National Science Foundation

National Science Foundation research is concerned with the entire Arctic region, including Alaska, Canada, Greenland, Svalbard, the Arctic Ocean and adjacent seas, the upper atmosphere, and near space. Research falls principally within eight major scientific disciplines: atmosphere, ocean, biology, earth science, glaciology, social science, engineering, and science education.

The NSF supports a formal Arctic research program within the Office of Polar Programs (OPP). Other divisions and programs throughout NSF, primarily in the Directorate for Geosciences and the Division of Environmental Biology in the Directorate for Biological Sciences, support research in and on the Arctic as part of their overall funding. Most research grants are awarded on the basis of unsolicited proposals and are merit reviewed.

In FY 03, NSF awarded funds for 356 Arctic research projects at 136 institutions in 43 U.S. states and the District of Columbia.

The following sections present highlights of several major programs and selected projects. A complete listing of NSF Arctic funded projects can be found in the publication *Arctic Science, Engineering, and Education Awards: FY 2003*, available from the Office of Polar Programs, National Science Foundation, Arlington, VA 22230.

	Funding (thousands)	
	FY 02	FY 03
Arctic Natural Science	11,472	12,200
Arctic System Science Prog	19,093	20,699
Arctic Social Sciences Prog	1,975	2,758
Arctic Education Research	250	300
Arctic Research Support	797	823
Arctic Data/Info/Coord	248	270
Arctic Research Commission	1,017	1,080
Arctic Logistics/Instrumentation	27,580	29,166
Subtotal for OPP	62,431	67,296
Other NSF Science Programs	23,557	25,786
Total	85,988	93,082

Arctic System Science

In 1989 the NSF established the Arctic System Science (ARCSS) program, an interdisciplinary program that examines the interactions within and between the climatic, geologic, biologic, and socioeconomic components of the Arctic system. ARCSS is predicated on the premise that the Arctic system is sensitive to, and important in, global change. The ARCSS goal is to understand the physical, chemical, biological, and social processes of the Arctic system that interact with the total Earth system and thus contribute to or are influenced by global change, in order to advance the scientific basis for predicting environmental change on a decade-to-centuries time scale, and for informing policy options in response to the anticipated impacts of changing climate on humans and societal support systems. The program is coordinated, managed, and supported financially by the OPP, with contributions from other NSF directorates and other Federal agencies where appropriate. NSF/ARCSS has been successful at establishing partnerships with other Federal agencies; considerable cost and in-kind sharing with NASA, ONR, and NOAA on current and past projects has occurred for projects dealing with Arctic climate and ocean processes and modeling research. ARCSS research continues to contribute to the U.S. Global Change Research Program.

ARCSS has employed a series of workshops and interactions with a broad scientific community to develop goals and priorities aimed at understanding the role of the Arctic as a system undergoing change. Planning is focused on three thematic questions: What are the limits of Arctic system predictability? How do human activities interact with changes in the Arctic to affect the sustainability of ecosystems and societies? How will changes in Arctic cycles and feedbacks affect Arctic and global systems? These questions emphasize three concepts fundamental to research on Arctic change: predictability, sustainability, and feedbacks. Focusing the ARCSS program on these concepts reflects the increased ARCSS emphasis on integrative, interdisciplinary research that weaves disciplinary knowledge into system science. An important assumption underlying these questions is that many changes in the global climate system affect the Arctic system. Changes in the Arctic may, in turn, have impacts on the global system.

ARCSS currently has several components, including Ocean/Atmosphere/Ice Interactions (OAII); Land/Atmosphere/Ice Interactions (LAII); Paleoenvironmental Arctic Sciences (PARCS); the Russian–American Initiative on Shelf–Land Environments in the Arctic (RAISE); and Human Dimensions of the Arctic System (HARC). However, the program is evolving to a more efficient structure, and it is anticipated that these components will change substantially, become woven into a structure more nearly reflecting the questions, and ultimately disappear, and that each of the ARCSS research efforts will contribute primarily to the three thematic questions above. OAII and LAII have long been scheduled to end their planning activities and will do so at the end of 2004. RAISE has been on a trajectory to broaden its scope to a pan-Arctic Land–Shelf Interactions (LSI) effort and has already produced a science plan to provide ideas to the ARCSS process. Similarly, new ideas emerged from the LAII group in the form of a Pan-Arctic Cycles, Transitions and Sustainability (PACTS) plan, which proved to have intellectual content that was highly interdisciplinary and went well beyond terrestrial science.

