes occurred across all trophic levels of the Gulf of Alaska and Aleutian Islands ecosystems that corresponded to the timing of the 1976-77 regime shift and the decline of Steller sea lions in the western Gulf of Alaska and Aleutian Islands.

The detailed regional influences of these climate changes are difficult to pinpoint among the sparsely observed populations, but they appear to be modulated by the effects of biogeographic features such as the Samalga Pass transition from coastal influence to open-ocean conditions and the fine structure of island distributions. These transition points delineate distinct clusterings of prey species, which are in turn correlate with differential population sizes and trajectories of Steller sea lions. The results support the idea that a fundamental change in the ecosystem occurred after the mid-70s, which may have cascaded up through the food web to influence the regional diets and health of sea lions. Other studies suggest that such changes were not unique to the 20th century.

Paleoecological Perspective

Paleoecological studies provide a long-term perspective on changes seen in recent decades. Indicators of oceanic productivity in two sediment cores, one from the central Gulf of Alaska shelf and one from the Bering Sea (Skan Bay), showed that considerable variability has occurred in ocean productivity over the last 150 years for each region. In the Gulf of Alaska, two productivity proxies increased since the 1976-77 regime shift, while the two proxy signals were mixed in the Bering Sea. The Bering Sea data imply significant changes in the phytoplankton community. Such changes in productivity could have affected the flow of energy up the food web and altered the favored species upon which Steller sea lions feed. This paleoecological record averages out seasonal changes, which may be an important effect in addition to total productivity. The regional differences in the paleoecological records may be important in explaining regional differences in the numbers and diets of Steller sea lions.

Long-term changes in the North Pacific and southern Bering Sea ecosystems have also been the subject of intensive investigations using archaeological and anthropological data. The archaeological data indicate that significant variations occurred in the distributions of key species over the last 5000 years. Correlations between changes in the relative abundances of species such as Steller sea lions and regional climatic regimes are only suggestive at this time, with cooler periods having near-average harvests of sea lions by Aleuts and warmer periods having below-average harvests. Notably, the greatest abundance of Steller sea lions occurred during the Little Ice Age, which may be significant. The end of the Little Ice Age also appears to have coincided with a reduction in Steller sea lion populations.

Decadal-scale changes in the marine ecosystem spanning nearly 150 years are identifiable using both ethnohistoric data and traditional ecological knowledge of local Aleut fishermen. Based on Russian and early American accounts of the region, there have been two periods in the last 250 years—one in the 1870s, coinciding with a warming period as observed in the Sitka air temperatures, and another in the 1790s—when there were few or no Steller sea lions in many areas of the North Pacific, leading to widespread starvation for the indigenous peoples who depended on them. These depressions in the population levels cannot be correlated with any human-based harvesting of either the sea lions or their food sources.

Traditional knowledge of local fishermen indicates that the North Pacific ecosystem underwent a series of disruptions over the last 100 years that may or may not have been caused by commercial fishing. For example, the North Pacific was heavily fished for cod between the 1880s and the mid-1930s, when the fishery collapsed. Cod appear to have been completely absent in many areas south of the Alaska Peninsula between 1945 and 1970, during which time shrimp and crab were dominant components of the ecosystem. The extent to which these changes were mitigated by predator–prey interactions, fishing, or changes in ocean climate is not known. However, it is interesting that the Aleut term for codfish can be rendered into English as "the fish that stops," meaning that it disappears periodically. It is also noteworthy that the major shifts in species abundances line up reasonably well with the major documented regime shifts recorded over the past century.

In summary, the archaeological and anthropological analyses provide data on time scales that are currently not available in any other form of analysis. They demonstrate that the North Pacific and southern Bering Sea have been dynamic and volatile and subject to great fluctuations over the last hundreds to thousands of years. This requires careful evaluation of current models to determine where sea lion populations are currently positioned within the large-amplitude swings in population sizes that are evident from the past. The results also provide additional evidence that climate may very well underpin ecosystem restructurings that can be manifest as large, regional changes in Steller sea lion abundance.

Summary

We examined the hypothesis that the decline of the Steller sea lion populations in the Aleutians Islands and Gulf of Alaska is a consequence of physical oceanographic changes caused by the 1976-77 climate shift. The available data suggest that ocean climate can affect the survivorship of key species of prey consumed by Steller sea lions. It is therefore conceivable that a change in climatic conditions following the 1976-77 regime shift may have enhanced the survivorship and distribution of leaner species of prey (such as pollock, flatfish, and Atka mackerel), which in turn negatively affected the survival of young sea lions from 1977 to 1998. Thus, physical environmental changes could have had consequential effects on the health and fecundity of Steller sea lions. Higher temperatures appear to be associated with an increased abundance of cod and pollock, while a return to cooler temperatures would favor Steller sea lions.

In broad terms, the suite of studies that have been undertaken to investigate the temporal and spatial differences in ocean climate in the North Pacific have identified ocean climate patterns that are consistent with the patterns of sea lion distributions, population trends, numbers, and diets. The oceanic response to climate forcing after 1976-77 has an east–west asymmetry, with stronger changes occurring in the western Gulf of Alaska. The geographic clustering of sea lion diets and population trajectories, and their correspondence with key biogeographic and oceanographic features of the Gulf of Alaska and Aleutian Islands, add credence to the view that there is a linkage between Steller sea lions and the physical environment. However, additional studies will be required on finer spatial scales to draw firmer conclusions, particularly in regions closer to shore, where sea lions spend more time foraging.

Our assessment of the ocean climate hypothesis does not discount the other leading hypotheses that have been proposed to explain the decline of Steller sea lions, such as the nutritional stress hypothesis, the fishing hypothesis, the disease hypothesis, and the killer whale predation hypothesis. Instead, the ocean climate hypothesis provides a holistic framework within which each of the alternative hypotheses can be aligned.

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Status of Alaska Groundfish Stocks

This article was prepared by Anne B. Hollowed and James N. Ianelli, of NOAA's National Marine Fisheries Service.

The Alaska Fisheries Science Center of the National Marine Fisheries Service produces stock assessments for major groundfish and shellfish stocks in the Alaskan waters on an annual basis. Stock assessment and fishery evaluation reports are prepared for the North Pacific Fishery Management Council meetings and use the assessments to recommend levels of acceptable biological catch (ABC).

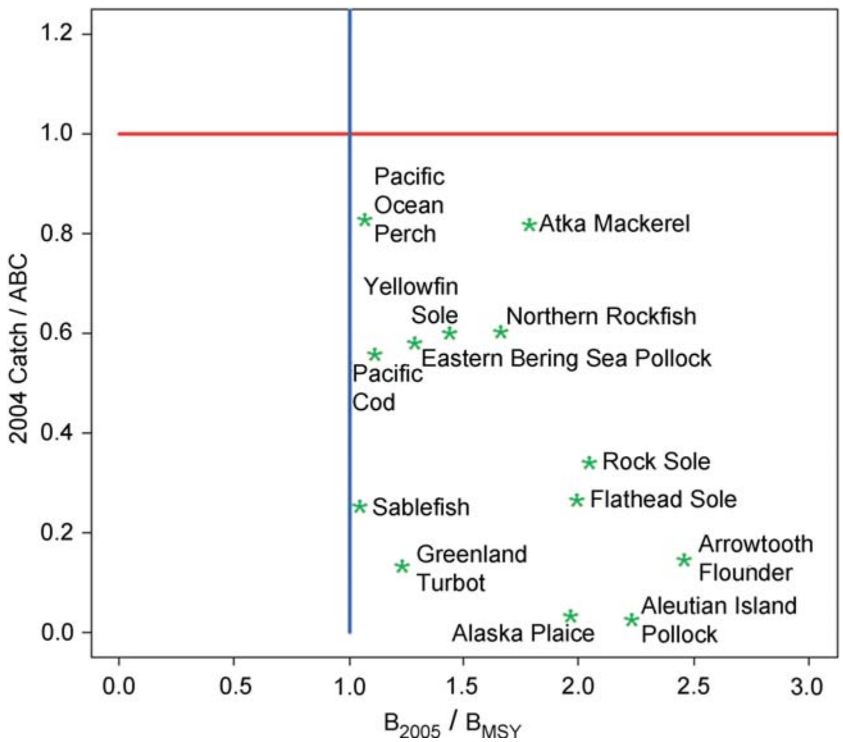
The Alaska groundfish management system is based on extensive data available from the National Marine Fisheries Service observer program and dedicated research cruises. Catches of target and prohibited species (such as salmon, crab, herring, and Pacific halibut) are estimated at sea or in processing plants to provide real-time information to ensure that fisheries do not exceed total allowable catches (TACs) or violate other fishery restrictions (such as time–area closures). Dedicated research cruises coupled with observer data make it possible to build detailed population dynamics models. The results of these modeling activities are used to determine the status of individual species.

The first step in determining the TAC begins with the preparation of stock assessment and fishery evaluation reports. These reports contain analyses summarizing the information about the individual stocks and groups and include ABC and overfishing level (OFL) recommendations for future years. The authors of these reports (generally National Marine Fisheries Service scientists) present their findings to the North Pacific Fishery Management Council's groundfish Plan Teams each September and November. At these meetings the reports are reviewed and recommendations for ABC levels are compiled into two stock assessment and fishery evaluation report volumes (one each for the Bering Sea/Aleutian Islands and the Gulf of Alaska regions). In addition, the Plan Team recommendations for ABCs are presented. The compiled reports are then submitted to the North Pacific Fisheries Management Council's Scientific and Statistical Committee for further review. This committee makes the final ABC recommendation to the Council, and the Council's Advisory Panel of industry representatives makes TAC recommendations. Finally, the recommended TAC levels are adjusted (for some species) by the Council to ensure that other constraints (for example, limiting the sum of all allowable catches in the Bering Sea and Aleutian Islands to be less than 2 million tons) are met. The following rule applies for all federally managed groundfish species in a given year: Catch $\leq$ TAC $\leq$ ABC $<$ OFL.

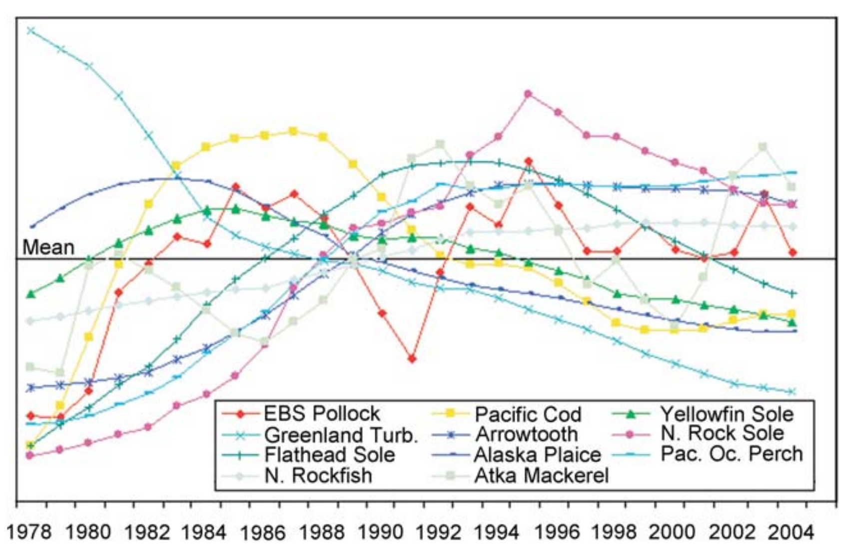
In practice, catch is often much less than the TAC, and the TAC is often much less than the ABC. The multispecies management system is, therefore, based on the premise that no individual components are overfished or below stock sizes that are considered detrimental to the ecosystem. Stock assessments can be obtained at www.afsc.noaa.gov/refm/stocks/assessments.htm.

A change in the timing requirements for conducting assessments was implemented in 2004. Based on an analysis conducted by scientists at the NOAA Alaska Fisheries Science Center in coordination with the NOAA National Marine Fisheries Service's Alaska Regional office, it was found that for longer-lived species, management advice on quotas could be based on biennial assessments. This cycle was designed to coincide with the current Alaska Fisheries Science Center survey regularity.

Presently, the main species of groundfish are all above their target stock size, and 2004 catch levels were below the maximum permissible ABC levels. During 2001–2003, fisheries for these groundfish species yielded 2.1 million metric tons annually, valued at $615 million. The abundances of the major stocks of Alaska pollock and Pacific cod are high but subject to variability because of recruitment fluctuations. Virtually all flatfish resources (for example, rock sole, yellowfin sole, Alaska



Relative 2005 spawning stock size compared to the target stock size versus relative 2004 catch levels compared to 2004 maximum permissible Acceptable Biological Catch (ABC) levels for Bering Sea–Aleutian Island stocks. Values below the red line indicate that the catch levels in 2004 are less than the ABC estimated for that year. Values to the right of the blue line indicate that the spawning stock biomass projected to 2005 is greater than the level that would theoretically provide the MSY (maximum sustainable yield).



Biomass trends for Bering Sea and Aleutian Islands stocks relative to their mean level, 1978–2004.

plaice, and arrowtooth flounder) are at high and healthy levels. Atka mackerel abundance is increasing and above average levels. Rockfish species comprise 5–8% of the groundfish complex biomass and are at healthy and stable levels. For the main stocks with age-structured analyses, the biomass trends for the Bering sea and Aleutian Islands regions suggest that stock conditions are fairly evenly split between those that are above average and those that are below in the past few years.

Data limitations make it difficult to assess less-abundant (minor) rockfish species. Together with other non-target species (such as sharks, skates, sculpins, and octopus), accurately assessing the vulnerability of these species represents a major challenge for NOAA. Efforts to monitor the status of non-target species have improved, and steps have been taken to ensure that adequate data collection programs are in place in advance of directed fishery development.

Status of Alaska's Salmon Fisheries

This article was prepared by William R. Heard, of NOAA's Alaska Fisheries Science Center, Auke Bay Laboratory, Juneau, Alaska; and Loh-Lee Low, of NOAA's Alaska Fisheries Science Center, Resource Ecology and Fisheries Management Division.

Pacific salmon have played a pivotal role in the development and history of Alaska. Many Alaskans still depend on salmon for recreation, food, and employment. The fishing industry has provided Alaska with its largest private sector employment, and subsistence use of salmon is still an important part of the life of rural Alaskans.

Monitoring the status of salmon involves measuring salmon run sizes, including both catch and escapement information. However, other factors are also used to measure the well being of salmon stocks, such as fish sizes, fish quality, disease and infestations, and run timing. All of these characteristics are difficult to quantify and standardize. Even run size data (particularly data on escapement sizes) are hard to obtain because the salmon escapement routes into different river systems are usually not well known. The primary goal of salmon management is to allow adequate escapement so that spawning and replenishment of the salmon stock will occur. Thus, the yearly variation of salmon catch, after allowing escapement, may be used as the most consistent measure of the status of salmon stocks.