The ARCSS committee of the Arctic Research Consortium of the U.S. provides recommendations for overall coordination and integration of ARCSS. The committee is actively engaged in the restructuring of ARCSS and in doing so is drawing on ideas emerging from a synthesis effort that explores our knowledge of the linkages and feedbacks within the system. In the past ARCSS had science steering committees and science management offices for each component to facilitate coordination and integration within the component and to provide a focal point for communication with the scientific community. As ARCSS evolves towards a more integrated structure, it is expected that some of this will change as the ARCSS committee engages more in the interdisciplinary, system-wide approach to ARCSS. A mechanism will be identified to maintain the function of community liaison that was provided by these offices.

Paleoenvironmental Studies

Paleoenvironmental research contributes to an understanding of past climate, atmosphere, and ecology of the Arctic, which can give valuable insight towards identifying system interactions. In recent years, PARCS, the principle paleoenvironmental research effort of ARCSS, has been supported through participation in the NSF Earth System History program.

The PARCS program is devoted to reconstructing paleoclimatic history from the sediments of Arctic and sub-Arctic bogs and lakes and from information in tree-ring records and in sediments from the marginal seas, continental shelves, slopes, and abyss of the Arctic Basin. A variety of proxy indicators (such as pollen, diatoms, sediment chemistry, and grain size) in the sediments yield vital information on the responses of terrestrial and marine ecosystems to climate, land use change, and the physical conditions and productivity of the Arctic Ocean.

Contemporary and Process Studies

A current example of a process-oriented ARCSS research activity is the Shelf–Basin Interactions (SBI) effort, begun to improve understanding of the role of the large continental shelf seas for marine biological productivity and the exchange of water, nutrients, heat, and energy with the permanently ice-covered central Arctic basins. Through integrated field and modeling efforts, the SBI project is investigating the effects of global change on production, cycling, and shelf–slope exchange of biogenic matter, both seasonally and spatially. To this end, there are five study objectives deemed both timely and essential to an improved understanding of the effects of global change on productivity as it contributes to shelf–basin interactions within the Arctic Ocean ecosystem, including:

- Understanding the roles of physical processes in the transport and modification of water and biogenic materials across the shelf and into the interior basin;
- Identifying mesoscale oceanographic features that support locally elevated concentrations of benthic and pelagic biota;
- Quantifying upper ocean (water column and sea ice) primary productivity in relation to the biomass and diversity of benthic and pelagic primary and secondary consumers;
- Assessing the relative importance of top-down as compared to bottom-up controls over pelagic–benthic coupling, biotic complexity, and carbon partitioning among different trophic levels; and
- Assessing food web changes consequent to

the impacts of changing ice cover and hydrographic parameters on remineralization of organic matter, recycling efficiency, and biogeochemical fluxes.

Human Dimensions of the Arctic System

Human Dimensions of the Arctic System (HARC) is a collaborative effort with the Arctic Social Sciences Program to integrate natural and social sciences research that will demonstrate the interactions of climate and human development with the use of natural resources. Arctic Native peoples have sustained themselves through hunting, fishing, whaling, and wage employment derived from petroleum revenues. The continued sustainability of their culture and regional development could be affected by global environmental changes that affect vegetation and marine productivity, year-round sea ice maintenance, and construction and land use practices. Research at the interface between natural sciences and human dimensions will increase policymakers' understanding of regional natural and social systems and build linkages between communities in the Arctic. Those linkages will enhance the knowledge base necessary for examining policy choices and risk assessments within the context of global and regional climate changes. So far there is no major research effort within HARC, but numerous collaborative projects have been supported over a period of several years.

Interdisciplinary Research

The first exercise in a new mode of ARCSS research, the Freshwater Cycle research effort, was developed as a thematic interdisciplinary approach that addressed a major part of the Arctic system. This research will address the physical, chemical, and biogeochemical character of the Arctic freshwater system and its interactions with the polar ocean and subpolar seas. It addresses the research planning embodied in the Study of Environmental Arctic Change (SEARCH) program, the Arctic/SubArctic Ocean Fluxes (ASOF) study, and the Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP) project. Areas of research include:

- Observation systems that take advantage of innovative technological advances and can serve as prototypes for sustained, long-term efforts to document and understand variability in key freshwater, ice, and chemical tracer fluxes and/or processes within the Arctic land, atmosphere, and upper-ocean systems and the teleconnection to the sub-Arctic oceans;
- Synthesis and integration of available data and modeling studies to reveal processes, linkages, and causes of variability in the Arctic terrestrial, atmosphere, and upper-ocean hydrologic cycle; and
- Documentation and assessment of the variability of the Arctic hydrologic freshwater cycle and associated changes in oceanic water-mass properties in the Arctic Ocean on the decade-to-century time scale.

Synthesis in ARCSS

Finally, ARCSS supports the integration of research results across components within ARCSS as well as with any other Arctic research program through a Synthesis, Integration and Modeling Studies (SIMS) effort. This activity is now achieving new prominence in the program, and as ARCSS ventures into its first program-wide synthesis, the program is increasingly interested in efforts that expand on the existing data-oriented SIMS effort and propose to synthesize knowledge of how the Arctic system works, with major emphasis on understanding the linkages between parts of the system and better articulation of the implications for the future.

The Arctic system includes physical, chemical, geological, biological, and cultural factors that may respond to global change. Some models that predict the climatic response to global change show greater change in the Arctic than in any other region. The predicted climatology, however, may not consider the largely unknown interannual-to-centennial variability in the Arctic. The presence of cultural institutions in a region subject to possible large perturbations, however, makes it important that scientists understand better the interactions of the global and Arctic systems. Therefore, the research supported in ARCSS extends beyond purely observational studies to those studies that predict and analyze the consequences of environmental variability and global change important to wise stewardship of renewable resources and the development of decision and policy options for resource managers and residents.

Arctic Natural Sciences

Arctic Natural Sciences (ANS) provides core support for disciplinary research in the following areas: glaciology, atmospheric sciences, ocean sciences, earth sciences, contaminants, environmental research, and biological sciences.

Glaciology

Glaciology research can focus on the history and dynamics of all naturally occurring forms of snow and ice, including seasonal snow, glaciers, and the Greenland ice sheet. The program also supports mass balance modeling, glacial geology, and remote sensing studies of ice sheets.

To date, the unique paleohistories preserved in Alaska's ice fields have not been tapped and thus have not contributed to this global climate synthesis. The sparseness of high-resolution climate histories from the northeastern side of the Pacific Basin has been a major obstacle to advancing our understanding of the rapid and recent changes in the dynamical state of the Pacific region and its global teleconnections. Ice cores recently obtained from the Bona–Churchill area in the Wrangell–St. Elias Mountains of southeastern Alaska will help fill this void by providing critical new insight into the climate history in this region. Ongoing research is assessing whether the warming of the last 30 years that appears to be amplified at high elevations in the tropics and subtropics extends to northwestern North America, characterizing the most recent "step" change in the dynamics of the Pacific Basin climate regime that occurred in 1976-77, exploring whether similar abrupt transitions have occurred in the past, and if so, determining when, and of what magnitude, were the changes. Ice cores were collected up to 460 m deep, the deepest ice core to be recovered from an alpine ice field. Short cores were recovered to determine the impact of drifting on the various chemical and physical signals preserved in the ice strata and to assess the reproducibility of the records. A light-weight, portable drilling system designed for coring to a depth of up to 700 m was developed for this project. The system was designed to be quickly switched from a dry hole electromechanical drill (used to 180 m) to a thermal-alcohol electric drill that collects cores from 180 to 460 m. The core quality ranged from good to excellent. A newly developed, quick-assembly geodesic dome housed all drilling and core processing activities.