Spawning salmon.

Overall Harvest Levels

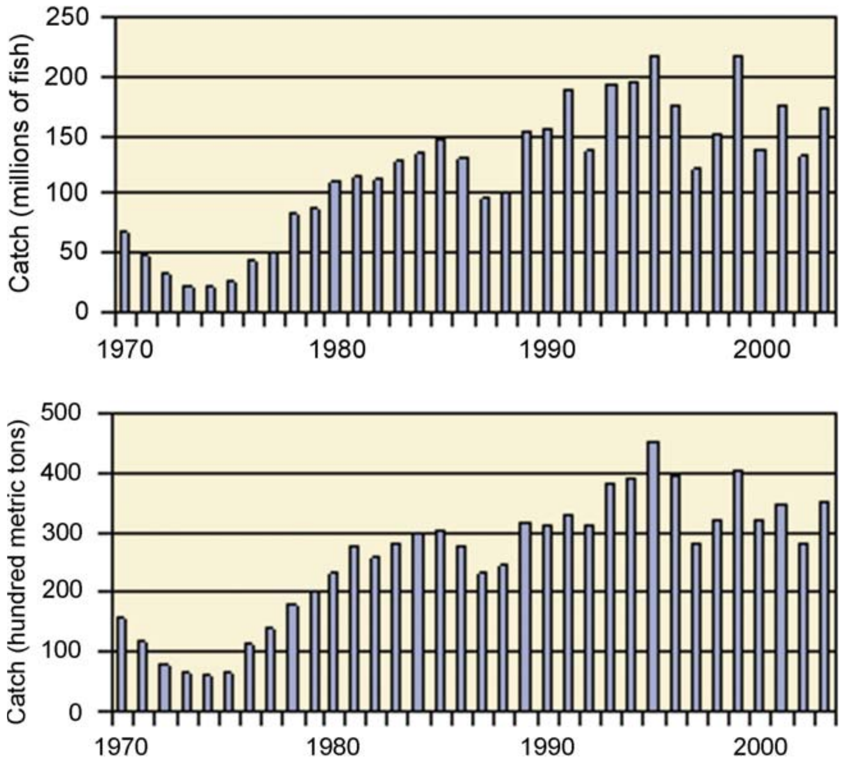
Alaska commercial salmon harvests have generally increased over the last three decades. After reaching record low catch levels in the 1970s, most populations have rebounded, and fisheries in recent years have been at or near all-time peak levels in many regions of the state. The record-high commercial landing of 218 million salmon in 1995 was 17% higher than the previous record of 196 million in 1994. Throughout the mid- to late 1990s, recreational and subsistence fishermen harvested 2–3 million salmon annually.

Significant declines in commercial catches during the three years following the peak harvest in 1995 were thought by many to indicate that a major downturn in productivity of Alaska salmon might have started. The history of commercial landings shows a distinct cyclic pattern of high and low harvest levels often lasting decades. Much of this fluctuation is now believed to be caused by interdecadal climate oscillations in the ocean environment that affect the marine survival of juveniles. A major climatic regime shift that occurred in 1977 helped Alaska stocks rebound from the previous low-cycle years, while another regime shift in 1989 may portend a future downward trend in Alaska's salmon resources.

An interesting correlation associated with Alaska's cyclic salmon harvest is an inverse production regime with abundance levels of West Coast salmon. Recent increases in the numbers of West Coast salmon, therefore, may also suggest a declining trend for Alaska salmon. However, the correlation is still debatable. Alaska's commercial catch did decline for three years after the record 1995 harvest, but it rebounded to 217 million fish in 1999, essentially matching the peak harvest year catch. Landings in 2000 fell to 137 million salmon, increased to 175 million fish in 2001, dropped to 131 million in 2002, and then increased to 173 million in 2003. All of these recent Alaska harvests were well above the long-term norm for Alaska, while West Coast salmon runs have continued to rebound from their lows.

A number of factors have contributed to the current high abundance of Alaska salmon:

- Pristine habitats with minimal impacts from extensive development;



Alaska salmon catch of all species combined, in numbers of fish and in metric tons.

- Generally favorable ocean conditions that allow high survival of juveniles;
- Improved management of fisheries by state and Federal agencies;
- Elimination of high-seas drift-net fisheries of foreign nations;
- A well-managed hatchery production system; and
- Reductions of salmon bycatch in fisheries for other species.

Management

Alaska's 44,000-mile coast is nearly two-thirds the length of the coastline of the United States. Along the Alaska coastline, over 14,000 water bodies support populations of five species of salmon. Salmon management over such a vast area requires a complex mixture of domestic and international bodies, treaties, regulations, and other agreements. Federal and state agencies cooperate in managing salmon fisheries. The Alaska Department of Fish and Game (ADF&G) manages salmon fisheries within state jurisdictional waters, where the majority of the harvest occurs. ADF&G's principal salmon conservation policy uses escapement-based management, providing adequate spawning escapement into natal streams over any preseason harvest goals. Management in the Exclusive Economic Zone (EEZ), 3–200 nautical miles offshore, is the responsibility of the North Pacific Fishery Management Council (NPFMC), which has deferred specific regulations to the State of Alaska. Management of Alaska's salmon fisheries is based primarily on regional stock groups of each species and on time and area harvesting using specific types of fishing gear.

Over 25 commercial salmon fisheries in Alaska are managed by a special limited-entry permit system that specifies when, where, and what type of fishing gear can be used in each area of the state. The commercial gear used includes drift gillnets, set gillnets, beach seines, purse seines, hand troll, power troll, or fish wheel harvest gear. Sport fishing is limited to hook and line, while subsistence fishers may use gillnets, dip nets, or hook and line. Some subsistence harvesting of salmon is also regulated by special permits, and in some rivers, fish wheels can be used for subsistence fishing.

Management of some Alaska salmon fisheries is also negotiated with Canada under the Pacific Salmon Treaty. Some major issues of concern occur in Southeastern Alaska, while others occur in the Yukon River area.

On a broader international scope, the management of salmon harvest in the high seas of the North Pacific Ocean from 1957 to 1992 was authorized by the International North Pacific Fisheries Commission (INPFC) and via bilateral and multilateral agreements and negotiations with Taiwan and the Republic of Korea. In 1993 the North Pacific Anadromous Fish Commission (NPAFC) was formed to replace the INPFC. Membership of the NPAFC has now expanded from the original three countries (Canada, Japan, and the U.S.) to include the Russian Federation and the Republic of Korea.

The NPAFC Convention prohibits high seas salmon fishing and trafficking of illegally caught salmon. Coupled with United Nations General Assembly Resolution 46/215, which bans large-scale pelagic driftnet fishing in the world's oceans, legal harvesting of Pacific salmon on the high seas no longer exists. This allows for effective management control to fully return to the salmon-producing nations.

Because salmon are anadromous species that spend up to seven years of their lives at sea and then return to freshwater streams, rivers, and lakes to spawn and die, the well-being of salmon in Alaska, in addition to harvest management practices, is also directly influenced by land management practices. The quality of freshwater habitats determines the success of reproduction and initial

Alaska Salmon Catch by Species in Numbers of Fish, 1970–2003.

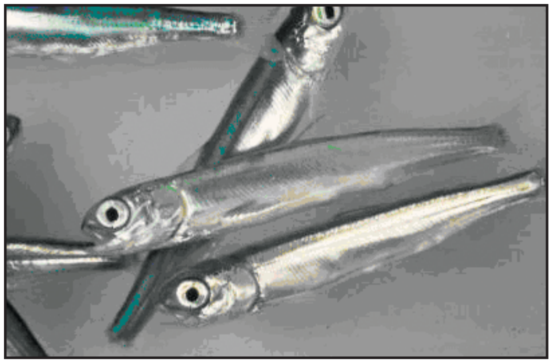
Year	Pink Salmon	Sockeye Salmon	Chum Salmon	Coho Salmon	Chinook Salmon	Total
1970	31,096,000	27,622,000	7,476,000	1,524,000	645,000	68,363,000
1971	23,539,000	14,177,000	7,679,000	1,444,000	661,000	47,500,000
1972	15,913,000	6,999,000	6,655,000	1,834,000	554,000	31,955,000
1973	9,805,000	4,448,000	5,928,000	1,455,000	550,000	22,186,000
1974	9,857,000	4,789,000	4,698,000	1,860,000	559,000	21,763,000
1975	12,987,000	7,458,000	4,323,000	1,014,000	455,000	26,237,000
1976	24,755,000	11,779,000	5,924,000	1,432,000	531,000	44,421,000
1977	28,647,000	12,465,000	7,326,000	1,789,000	620,000	50,847,000
1978	53,852,000	18,140,000	6,677,000	2,821,000	836,000	82,326,000
1979	50,137,000	28,696,000	5,608,000	3,122,000	779,000	88,342,000
1980	63,304,000	33,295,000	9,603,000	3,115,000	675,000	109,992,000
1981	60,089,000	36,348,000	12,613,000	3,416,000	823,000	113,289,000
1982	64,859,000	28,954,000	10,994,000	6,040,000	877,000	111,724,000
1983	60,359,000	52,875,000	10,222,000	3,636,000	828,000	127,920,000
1984	76,343,000	38,450,000	13,096,000	5,405,000	667,000	133,961,000
1985	90,335,000	38,983,000	10,570,000	5,749,000	721,000	146,358,000
1986	77,320,000	32,208,000	12,510,000	6,293,000	616,000	128,947,000
1987	46,493,000	35,431,000	10,527,000	3,493,000	680,000	96,624,000
1988	50,358,000	30,038,000	15,105,000	4,473,000	589,000	100,563,000
1989	96,869,000	44,139,000	7,896,000	4,650,000	572,000	154,126,000
1990	88,208,000	52,693,000	8,010,000	5,478,000	666,000	155,055,000
1991	128,336,000	44,646,000	9,769,000	6,153,000	613,000	189,517,000
1992	60,597,000	58,283,000	10,223,000	7,095,000	606,000	136,804,000
1993	109,631,000	64,314,000	12,238,000	6,050,000	667,000	192,900,000
1994	116,720,000	52,816,000	16,135,000	9,551,000	640,000	195,862,000
1995	128,333,000	63,532,000	18,796,000	6,471,000	663,000	217,795,000
1996	97,310,000	50,270,000	21,856,000	6,150,000	500,000	176,086,000
1997	71,280,000	30,910,000	15,620,000	2,900,000	650,000	121,360,000
1998	104,770,000	22,720,000	19,070,000	4,680,000	580,000	151,820,000
1999	145,990,000	45,120,000	20,480,000	4,590,000	430,000	216,610,000
2000	74,800,000	33,500,000	24,290,000	4,200,000	360,000	137,150,000
2001	127,620,000	26,520,000	15,400,000	4,950,000	370,000	174,860,000
2002	87,310,000	22,211,000	16,210,000	5,059,000	584,000	131,374,000
2003	121,696,000	31,013,000	15,931,000	4,105,000	599,000	173,344,000

rearing of juveniles. Several entities have significant influence on the quality of freshwater spawning and rearing habitats for salmon throughout Alaska. Among these are the U.S. Forest Service, the Bureau of Land Management, the National Park Service, the U.S. Fish and Wildlife Service, Alaska state parks and forests, Alaska Native regional and village corporations, municipalities, boroughs, and private landowners that control watersheds used by salmon.

Species and Status

All five species of Alaska salmon—pink, sockeye, chum, coho, and chinook—are fully utilized, and stocks in most regions of the state generally have rebuilt to near or beyond previous high levels. Although in recent years there has been a high statewide abundance of salmon in Alaska, there are also issues of serious concern for these resources, especially with some species in certain regions. For example, stocks in western Alaska, especially chinook and chum salmon, generally have been at very depressed levels since the mid-1990s. Also, some of the same factors affecting declines of salmon in the Pacific Northwest—issues associated with overfishing, incidental take as bycatch in other fisheries, and losses of spawning and rearing habitats in freshwater and in near-shore ocean environments—are of concern in some areas of Alaska.

Recreational fishing for salmon continues to grow and is an important component of the Alaskan lifestyle. This is partly because many Alaskan



Pink salmon fry.

households use sport fishing as a convenient method to collect seafood for the table. Some part of the total sport fish harvest of salmon in Alaska, therefore, might more appropriately be included in subsistence fishery statistics. Much of the recent growth in sport fishing is because of increased guided recreational fishing by tourists visiting Alaska. A total of 392,980 Alaska sport fishing licenses were issued in 2002, with 71% issued to nonresident anglers. More nonresident sport fishing licenses have been sold in Alaska than resident licenses since 1990. Sport fishing for salmon is a vital part of the recent rapid growth in Alaskan tourism. Coho salmon were the most popular sport-caught salmon in Alaska, representing 38% of the 3.2 million salmon caught by recreational fishermen in 2002, followed by pink salmon (25%), sockeye salmon (21%), chum salmon (7%), chinook salmon (5%), and non-anadromous landlocked salmon (4%).

Pink Salmon

Pink salmon are the most abundant of Pacific salmon in Alaska, accounting for 40–70% of the total harvest each year. During the past 33 years (1970–2003), pink salmon made up 58% of the average annual commercial harvest of salmon in Alaska. Pink salmon are harvested mostly in the southeastern, southcentral, and Kodiak Island regions of the state.

Unique among Pacific salmon, pink salmon have a fixed life-history cycle whereby the species always matures and spawns at two years of age. This cycle is genetically fixed, so spawners in even-numbered years are always separate and distinct from spawners in odd-numbered years.

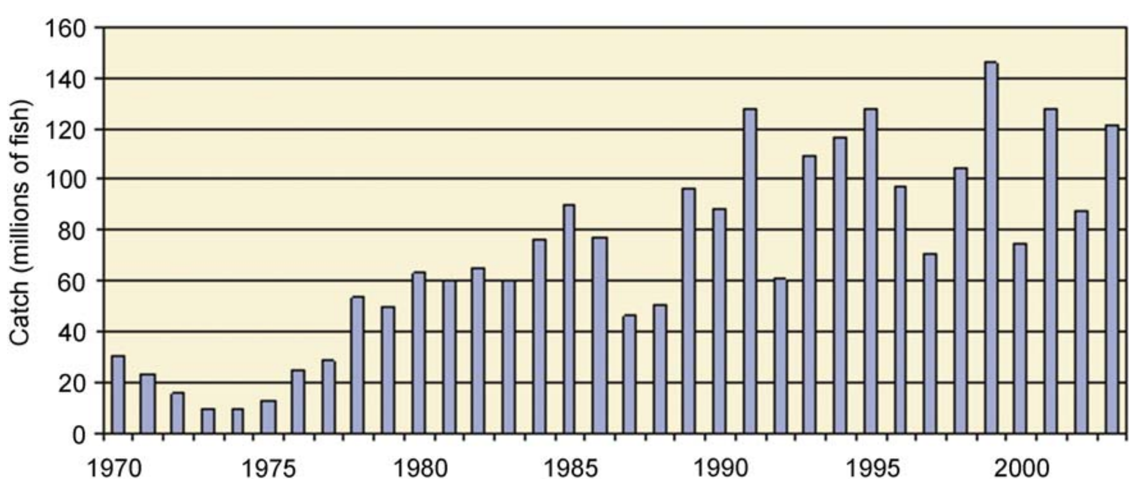
Throughout much of its range, the species has viable populations in both odd- and even-numbered years; however, in some areas, pink salmon only occur in one or the other cycle year. In Bristol Bay and western Alaska, for example, pink salmon, near the effective limit of their northern range, essentially occur mostly in even-numbered years, whereas in the Pacific Northwest, near the effective limit of their southern range, they occur primarily in odd-numbered years.

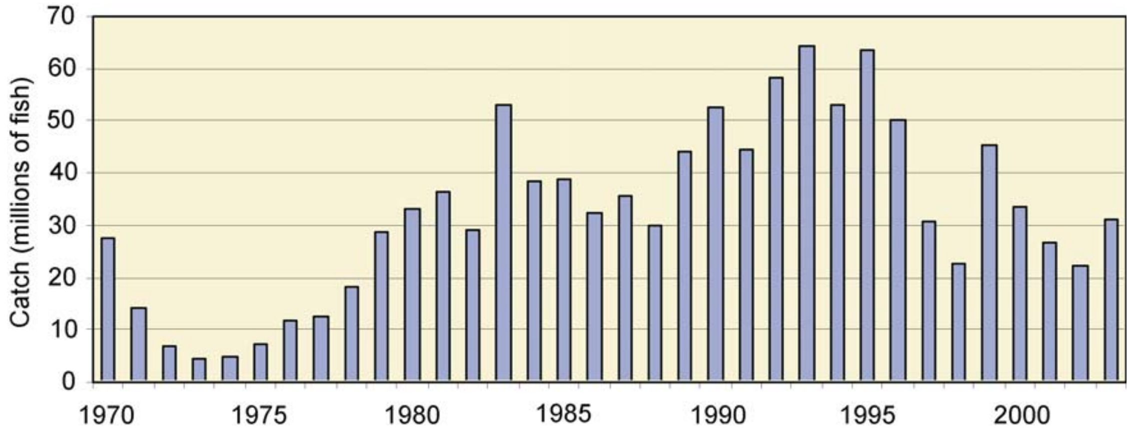
Sockeye Salmon

Sockeye salmon, second in abundance among species caught in Alaska fisheries, generally accounted for 27% of the harvest in recent years. Sockeye salmon, however, provide greater dollar value to fishermen than all other commercially caught salmon in Alaska combined, usually yielding 60–70% of the ex-vessel value of the annual harvest. In more recent years, however, world salmon prices have declined significantly but have rebounded a little in 2004.

The largest fisheries for sockeye salmon occur in Bristol Bay, Cook Inlet, the Alaska Peninsula and Aleutian Islands, and the Kodiak regions, but there are also significant fisheries for this salmon

Alaska pink salmon catch, 1970–2003.





Alaska sockeye salmon catch, 1970–2003.

in the southeastern, Prince William Sound, and Chignik regions.

The most common sockeye salmon life-history pattern is for juveniles to rear in lakes for 1–2 years before migrating seaward as smolts. The large lake complexes on Bristol Bay rivers provide this necessary life-history component and form a critical part of the important fishery in this region. The Bristol Bay fishery is concentrated in a narrow window of time from late June until mid-July, when millions of returning adult sockeye salmon pour into Bristol Bay rivers from the ocean.

During the five-year period from 1992 to 1996, returns to Bristol Bay ranged from 29.6 to 44.4 million and averaged 36.5 million sockeye salmon per year. The return to Bristol Bay in 1997, however, was only 18.9 million, with a fishery harvest of 12.1 million. This unexpectedly low return of sockeye salmon created a serious shortfall in the catch and in the incomes of fishermen and communities.

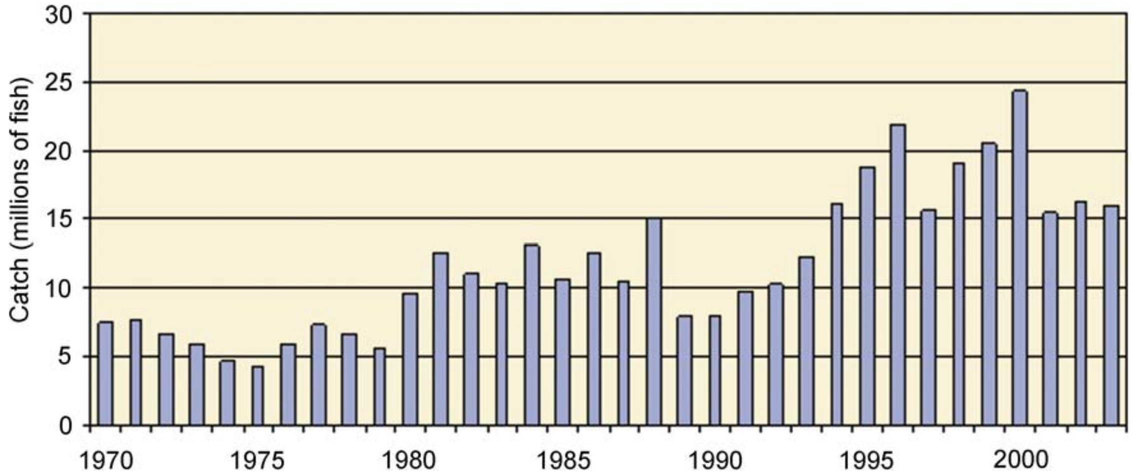
As bad as the 1997 sockeye salmon harvest in Bristol Bay was, commercial landings in 1998 were even worse, with a harvest of only 10.0 million fish. Returns improved somewhat in 1999 and 2000, with commercial catches of 26.1 and 20.5 million sockeye salmon, respectively, but more recently have declined again, with commercial catches of only 14.2, 10.7, and 14.9 million fish, respectively, in 2001, 2002, and 2003. All of these recent harvest levels of sockeye salmon in Bristol Bay are well below previous decadal averages.

Several hypotheses have been suggested to explain recent shortfalls of sockeye salmon returning to Bristol Bay. Unusually warm, calm weather during summers has resulted in high water temperatures, which may have caused high mortality and changes in the migration behavior of adult salmon entering Bristol Bay. Other suggested causes include changes in freshwater or ocean rearing conditions that affect the growth and survival of juveniles or immature adults, increased predation at sea, interception by other fisheries, disease, and, in some instances, over-escapements on spawning grounds. The true causes of these shortfalls, which likely involve a combination of many factors, remain unknown. A paramount unanswered question, however, is whether or not cyclic changes in oceanic environmental conditions have occurred that portend lower survival rates and smaller sockeye salmon returns to Bristol Bay in future runs.

Chum Salmon

Over the 33 years from 1970 to 2003, chum salmon have accounted for 10% of Alaska's salmon harvest. Over the past eight years (1996–2003), the average annual chum salmon harvest across Alaska was 18.6 million fish, with the 2000 harvest well above this average at a record 24.3 million fish. Currently 60–70% of the commercially harvested chum salmon in Alaska occur in the southeastern region, where hatcheries produce a significant portion of the catch.

Chum salmon runs in southwestern and western Alaska, similar to sockeye salmon in Bristol Bay, were well below long-term averages. Managing chum salmon fisheries in western Alaska is complicated by another commercial fishery at False Pass in the Aleutian Islands. Western Alaska chum salmon may spend part of their ocean life in the Gulf of Alaska. These salmon, as maturing adults on their return migration, funnel through Aleutian passes into the Bering Sea. The False Pass fishery, targeted primarily on sockeye salmon returning to Bristol Bay, must be managed so as to not overharvest chum salmon destined for the Kuskokwim and Yukon Rivers in western Alaska.



Alaska chum salmon catch, 1970–2003.

The Alaska Board of Fisheries has placed major restrictions on the False Pass fishery in an effort to help rebuild depleted chum salmon resources in western Alaska. Chum salmon in western Alaska not only are an important part of commercial fisheries in that region but are also a significant subsistence resource for local residents.

Coho Salmon

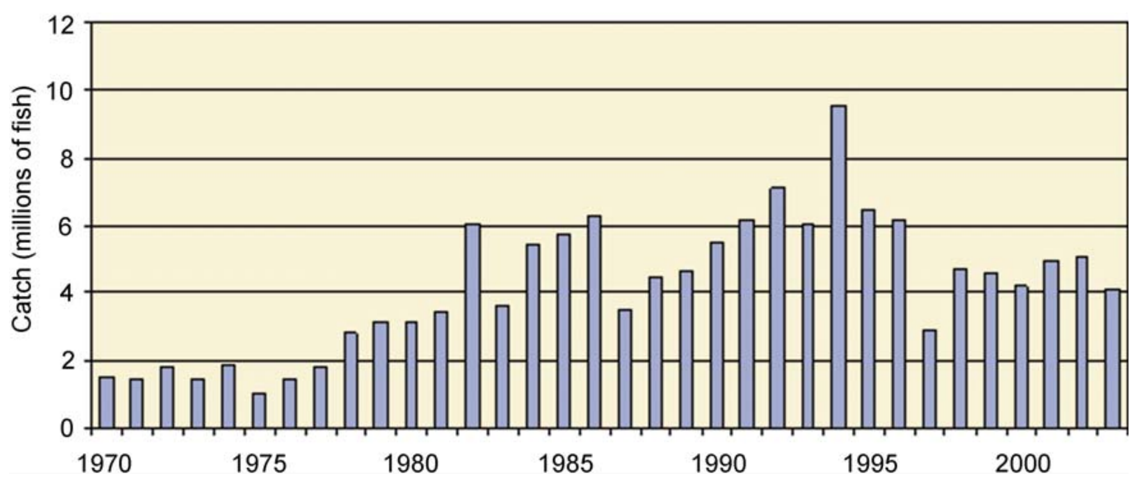
Commercial catches of coho salmon across Alaska in 2003 totaled 4.1 million fish, a half million less than the recent six-year average but still well above the record low catches of the 1970s. This relatively high commercial harvest was due to generally favorable returns in the southeastern region, where 3.0 million or more coho salmon from hatchery and wild stock production were caught in four out of the last six years. Coho salmon, along with sockeye and chinook salmon, are a popular target species in recreational fisheries throughout Alaska.

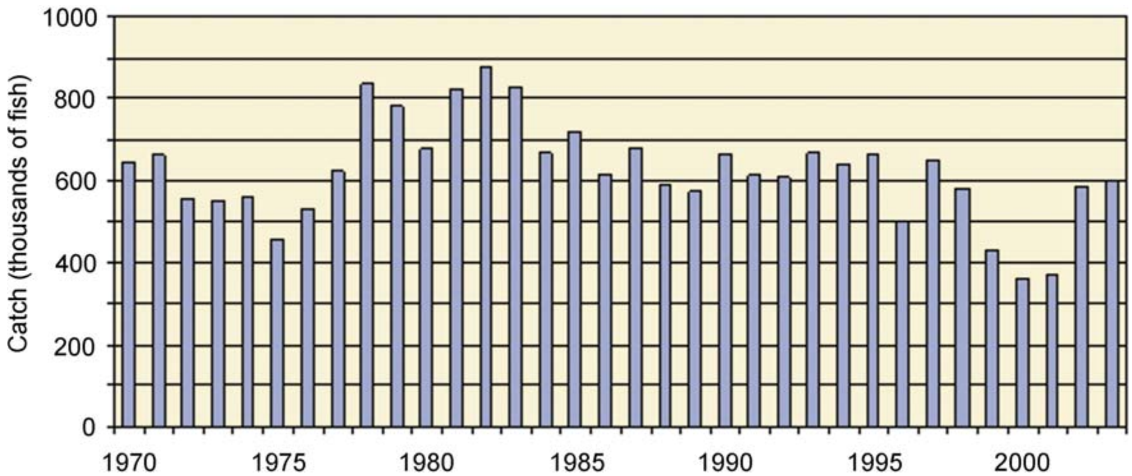
Chinook Salmon

The annual commercial harvest of chinook salmon in Alaska has ranged between 300,000 and 700,000 fish over the past two decades. The statewide 13-year (1991–2003) average annual harvest was 559,000 fish. In general, chinook salmon are the first species each year to begin spawning migrations into Alaskan rivers. Only in a few Bristol Bay and western Alaskan rivers are fisheries permitted to directly target these early returning runs of chinook salmon. However, in fisheries targeting other salmon, chinook salmon are often taken incidentally.

The region-wide chinook salmon harvest in southeastern Alaska, where significant numbers of non-Alaska-origin fish are caught, is normally regulated by a quota under provisions of the Pacific Salmon Treaty. This annual harvest quota is then re-allocated among various fisheries by the Alaska Board of Fisheries.

Alaska coho salmon catch, 1970–2003.





Alaska chinook salmon catch, 1970–2003.

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Russian–American Long-term Census of the Arctic

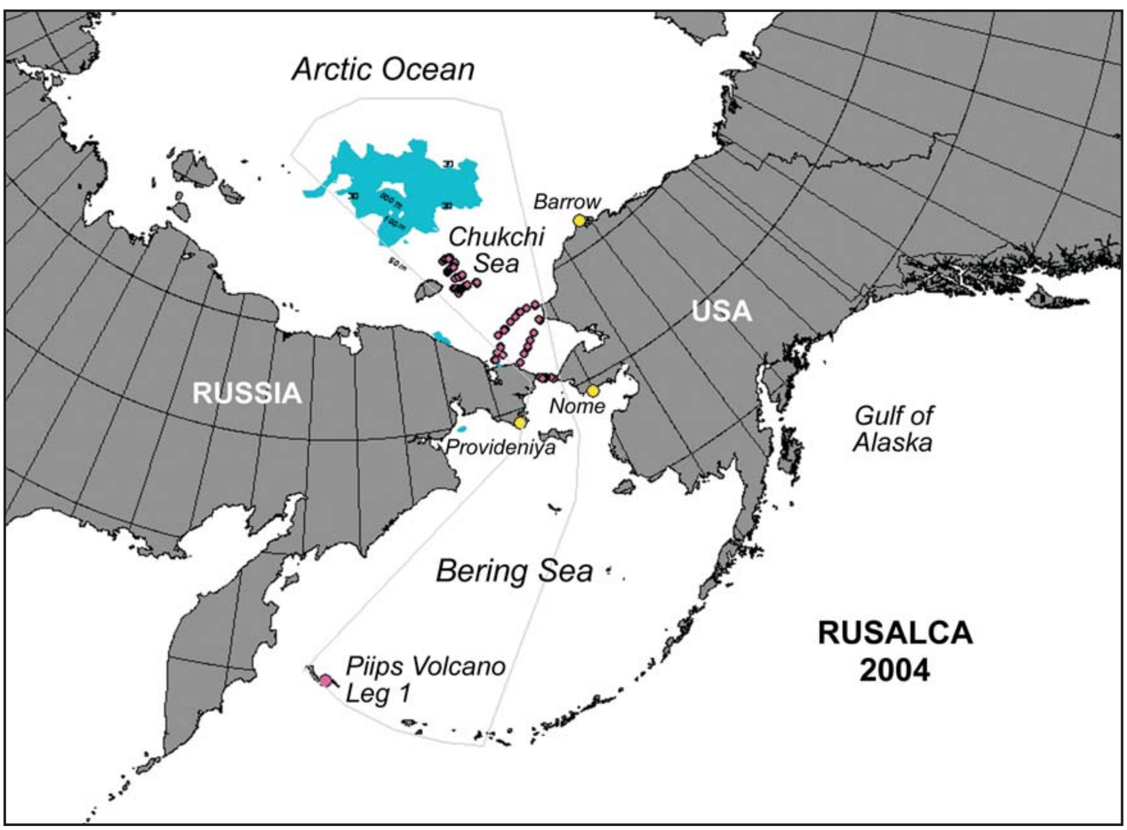
Initial Expedition to the Bering and Chukchi Seas

This article was prepared by Kathleen Crane, of NOAA's Arctic Research Office.

July 23, 2004, marked a historic day in Arctic research and exploration, as well as in Russian–U.S. relations. On this date the Russian research ship the *Professor Khromov* left Vladivostok, Russia, packed with U.S.- and Russian-funded scientists to begin a 45-day collaborative journey of exploration and research in the Arctic.

Stemming from a 2003 Memorandum of Understanding for World Ocean and Polar Regions Studies between NOAA and the Russian Academy of Sciences, this cruise was the first activity under the Russian–American Long-term Census of the Arctic (RUSALCA). RUSALCA means "mermaid" in Russian. In November 2003 a RUSALCA planning workshop was held in Moscow to outline the biological, geological, chemical, and physical oceanographic sampling strategies to be pursued in the Bering Strait and Chukchi Sea.

This initial cruise was a collaborative U.S.–Russian Federation oceanographic expedition to the Arctic seas regions shared by both countries: the Bering and Chukchi Seas. These seas and the life within are thought to be particularly sensitive to global climate change because they are centers where steep thermohaline and nutrient gradients in the ocean coincide with steep thermal gradients in the atmosphere. The Bering Strait acts as the only Pacific gateway into and out of the Arctic Ocean and as such is critical for the flux of heat between the Arctic and the rest of the world.



Stations undertaken during the voyage of the Professor Khromov*, a Russian research vessel engaged in the RUSALCA expedition. The colored area in the Arctic Ocean indicates a region of enhanced ice melting between 1970 and 2001.*

Vice-Admiral Lautenbacher (NOAA) and Vice-President Laverov (RAS) signing the Memorandum of Understanding between NOAA and the Russian Academy of Sciences.

Monitoring the flux of fresh and salt water and establishing benchmark information about the distribution and migration patterns of the life in these seas are also critical tasks that must be completed prior to the placement of a climate-monitoring network in this region.

The cruise was divided into two legs, which included sampling and instrument deployment in U.S. and Russian territorial waters. The cruise objectives were to support the U.S. interagency Study of Environmental Arctic Change (SEARCH) program and the NOAA Ocean Exploration Program.

Many Russian Federation agencies participated in the planning and execution of the RUSALCA 2004 mission. These included the Ministry of Defense, Roshydromet, the Ministry of Natural Resources, the Ministry of Science, and the Russian Academy of Sciences, the initial partner of NOAA. Group "Alliance," a private company registered in Moscow, Russia, facilitated the international agency support.

Leg 1: Piips Volcano

The first leg was in the Bering Sea, with the ship leaving Vladivostok, Russia, on July 23 and arriving in Nome, Alaska, on August 6. The U.S. chief scientist was Kevin R. Wood, of NOAA's Pacific Marine Environmental Laboratory. The chief of the expedition was Captain Vladimir Smolin, of the Ministry of Defense, Russian Federation.

Bordering the Bering Sea at its southern terminus with the Pacific Ocean is the Aleutian Volcanic Arc. Waters entering and exiting the Bering Sea from and to the Pacific Ocean transit through this arc and are most likely chemically and dynamically modified by their interaction with the intense hydrothermal activity resulting from the mid-water volcanoes. Quantifying the flux from this relatively shallow volcanic arc and its influence on the waters and atmosphere above are important factors when considering the relationship between earth processes, the ocean, and greenhouse gas exchanges.

Russian Federation scientists have explored this region in the past. However, this was the first opportunity for scientists from the U.S. and Russia to work together to map the volcanic features and search for fluxes of methane, mercury, and other hydrothermal fluids and gases.

The first leg of the RUSALCA expedition focused on the hydrothermal activity and related geological and biological processes associated with the Piips volcano, which lies at a depth of 300 m in the southern part of the Komandorskaya depression of the western Aleutian Arc.

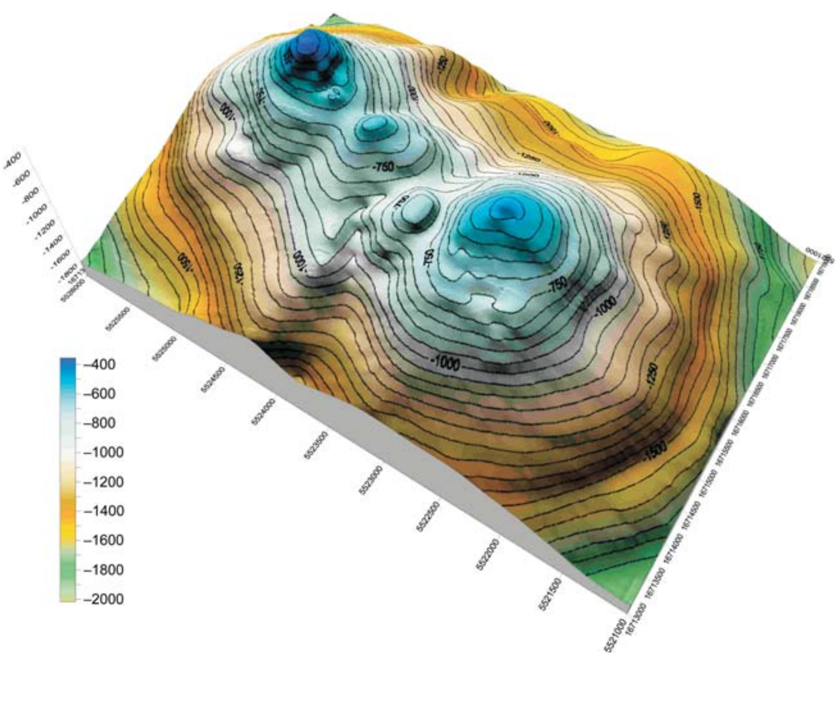
Russian marine geologists discovered the Piips hydrothermal field in 1987. Temperatures of up to 130°C were measured, and hydrothermal deposits composed of sulfates, carbonates, amorphous silica, and other materials were discovered. In addition, large fields of bacterial mats and numer-

Dirty ice near Herald Island, as seen from the Khromov. *Arctic scientists are continuously finding new and interesting, sometimes even alarming, information about changes in the sea ice over time.*

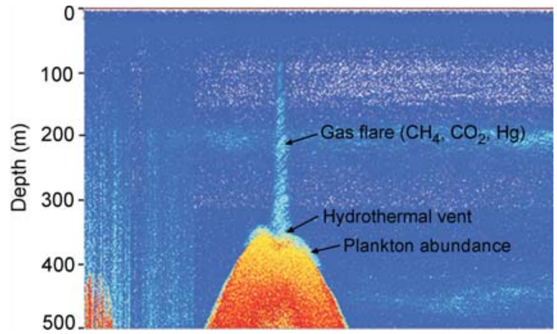
Starfish from the Russian waters of the Bering Strait.

ous hydrothermal fauna were detected. However, very little is known about the influence of hydrothermal activity on the regional biochemical and physical environment of the neighboring ocean.

During the RUSALCA expedition, the combined Russian side-looking sonar–CTD–methane sensors were lowered over the volcano. However, upon retrieval after the second launch, the sonar was lost at sea. Atmospheric monitoring of mercury along this leg from Vladivostok revealed high con-



Bathymetry of the Piips volcano.



Gas plume venting from the Piips volcano .

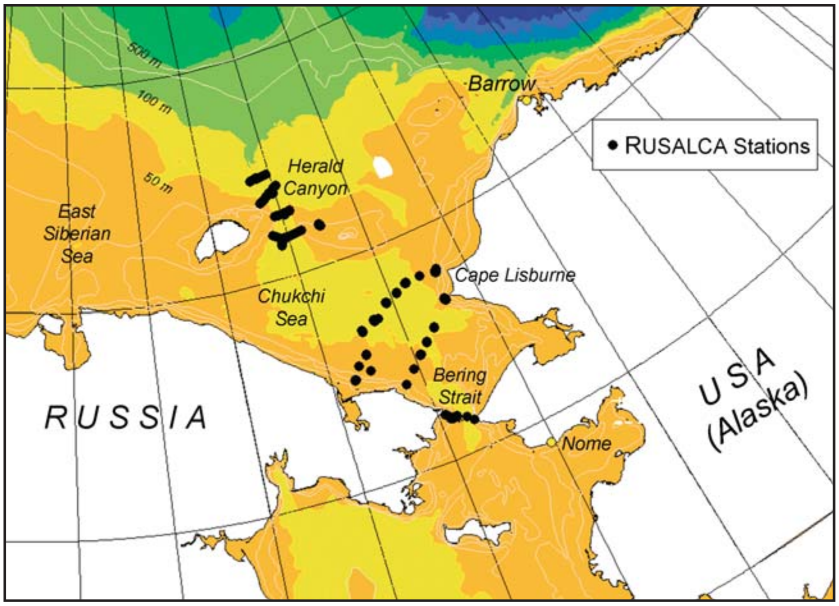
centrations near the Asian coastline and again over the volcano. Because of the relatively shallow depth of the volcano, the data suggest that mercury is released to the water column and the atmosphere above as a result of vigorous hydrothermal activity at this site.

Leg 2: Bering Strait through the Herald Canyon

The second leg was in the Chukchi Sea, leaving Nome, Alaska, on August 8 and returning to Nome on August 24. The U.S. chief scientist was Dr. Terry Whitledge, of the University of Alaska. The chief of the expedition was Captain Vladimir Smolin, of the Ministry of Defense, Russian Federation.

Because of the reduction of ice cover in the Arctic and the possibility of permanent loss of the seasonal ice cover in the Chukchi Sea study region as shown by climate models, it is thought that this area might be subject to significant ecosystem change. A program of ecosystem-oriented exploration was planned for Leg 2 of the RUSALCA expedition to provide a foundation for detecting future ecosystem indicators of climate change.

Twelve scientific programs examined benthic processes, a census of Arctic zooplankton, biodiversity of adult and juvenile fish, nutrient and primary productivity, marine chemistry, physical oceanography, microbial reactions and fluxes, side-looking sonar and video imagery of the seafloor, paleoceanography, and atmospheric contaminants. The primary study area lay between Wrangel Island and Herald Canyon in Russia Federation territorial waters to Cape Lisburne in Alaska to Point Barrow and south to the Bering Strait. A series of hydrographic transects were taken to allow sampling of all water masses during this summer period. A high priority of the hydrographic survey was to collect samples across the Bering

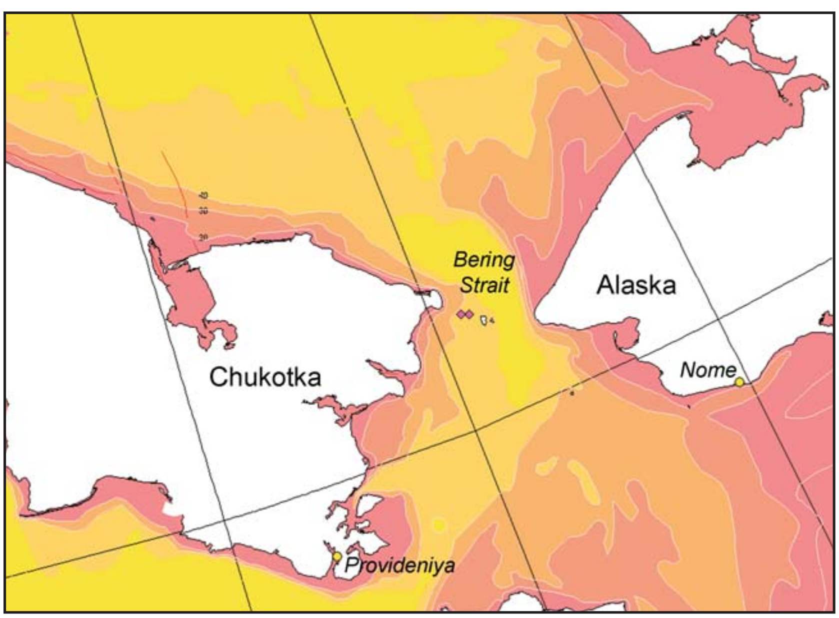


RUSALCA Leg 2 station locations.

Strait in support of the Russian and American moorings in the western Bering Strait, to collect a series of high-speed CTD transects across Herald Canyon, and to enhance the knowledge of faunal distributions for the Arctic census of marine life. The long-term goal in this region is to obtain continuous and comprehensive monitoring within the Bering Strait for several years, which will require routine access to the eastern and western portions of the study area for scientific operations.

High-density CTD stations also examined the role, rates, and rhythms of Pacific water transport through the Herald Canyon and analyzed the dispersion of this water into the greater high Arctic beyond. Until recently the transport pathways of water into and out of this region have been only poorly mapped. The degree to which these waters mix with newly invasive Atlantic waters over the Chukchi Plateau and the Mendeleev and Canada Basins is also not well known. Understanding these physical pathways and the consequent nutrient pathways is critical for mapping the distribution of biota and its migration routes through this region of the Arctic.

RUSALCA mooring locations in the western Bering Strait.



Leg 2 resulted in the following:

- 77 CTD and nutrient casts;
- Two moorings (both Russian and U.S.) placed in the western waters of the Bering Strait;
- 87 phytoplankton samples;
- A comprehensive survey and census of zooplankton species at 33 stations in the Bering Strait through the central Chukchi Sea;
- Benthic grabs at 11 stations;
- Benthic epifauna sampled at 17 stations;
- Larval and juvenile fish collected at 17 sites;
- 31 species of fish sampled;
- 27 trawls for adult fish, collecting 24 species; and
- Eleven remotely operated video lowerings from the Bering Strait into the Herald Canyon.

During Leg 2, the hydrographic, biochemical, and productivity sampling was integrated from all stations sampled, and the data from U.S. and Russian collaborators will be combined for the joint assessment of climate change, water mass properties, and a census of marine life in the Arctic.

Future Programs

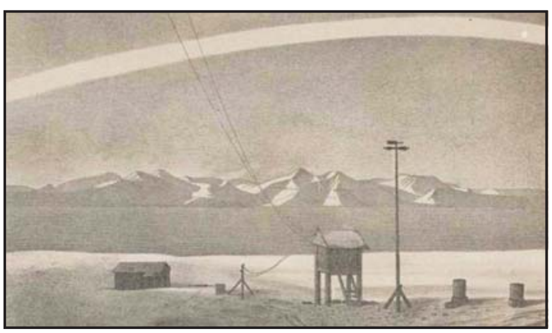
The RUSALCA program anticipates returning annually to the Bering Strait to service the two Russian–American moorings left at their sites in the western part of the strait in 2004. Negotiations are developing to use a Russian Navy hydrographic research vessel to carry out the Bering Strait operations in 2005–2007.

NOAA anticipates that it will expand the breadth and range of the RUSALCA program during the International Polar Year if funding permits. Efforts are underway to design ship-based traverses from the Chukchi and East Siberian Sea shelves north into the deeper Makharov Basin to investigate ecosystem indicators of climate change, examine the physical and chemical properties of the ocean in the region where the greatest amount of thawing of Arctic sea ice has taken place, and carry out a census of marine life in this poorly explored and mapped region.

On the Creation of Environmental Data Sets for the Arctic Region

This article was prepared by Florence Fetterer, NOAA Liaison, National Snow and Ice Data Center/World Data Center for Glaciology, Boulder, Colorado, and Igor Smolyar, of NOAA's Ocean Climate Laboratory, National Oceanographic Data Center, Silver Spring, Maryland.

When Karl Weyprecht proposed better coordination of research in 1874, leading to a series of coordinated synoptic observations in the Arctic, little did he think that his ideas would produce scientific data that remains of intense interest to researchers 130 years later. And still less would he have imagined that his proposals, and the resulting International Polar Year of 1882–1883, would inform goals for creating and managing scientific data in the 21st century. Because of advances in observation and data technologies, the questions that Weyprecht addressed have only increased in significance. What constitutes useful environmental data? How are data both a product of research and a catalyst for new research? How should data be managed to ensure continued accessibility and usefulness? The NOAA Arctic research activities described elsewhere in this edition of *Arctic Research of the United States* both use and produce data. This article examines the process of creating environmental Arctic data sets and the symbiosis of research, data, and data management. These data sets may have value beyond that of advancing Arctic research objectives: they may be, for example, monitoring tools for change detection, or they may underlie decision support applications.



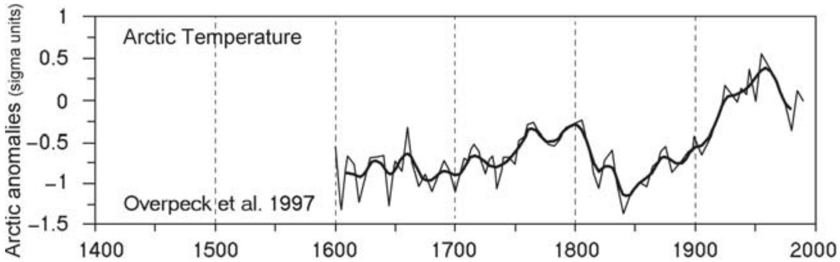
IPY meteorological station, 1882.

This focus on data and data management has become a proper discipline at NOAA in the 130 years since Weyprecht's call for better coordination of research and data resources. Arctic environmental data sets can be found in almost every NOAA line office, but it is the NOAA National Environmental Satellite, Data, and Information Service Data Centers that share a mission of data management. The NOAA National Data Centers' commitment to long-term data management provides institutional support for producing exemplary environmental data sets. Each center has a particular research focus and expertise that adds value to its data management results. After a brief profile of these centers, we will discuss what general characteristics make certain data sets especially valuable and what elements come into play during the production of these data sets, highlighting enough of them here to provide a sense of the breadth of NOAA's Arctic data production activities. An atlas, the *Climatic Atlas of the Arctic Seas 2004*, serves as a case study. We also cite a number of NOAA operational, research, and modeling products as examples of particular aspects of data product creation.

National Data Centers

National Oceanographic Data Center

Located in Maryland, the National Oceanographic Data Center (NODC) is a repository and dissemination facility for global ocean data. Researchers from NODC's Ocean Climate Laboratory (OCL) announced in 2000 that the world ocean has warmed significantly over the past 40 years. Just as the atmosphere has a climate, with variability on different time scales, the ocean's temperature, salinity, and other characteristics change over time. OCL researchers based their conclusions on data laboriously collected, quality controlled, and assembled into a special form of environmental atlas called a climatology. To facilitate comparisons of the past with the present, and to investigate interannual-to-decadal ocean



Arctic temperature anomalies

climate variability, many thousands of raw observations acquired from ships were interpolated to a regular spatial grid and combined over annual, seasonal, and monthly compositing periods. A definitive statement about oceanic warming would not be possible without these climatologies.

In addition to supporting scientific studies, OCL's International Ocean Atlas and Information Series (currently nine in number) exemplify international cooperation. Much of it is taking place through the OCL's World Data Center (WDC) for Oceanography, in Silver Spring, Maryland. International collaboration is an absolute necessity for acquiring a sufficient number of observations for climatologies. The Global Oceanographic Data Archaeology and Rescue (GODAR) Project, for example, has added over six million historical ocean temperature profiles to the archives, as well as a large amount of other data. Initiated by the NODC and WDC, this OCL-directed project was subsequently endorsed by the UNESCO Intergovernmental Oceanographic Commission.

National Climatic Data Center

Among the hundreds of climate data compilations housed at the National Climatic Data Center (NCDC) in Asheville, North Carolina, are Arctic station data from the Global Historical Climate Network, the most comprehensive homogeneous collection of station temperature data available. "Homogeneous" means consistent over the years and from place to place, through changes in instrumentation, acquisition method, and site characteristics, so that scientists may look for trends in the data. Homogeneous data sets require careful quality control. Historical data are made homogeneous with present-day observations by adjusting for non-climatic discontinuities, such as a jump in precipitation that might be caused by a change in instrumentation. An important part of the quality control process is compiling station inventories that detail the history of each station, including changes in instrumentation, changes in location, and changes in surroundings. If a town grows up around a formerly rural station, for example, a heat island effect may be present in the data record.

Ice core samples. Ice cores are taken from ice sheets or ice caps and are used by paleoclimatologists as a record of past climate.

NCDC also operates the World Data Center for Paleoclimatology (WDC Paleo), located in Boulder, Colorado. Paleoclimatology puts the relatively recent changes in Arctic climate, apparent in the instrumented record, in long-term context. Proxy data from tree rings, ice cores, and lake and marine sediments available from the WDC Paleo were used by an international team of scientists for a circum-Arctic view of surface air temperature changes over the last 400 years.

The WDC Paleo web site provides interpretations of the record: A steep increase in warming between 1850 and 1920 was most likely due to natural processes. Warming since 1920 is more difficult to ascribe to natural forcing alone. For an even longer view, ice core data are valuable. WDC Paleo and the National Snow and Ice Data Center jointly maintain the Ice Core Gateway. Proxy climate indicators from ice cores such as oxygen isotopes, methane concentrations, dust content, and other parameters stretch the record back more than 1000 years.

National Geophysical Data Center

The National Geophysical Data Center (NGDC), Boulder, Colorado, contributes significantly to Arctic science through participation in the development of the International Bathymetric Chart of the Arctic Ocean (IBCAO). IBCAO bathymetry provides a detailed and accurate representation of the depth and morphology of the Arctic Ocean seabed. This dynamic database contains all available bathymetric data north of 64°N. It is maintained as a gridded database, and a version has been published in map form. The IABCO team remapped the Lomonosov Ridge, showing it to be more segmented in structure, wider, and shallower than had previously been mapped. The Lomonosov Ridge is an important topographic barrier that influences deep water exchange between the eastern and western basins of the Arctic Ocean. An accurate seafloor is important for applications including ocean modeling, mapmaking, and other research endeavors. The IABCO effort involves investigators from eleven institutions in eight countries. It has been endorsed and supported by the Intergovernmental Oceanographic Commission, the International Arctic Science Committee, the International Hydrographic Organization, and the U.S. Office of Naval Research.

National Snow and Ice Data Center

Operational products, such as sea ice charts for shipping interests from the NOAA/Navy/Coast Guard National Ice Center, are often laboriously produced by manually interpreting and synthesizing data from many sources, both satellite and in situ. They are generally more accurate than similar products from single sources. The National Snow and Ice Data Center (NSIDC) works with operational groups within NOAA to make these products available to a different user base by archiving operational data, making data available online, providing documentation, and fielding questions from researchers about the data.

Originally founded to manage scientific data from the International Geophysical Year of 1957–1958 (the follow-on inspired by the IPY of 1882–1883), the World Data Center (WDC) for Glaciology is operated by NSIDC in Boulder, Colorado. Today, NSIDC is a NOAA-affiliated data center, designated by NOAA in 1976, affiliated with NGDC, and part of the University of Colorado's Cooperative Institute for Research in Environmental Sciences (CIRES).

The NOAA program at NSIDC supports the WDC and emphasizes data rescue and data from operational sources that can be used for climate research and change detection. NOAA-funded activities complement the activities of NSIDC's Distributed Active Archive Center (DAAC) and its NSF-funded Arctic System Science Data Coordination Center. The latter centers handle large volumes of satellite data (about 80% of NSIDC's funding comes from NASA for operation of the DAAC) and data from individual scientists.

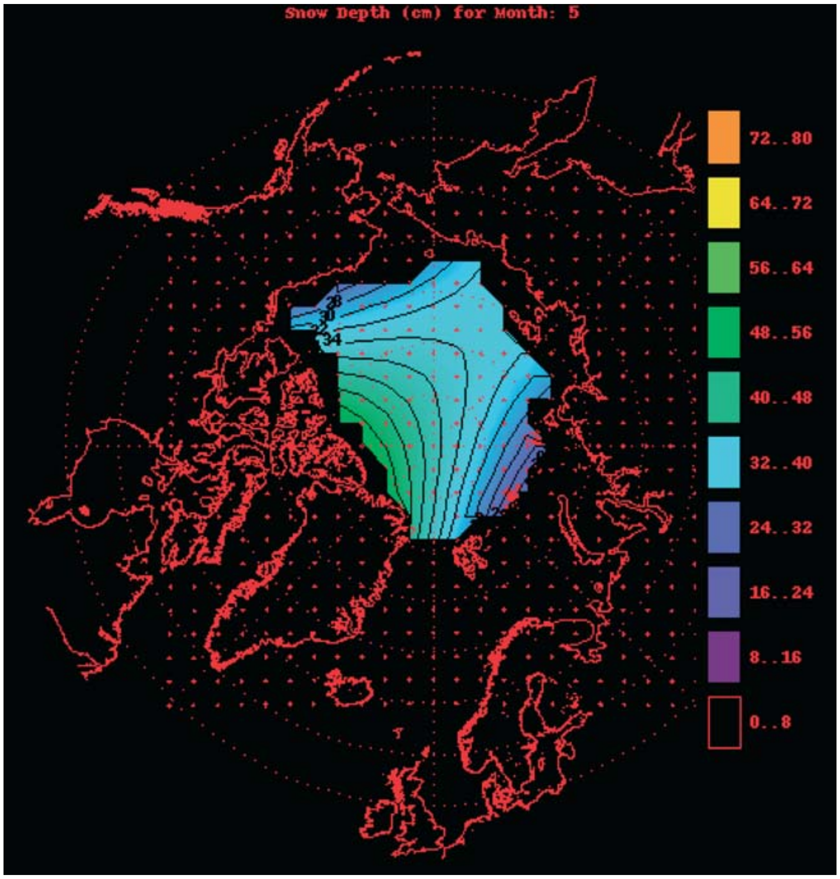
NSIDC has 522 data products in its on-line archive. Excluding satellite data sets, 104 of these are Arctic data sets, and of these about 20% are the more evolved compilations termed Arctic environmental data products.

What Makes a Good Environmental Data Product?

To make a good environmental data product, one starts with raw data and then processes or presents them in such a way that they become information. Data are transformed into a product that can advance a user up a hierarchy from data to information, to knowledge, to wisdom, shortening the user's path from data to knowledge or to the why and how of environmental interactions and change. Following is a summary of some of the data management practices that effect this transformation.

Context

Simply presenting data systematically is sometimes enough to transmit any underlying meaning. That is, even a well-organized collection of raw data can be an environmental data product. Usually, though, data products are more sophisticated. Presenting data in context is important, and the data product creator must decide what "context" means for the particular data under consideration. Temporal context usually means having as long a record as possible, while spatial context may mean covering as much of the Arctic as possible at an appropriate resolution or station density. Context may mean including population data for both predator and prey in an Arctic species survey or including as complete a set of oceanographic hydrochemical parameters as possible. The point is to make significant patterns evident, while committing no "sins of omission" in choosing what to include. Methods are important, as is documenting uncertainty. For example, if the product is a gridded climatology of snow depth on Arctic Ocean sea ice, some analysis should be done to ensure that enough observations are included in each grid cell for an acceptable level of accuracy. Sometimes the way in which data are gridded, interpolated, and presented implies a certain level of precision. For example, a two-dimensional quadratic function fit to snow depth on sea ice tells the user immediately that the snow depth information is not very precise.



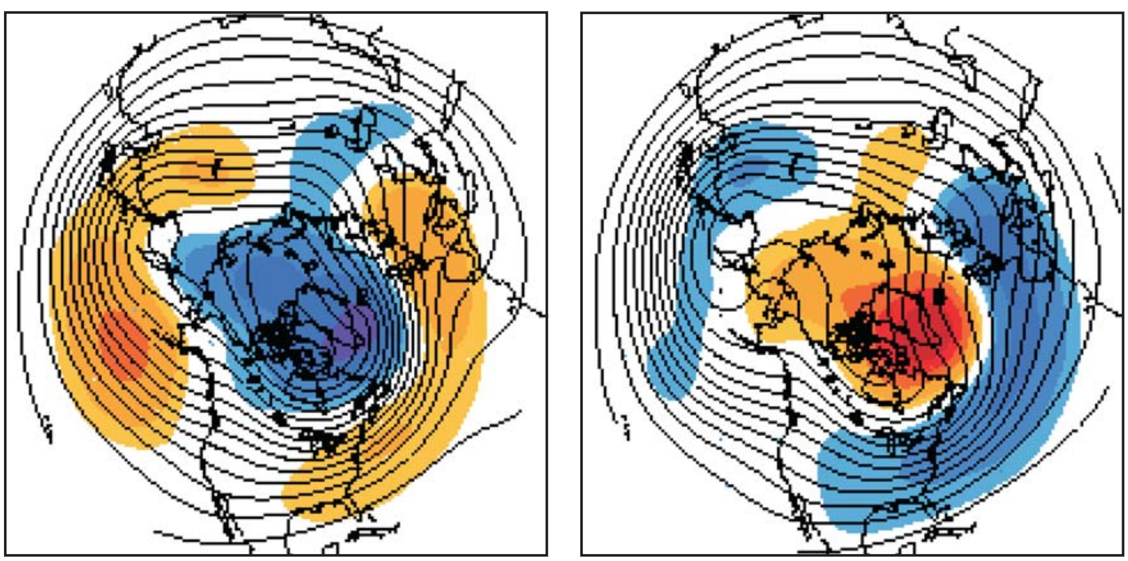
Variation in snow depth on Arctic sea ice, depicted by fitting a two-dimensional quadratic function to available data by month. There are very few measurements of snow characteristics on Arctic sea ice. This representation, from the Environmental Working Group's Meteorology Atlas, is the best possible in the absence of dense station coverage. While it appears unrealistic, product documentation explains why a more sophisticated gridding method for the available data is not appropriate.

Data products may include the results of an analysis, such as an empirical orthogonal function analysis of surface pressure data that shows the Arctic Oscillation pattern (that is, the tendency of pressure near the pole to act counter to pressure at mid-latitudes) or the addition of a trend line or other model fitting to observations. In such cases, the product creators have an extra responsibility to explain the limitations of their method of analysis, since these methods, if appropriately used, draw the pattern in the data rather than leave it to inference.

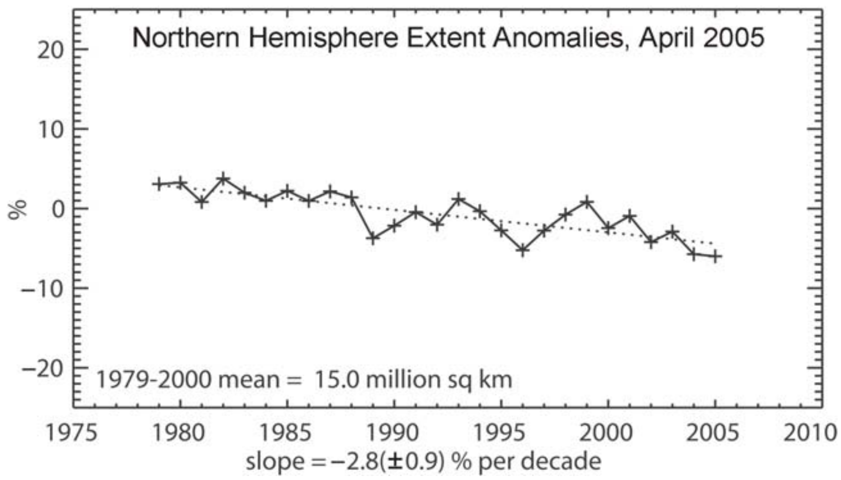
Documentation

Words are often the only way to provide appropriate context. The heat island effect, known only if the weather station history is known, is but one example of the importance of clear and complete documentation. Good documentation is written with the user in mind. For example, if the users are scientists, they will need to know about any known biases in the data record. If the data product is created for the general public, this information is just as important because it influences what a user infers from the data, but the information must be given in non-technical language. Operational users often need today's data irrespective of historical biases and may require little or no documentation.

For example, the NOAA National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC), located in Minneapo-



Examples of the Arctic Oscillation in its positive phase (left) and negative phase (right) from the NOAA National Weather Service's Climate Prediction Center web site. Blue indicates negative pressure anomalies, and orange indicates positive. The Arctic Oscillation is a large-scale atmospheric circulation pattern. Variability in the AO has been implicated in changes such as the recent steep decline in ice extent.



Sea ice extent trends. When data are presented with a trend line, as in this example, data providers should include error bars and document the limitations of the method (linear regression in this case) when it comes to providing information from the raw data.

lis, Minnesota, provides snow information in a variety of products and formats to meet operational forecasting needs. The NOHRSC web site (http://www.nohrsc.noaa.gov/) is designed to serve these users efficiently with interactive products and brief documentation. NSIDC archives assimilation model output (http://nsidc.org/data/g02158.html) from NOHRSC and gives the research community access to this unique data set. Extensive documentation on the NSIDC site, not needed on the NOHRSC site, covers alternative products, data quality and value, and potential research uses of the data. Similarly, the NOAA NESDIS Satellite Services Division Operational Daily Northern Hemisphere Snow Cover Analysis is made available to the operational community at http://www.ssd.noaa.gov/PS/SNOW/ and is archived for the research community at NSIDC (http://nsidc.org/data/g02156.html). Likewise, the NODC web site (http://www.nodc.noaa.gov/) is designed to provide users access to various products with a higher level of documentation than would be needed for operational users.

Graphics and Site Design

Graphical presentation and site design are aspects of information architecture that are especially important for complex environmental data sets that are viewed or used through a web page. Though not an environmental data set per se, the NOAA Arctic Theme Page (http://www.arctic.noaa.gov/) offers an example of good site design.

Careful attention must be paid to the graphical presentation of data. Gridded data to which a color table has been applied, or data smoothed by interpolation, are often subject to misinterpretation. The display resolution of pixels should faithfully represent the underlying resolution of the data, lest a scientist infer regional relevance that is not supported. Color tables should not have sudden jumps in intensity or hue that can draw the eye to a sea surface temperature difference, for example, that is an arbitrary point in a continuum, thus suggesting a pattern that is not there.

Data Integrity

Three main components ensure environmental data product integrity:

- The product must have scientific integrity; peer review of the data and a citation for the data set are needed to accomplish this.
- The data repository must be trustworthy.
- The data must not have been altered since the data were acquired or produced (or any alteration must be well described). The data management concepts of fixity, provenance, and source authentication come into play here.

Often it is the reputation of an individual scientist that imbues his or her data product creation with an aura of integrity. Data centers work with scientists to ensure that the reality measures up. Though it is common in the U.S. for investigators to manage their own data, this is rarely successful over the long term because scientists rarely have the requisite data management background needed to keep their data useful and accessible to the next generation of scientists or the resources to deal with technical issues that keep data secure, such as media migration and off-site backups.

What Makes a Well-Used Environmental Data Set?

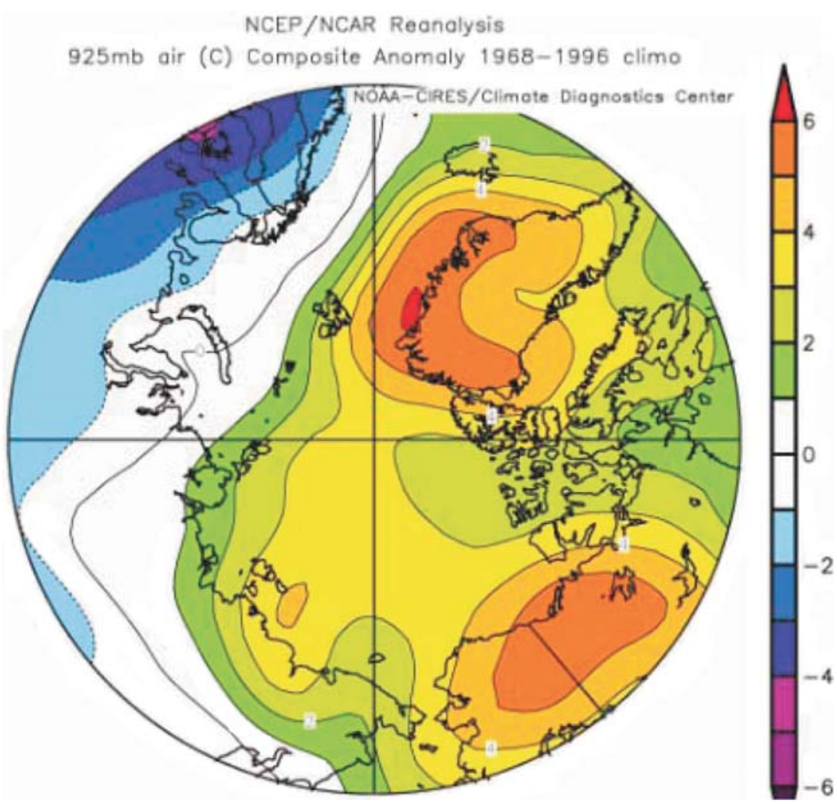
Certain attributes will ensure that a data set will have many users. In such cases it is especially important to follow the design precepts above. Data products that include unique data, that are comprehensive collections, that offer continuous coverage over a long time period, that are easy to use, and that provide a synthesis of available information are characteristics of the most popular Arctic data products.

Uniqueness

Upward-looking sonar data from submarines provide the only measurements of ice thickness over a large portion of the Arctic. Ice thickness estimates are critical to estimating the mass balance of ice in the Arctic Ocean—ice extent and concentration are only two dimensions of a three-dimensional problem. One difficulty in working with original records is that almost all submarine data are classified. Investigators at the U.S. Army's Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire, and the Polar Science Center, Applied Physics Laboratory, University of Washington, worked with the U.S. Navy's Arctic Submarine Laboratory to find a way to "fuzz" the submarine track positions so that the data could be cleared for release by the Chief of Naval Operations. NSIDC distributes the data set, Submarine Upward Looking Sonar Ice Draft Profile Data and Statistics (http://nsidc.org/data/g01360.html). It has been the basis of a number of research articles on the controversial topic, "Is Arctic ice thinning?"

Comprehensiveness

Comprehensive data products offer more value than data sets that must be combined with others in order to have enough data of a single type for a scientific study. It takes a well-funded project, a multi-year commitment, and many individual and institutional partners to assemble, for example, "all" surface marine reports from ships, buoys,



Temperature anomalies for October through December 2002 in the Arctic. This illustration assisted in attributing the causes of the 2002 and 2003 sea ice extent minima to, in part, anomalously warm air temperature. The NOAA-CIRES Climate Diagnostic Center (http://www.cdc.noaa.gov) display tool allows users to choose the month and year to display from the NCEP/NCAR re-analysis products. The color table is intuitive (warm colors are warmer than average temperatures), and the resolution of one degree shown in the color bar is appropriate to the data set.

A submarine surfacing through sea ice. This photo comes from SCICEX (Scientific Ice Expeditions), a collaboration between the U.S. Navy and civilian scientists for environmental research in the Arctic.

and other platform types. As such, the International Comprehensive Ocean Atmosphere Data Set (ICOADS, http://www.cdc.noaa.gov/coads/) of quality-controlled data dating from the late 18th century is a remarkable achievement. An entire body of literature has grown up around topics related to the quality control of historical ship data in ICOADS. For example, sea surface temperatures acquired by throwing a bucket over the side and measuring the temperature of the retrieved water are not the same as temperatures acquired from the engine intake. A "bucket correction" must be applied. This correction is based on modeled heat loss for water in a bucket on deck and should take into account ship speed (and its uncertainty) and the material of the bucket (wood or canvas). Clearly, quality controlling the millions of observations of various types so that they are homogeneous over time is a Herculean task.

ICOADS began as a U.S. project (COADS) in 1981 as a partnership between the NOAA Office of Oceanic and Atmospheric Research's Environmental Research Laboratories and NCDC, CIRES, and NSF's National Center for Atmospheric Research. The NOAA portion of ICOADS is currently supported by the NOAA Climate and Global Change Program. NSIDC makes an Arctic subset available (http://nsidc.org/data/nsidc-0057.html).

Continuous Spatial and Temporal Coverage

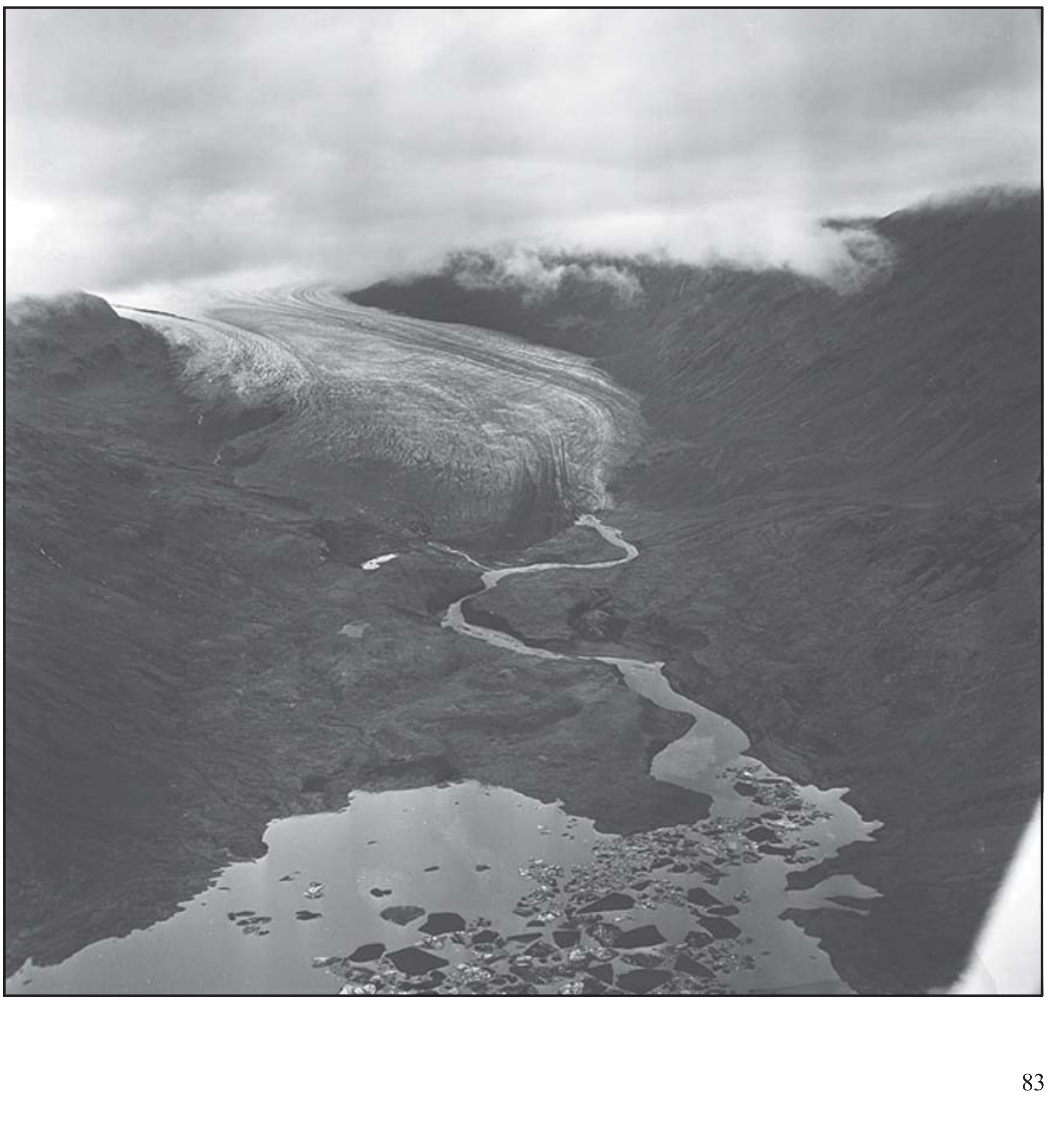
Products that are as close as possible to continuous in space and time are often desirable because, for example, the danger of aliasing is minimized (that is, there is a smaller chance of missing a significant event or pattern in the data). The enormously popular "reanalysis" products are an example.

Reanalysis projects take data such as those in ICOADS and assimilate them through a numerical weather prediction model to produce a series of analyses in which parameters such as surface pressure and temperature fields are physically consistent with one another. The fields cover a large area (the Northern Hemisphere, for instance) without gaps and are available at regular time intervals over a long record, making reanalysis output more useful than observations for many applications. One example is studying the spatial and temporal variability of large-scale atmospheric circulation patterns, such as the Arctic Oscillation. NOAA's Arctic Research Office is planning a coupled atmosphere–sea ice–ocean–terrestrial reanalysis optimized for the Arctic region. The description of the climate system it will produce can be used to detect Arctic change and assist in attributing change to specific causes.

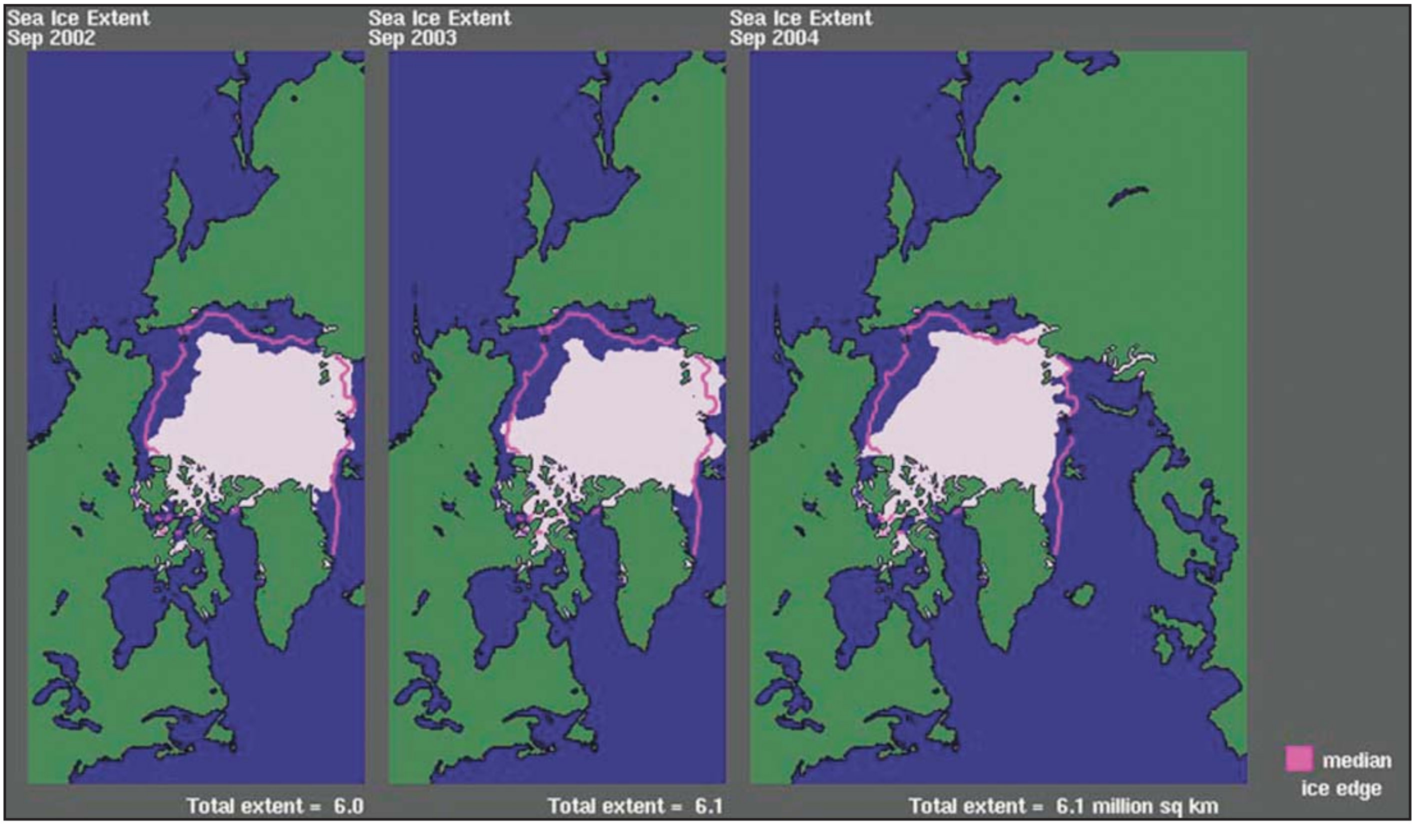
Ease of Access and Use

Many valuable data sets lie unused in archives simply because they are not easily accessible. Formerly, NSIDC's Glacier Photograph Collection of thousands of historical glacier photographs dating from the 1880s saw only a handful of users each year because users had to travel to NSIDC to view the fragile collection of prints. Now, thanks to NOAA's Climate Database Modernization Program funding for scanning the photos, many of the photographs can be viewed on line, and high-quality digital images can be downloaded (http://nsidc.org/data/g00472.html). As a result, the number of users has climbed to about a thousand each month.

Improving access can broaden the user base for a data set. NSIDC's satellite passive microwave



Cushing Glacier, Alaska. This photograph, taken in 1967, is one of thousands that are part of the Glacier Photograph Collection, created by the National Snow and Ice Data Center and available on line at http://nsidc.org/data/g00472.html.



Sample result from the Sea Ice Index, which displays anomalies in ice extent and other ice parameters going back to 1979. Here, recent summer ice extent, which has been the lowest in the data record, is displayed with the median extent (pink line) to give climatological context to the information.

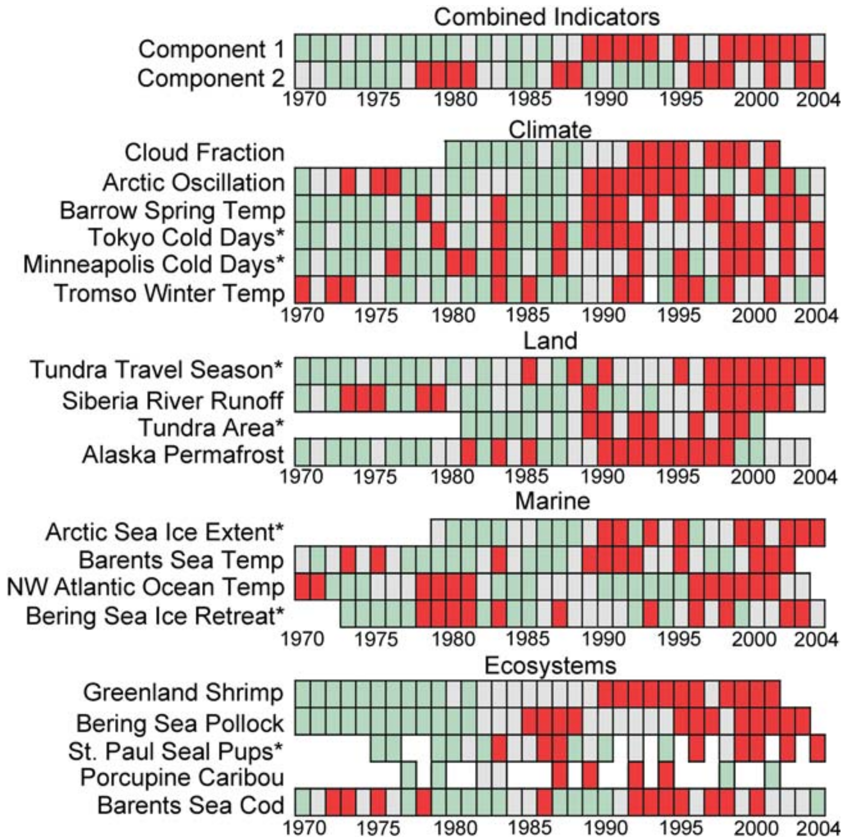
sea ice concentration data are popular among scientists but not geared toward the general public. The data are voluminous, and some technical and scientific sophistication is needed to simply read and interpret the data. To mitigate these issues, NSIDC developed the Sea Ice Index, which provides an easy way to visualize the satellite data. The Sea Ice Index web site lets any user track changes in sea ice extent and compare conditions between years. About 3,000 users visit the Sea Ice Index site every month.

Similarly, the OCL web site (http://www.nodc.noaa.gov/OC5//SELECT/dbsearch/dbsearch.html) allows users to extract data from the World Ocean Database 2001. While contributors to an environmental data product often prefer that the data be compiled on CD-ROM or DVD for reasons of fixity and attribution, data sets are much more likely to be used if they can be easily browsed or manipulated on line with a selection tool to facilitate access.

Synthesis

Data products that offer synthesis—a "big picture" version of the information in the data—are rare because they are difficult to construct. Synthesis products are built by distilling information from multiple sources. An exciting and successful example of this kind of product is NOAA's Near Realtime Arctic Change Indicator web site (http://www.arctic.noaa.gov/detect/), which summarizes "the present state of the Arctic climate and ecosystem in an accessible, understandable, and credible historical context." Designed for decision makers and the general public, it presents a sophisticated 30-year principal components analysis (the synthesis) of 19 climate, land, marine, and ecosystem "indicator" time series, such as the length of the travel season over tundra, the Bering Sea pollock population, the number of extremely cold days each year in cities such as Minneapolis, and the extent of Arctic sea ice.

Taken alone, any one of these time series would not present a compelling account of Arctic change. Taken together, the big picture emerges. The site tracks the rate and extent of changes in the Arctic to facilitate informed decisions concerning the impacts that result. Web pages for each of the indicators give a succinct but complete analysis of the data record in non-technical terms. Changes are given in context, including the context of the human dimension. Links to reports and more detailed data make it a useful resource for scientists as well.



Selection of time series representing Arctic change. The combined indicators are the result of a mathematical analysis (principal component analysis) that resolves the trends in all the time series into two major components. Series noted by an asterisk have been inverted. Red indicates large changes in recent years.

The Arctic Change Indicator web site was developed by NOAA's Arctic Research Office under the stewardship of investigators at the NOAA Pacific Marine Environmental Laboratory. It draws on the work of hundreds of investigators around the globe. A major challenge will be to keep the site updated. As NOAA looks toward building new observing systems, it will be critical to maintain data flow from existing observing stations.

The Climatic Atlas of the Arctic Seas

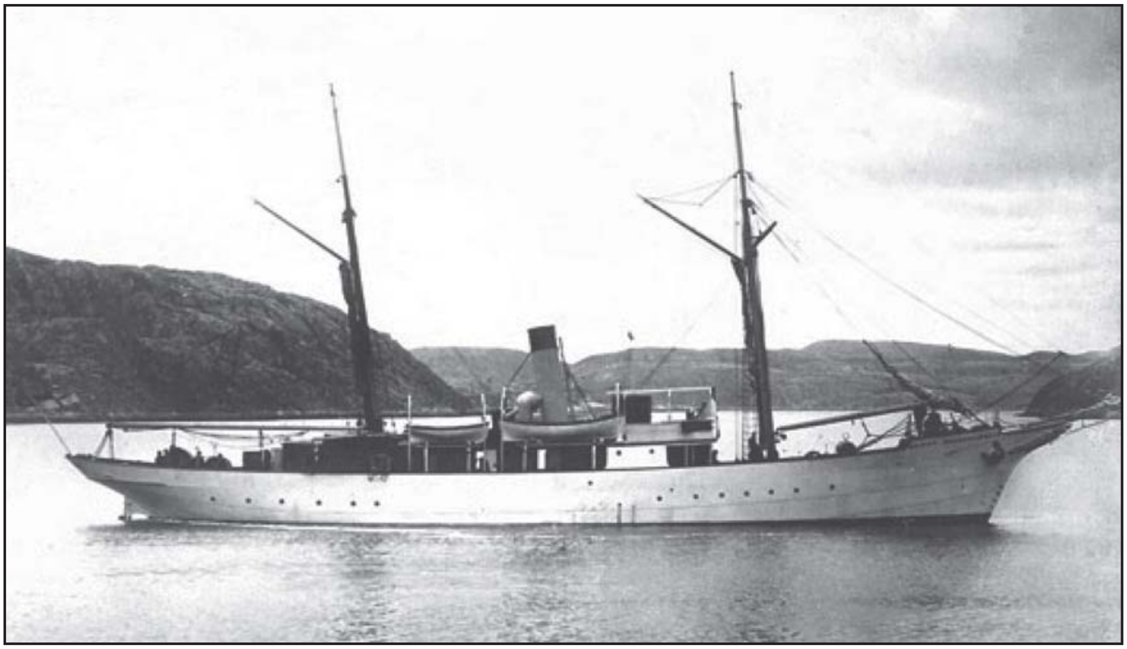
With these principles in mind, we now turn to a case study of active, collaborative data management that produces new knowledge and disseminates this potential across a wide community of researchers.

The WDC for Oceanography in Silver Spring , Maryland, and OCL/NODC have a long history of collaborating with Russian institutions to add more historical data to the OCL World Ocean Database Project. The most recent result is the *Climatic Atlas of the Arctic Seas* on DVD, with meteorology, oceanography, and hydrobiology (plankton, benthos, fish, sea birds, and marine mammals) data from the Barents, Kara, Laptev, and White Seas, collected by scientists from 14 countries during the period 1810–2001. The Murmansk Marine Biological Institute of the Academy of Sciences of the Russian Federation and OCL/NODC prepared the atlas with support from NOAA NESDIS and the Climate and Global Change Program.

The atlas provides historical context for its observations by including a written history of oceanographic observations in the Arctic, as well as scanned copies of selected rare books and articles. A gallery with photos and drawings gives the user some idea of what historical data collection platforms and expeditions looked like.

As is often the case with projects involving data rescue, libraries provided much of the material and documentation; the NOAA Central Library

Marine biologists P. Savitsky and I. Molchanovsky sampling plankton in the Kara Sea as part of an expedition of the Murmansk Marine Biological Institute on the nuclear icebreaker Sovetsky Soyz *in April–May 2002. The* Climatic Atlas of the Arctic Seas *weds early observations with contemporary observations in a seamless package.*



One of the first Russian research vessels, Andrey Pervozvanny*, on an expedition at the beginning of the 20th century, in the Barents Sea.*

(Silver Spring, Maryland), the Slavic and Baltic Branches of the New York Public Library, the New York Museum of Natural History Library, the Dartmouth College Library (Hanover, New Hampshire), the Slavic Library (Helsinki, Finland), and the public libraries of Moscow, Murmansk, and St. Petersburg (Russian Federation) all contributed.

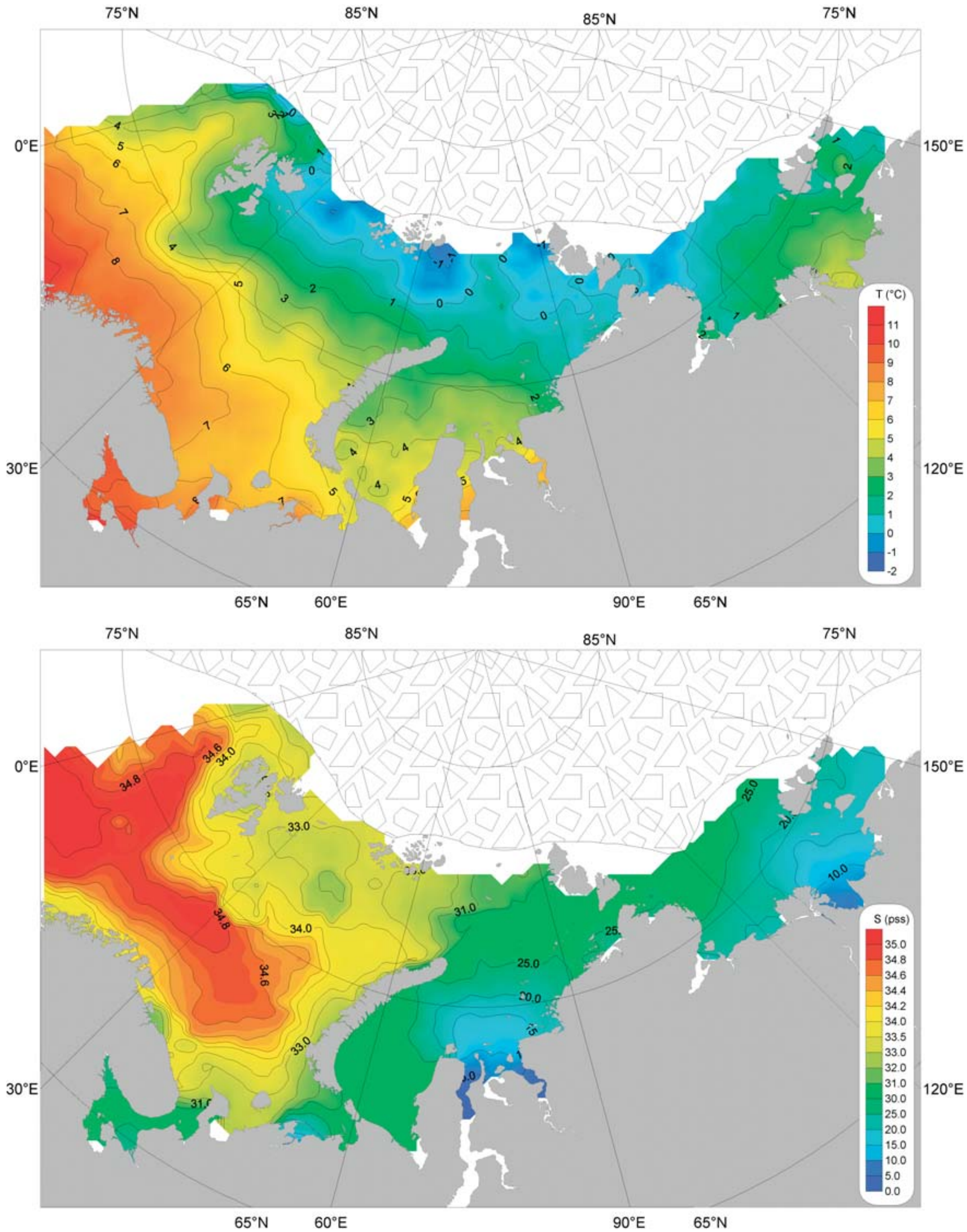
Assembling an atlas on this scale presents a number of challenges. A surprisingly difficult one is the elimination of duplicate stations from different data sources. As databases or parts of databases are shared, metadata are altered. For example, one database may have a station location in degrees, minutes, and seconds, and another may convert to decimal degrees. Rounding errors may give the appearance that these are two stations separated by as much as a few miles. Values of parameters may be presented at observed levels in one data set but interpolated, often by an unknown method, to a standard level in another data set. Another source of uncertainty is converting units of measurement. As a result, the same station data from different sources may differ in coordinates, time of measurement, and values of the parameters themselves. To help choose what station records to include, the atlas authors used a system of priorities: cruise reports, ship logs, and expedition diaries (all original sources) were deemed more reliable that data sources where the data apparently were repeatedly transformed. Elimination of duplicates and "near duplicates" brought the number of stations down from an initial 1,506,481 to a still sizeable 433,179.

Users have two ways of accessing raw observations: by oceanographic cruise or through 1° squares. For every month, a distribution map of stations is generated that allows a user to access data from a chosen square. Data may be easily imported into Excel or other database applications. Access to the actual observations is important for many users. Other users are likely to prefer a climatological presentation, since climatologies provide a convenient representation of average conditions, such as monthly or decadal means. The atlas satisfies both by including mean monthly temperature and salinity distribution fields at five standard depths, using an objective data analysis method.

A Long Journey from the Past: The International Polar Year

The International Polar Year serves as an important milepost for assessing our efforts and establishing stronger standards to carry the value of observations and research far into the future. As we look back over past IPY/IGY efforts and forward to those coming in 2007–2008, those of us who create Arctic environmental data sets have observed some lessons over the years.

Many of us know the tragic story of the Greely Expedition, an American venture sent into the Arctic in 1881 to establish an IPY station that ended in starvation for most of the party, but



Average September surface temperature (top) and salinity (bottom), from the Climatic Atlas of the Arctic Seas*. Note the low salinity at the river mouths. Scientists are working to understand the role of freshwater input from rivers on Arctic Ocean (and global ocean) circulation. Climatologies provide a picture of average conditions against which to evaluate changes.*

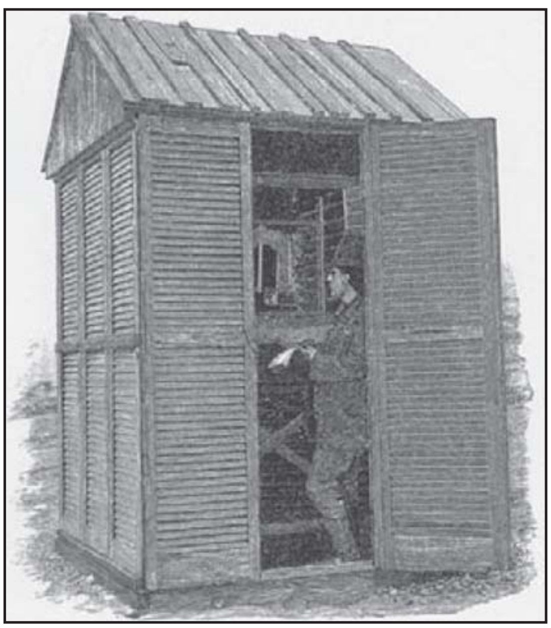
fewer of us are aware of the sad tale of their scientific data. Their observational records should have become a legacy to their efforts and sacrifice, but this is not the case. As Kevin Wood of NOAA writes, narrating the story of their data:

> "Perhaps the most compelling aspect of the Greely tragedy is the utter commitment of these men to preserve their scientific work. Aware that if relief didn't arrive in time they would be left to retreat on their own, Greely began making copies of their scientific work (amounting to some 500 observations per day). When they were forced to abandon Fort Conger in August 1883 they took with them—in lieu of extra rations—these copies sealed in three tin boxes of 50 pounds each, all of the daily journals, 70 pounds of glass photographic plates, and all of the standard thermometers and several other impor-

tant instruments. They also continued a program of scientific observation, in the face of starvation, until just 40 hours before they were rescued."

Surely, Greely and his men hoped that their work would lead to important advances in science. Greely expressed this sentiment when he wrote in his official report, "The conviction that at no distant day the general laws of atmospheric changes will be established, and later, the general character of the seasons be predicted through abnormal departures in remote regions, causes this work to be made public…in the hope that it may contribute somewhat to that great end." The desire to be able to "predict the character of the seasons" still motivates researchers today.

Unfortunately, the research program of the first IPY was never completed as Weyprecht had originally planned. Each nation issued an individual report over the ensuing years, but no systematic study of the simultaneous observations—the heart of the IPY program—was undertaken. The International Polar Commission dissolved, and the data collected at such cost during the first IPY soon fell into obscurity.



Sgt. Jewell recording temperature, Fort Conger, during the Greely expedition, 1881–1883.

Today the original records of the first IPY are widely scattered in various libraries and archives and are often in a perilous state of preservation. Some of the published reports are extremely rare and are very difficult to obtain. The fate of the first IPY records, gained at such high cost, underutilized both then and now, and scattered over the course of time, highlights how important it is to provide for the effective preservation and management of such extremely valuable data.

The scientific legacy of the Greely Expedition and the other expeditions of the first IPY has only with difficulty been preserved. NOAA has recently made meteorological data from the first IPY available in digital format, along with an extensive collection of documentary images (see http://www.arctic.noaa.gov/aro/ipy-1).

There is another kind of legacy that we can create from the experience of the first IPY. As we look forward to a new International Polar Year, we must remain focused on these key lessons about data management.

Lesson 1: Applying the Right Kind and Right Amount of Effort at the Right Time is Imperative

While data rescue is difficult, tedious, and often expensive, it is crucial. The only way to reduce uncertainty in our estimates of past, and predictions of future, Arctic environmental change is to incorporate more, older, and better data into our analyses. NOAA's Climate Database Modernization Program, now in its sixth year, has keyed or scanned and placed on line over 45 million environmental records. More needs to be done, especially in documenting and quality controlling these records, because these last steps require capturing the knowledge of people who know the "rescued" data best, often a cadre that are beyond retirement age.

Lesson 2: Structures that Enable International Collaboration can Dramatically Increase Value

As a result of Arctic geography, the most comprehensive data sets result from international cooperation. GODAR and ICOADS are models for this cooperation. International data-sharing agreements are essential. In contrast to the National Data Centers, the World Data Center system provides a structure within which data sharing can occur with a minimum of diplomatic overhead. WDCs in the U.S. that share Arctic data internationally are the WDC for Glaciology, Boulder (co-located with NSIDC), WDC for Oceanography, Silver Spring (co-located with NODC), the WDC for Marine Geology and Geophysics, Boulder (co-located with NGDC), the WDC for Meteorology, Asheville (co-located with NCDC), and the WDC for Paleoclimatology (affiliated with NCDC).

Lesson 3: Good Data Stewardship is Superior to Untimely Data Rescue

We can avoid expensive and possibly fruitless data rescue efforts in the future by heeding the lessons of the past. The International Polar Year, 2007–2008, will be a catalyst for reinvigorating professional data management. The IPY promises new international collaboration and the potential for synthesis of knowledge under the headings of cross-disciplinary research themes. Good data stewardship will help ensure that this major undertaking will not shortly become a dimly receding spot on the horizon behind us.

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This effort requires not only attention to the data, but also to capturing the "data about the data" that enables continuing understanding and value. A disciplined effort to define and organize the metadata will enable other researchers to locate, understand, and interpret data for years to come, providing the foundation for long-term coordination and synthesis. In the instance of the first IPY, Weyprecht's vision of coordinated synoptic observations led to the acquisition of a data set that serves as a snapshot of climatic conditions as they existed in that now long-past year. Data collected then can now be compared with conditions as they are today. Making that comparison, Wood and Overland (2005) found that monthly mean air temperatures at IPY-1 stations were generally within recent climatological limits, and spatial patterns in temperature anomalies (departure from the long-term mean) were consistent with Arctic-Oscillation-driven patterns of variability. In a nod to the value of documentation and metadata, Wood and Overland noted that "the qualitative logs are particularly useful in validating climate information."

NOAA will focus its strength in environmental observations and analysis on the polar regions during IPY. NOAA's Arctic Research Office has endorsed a fundamental goal for IPY data management: to securely archive a baseline of data against which to assess future change, and to ensure that IPY data are accessible and preserved for current and future users.

What will this IPY snapshot look like, and how will data be preserved? In contrast to Weyprecht's IPY, most data from the coming IPY will be "born digital." Station logbooks from Weyprecht's day could be preserved in libraries, where they had to be physically protected from destruction by fire, insects, and chemical decomposition of paper and ink. One might think it is easier to preserve digital information, but digital data are not immune from physical destruction, and they require a host of measures to ensure their usability into the future: "digital objects require constant and perpetual maintenance, and they depend on elaborate systems of hardware, software, data and information models, and standards that are upgraded or replaced every few years."*

During the coming IPY, hundreds of investigators and agency programs will produce raw observations, satellite data, and environmental data products in a number and of a complexity that would have been hard to imagine in the late 1880s. To ensure preservation,

- NOAA's Data Centers and the Arctic Research Office will work to advance standards and technologies that support this goal. NOAA advocates the use of the Open Archival Information System (OAIS) Reference Model for metadata. Work on the OAIS model and on technological advances such as GRID computing and interoperable catalogs is happening now at NOAA's National Data Centers.
- Cross-agency support for IPY data management is needed. Because of the international, distributed nature of IPY activities, the data they produce will necessarily be archived and made accessible through distributed data management. This distributes the burden of data management but imposes additional coordination challenges. Within the U.S., the National Academy of Sciences' Polar Research Board has endorsed the concept put forward by the International Council of Scientific Unions' IPY Planning Group of a coordinating IPY Data and Information Service (IPY-DIS). Cross-agency support of the DIS at a national level will ensure that the U.S. leaves a secure IPY data legacy.
- Adequate funding is needed. Funding for the management of data acquired through research programs is often difficult to obtain, either because the importance of data management as a discipline is not recognized or because there are simply not enough dollars to go around. Currently, for every $30 dollars spent nationally on Arctic research, about $1 is spent on Arctic data management.

In the end, it is important to remember that technological advances and digital archives will secure data for future generations of researchers only to the extent that they are successful in capturing what people know about the data. We must also keep today's equivalent of the IPY-I station's "qualitative logs." With them, future researchers will have the appropriate contextual material to turn the coming IPY data into information-filled Arctic environmental data products.

* From *It's About Time: Research Challenges in Digital Archiving and Long-Term Preservation*, final report of a workshop sponsored by NSF and the Library of Congress, August 2003.

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