The dust and calcium concentrations in the ice cores show distinct annual variations, and the preliminary results suggest that the annually resolved record will cover more than 2500 years. This bodes well for the recovery of a very high-resolution record of past climatic and environmental variability from these cores.

Lake ice studies in Alaska focus on understanding contemporary processes and predicting the consequences of climate variability and change. Ice thickness, ice type (snow ice and congelation ice), ice temperature, snow depth, and snow density are measured at the primary field sites in the vicinity of Poker Flat Research Range 50 km northeast of Fairbanks. In collaboration with a home-school group, a secondary site is maintained at a pond in central Fairbanks. The snow depth and density data are among the inputs used to force a one-dimensional thermodynamic model of lake ice growth and decay. The performance of the model is evaluated using ice thickness and composition data, as well as the dates of freeze-up and break-up. The model simulates contemporary processes well and is being used to investigate the effects of variation in the magnitude and timing of changes in air temperature and precipitation. Precipitation change has a greater effect than air temperature change on ice thickness and composition. The involvement of Fairbanks K-12 teachers and students in the Fairbanks research program has provided the impetus for the development of ALISON (Alaska Lake Ice and Snow Observatory Network), a science research and education program that promotes K-12 scientific inquiry and learning in the local context with those familiar and abundant materials, snow and ice, and that provides data on the variability of lake ice thickness, snow depth, and snow density around Alaska.

Petermann Glacier is the largest and most influential outlet glacier in central northern Greenland. Located at 81°N, 60°W, it drains an area of 71,580 km^2, with a discharge of 12 km^3 of ice per year into the Arctic Ocean. Ground-based, phase-sensitive radar measurements of ice thickness and thinning rates, ice velocity, strain rates, and climatological variables were made near the grounding line of the floating ice tongue of Petermann Glacier during the 2002 and 2003 spring field seasons. Last year's findings have confirmed that large channels, located several hundred meters deep at the underside of the floating ice tongue, are running roughly parallel to the flow direction. These channels were mapped using ground-penetrating radar at 25 MHz frequency and multi-phase radar in profiling mode over half of the glacier's width. NASA airborne laser altimeter and radar data were collected in both field seasons along and across the glacier for accurately assessing the surface and bottom topography.

Remote sensing has shown that 95% of the ice that crosses the grounding line of the Petermann

Glacier melts before it reaches the calving front. The dominant form of this mass loss (55%) has been attributed to basal melting of the ice tongue, with the never-before-measured surface ablation thought to account for about 2–3 m/yr. However, a transmitting automatic weather station on the Petermann Glacier, installed prior to the onset of melt during an extensive field campaign in 2002, allows surface ablation to be described for the first time. Although surface melting does not dominate the mass budget of the Petermann Glacier, field observations lend support to the notion that it may be relevant with regard to weakening and fracturing the floating tongue.

The movement of glaciers and ice sheets results from the deformation of the ice itself and sliding over the basal substrate. Where sliding occurs, its rate is about equal to that of flow due to internal deformation and therefore doubles the flow speed of a glacier, all else being equal. Under some circumstances, glacial sliding can accelerate rapidly, resulting in a surging glacier where flow speeds reach tens of meters per day before returning to its "normal" flow speed. Under other circumstances sliding may be always fast. In any case, water at the base of a glacier controls, in part, the sliding speeding by reducing the friction against the substrate. For temperate glaciers—those glaciers with temperatures at the melting point throughout the ice mass—water at the base of a glacier comes from surface melt. Streams flowing from glaciers have too great a discharge to be explained by geothermal melting at the glacier bottom. Our fundamental question is: How does the water get from the surface to the bottom of the glacier? Theory suggests that the water flows in naturally formed conduits in the ice. Frictional heating of the flowing water melts a passage into a sizeable conduit, somewhat analogous to solution channels (caves) in karst (limestone and dolomite). This project empirically tested this theory.

In the summers of 2000–2003 scientists traveled to Storglaciären, a small alpine glacier in Sweden and the site of long-term study by the University of Stockholm. Boreholes were drilled into the glacier until areas of hydraulic connection were intersected. A borehole camera was used to investigate the area of intersection, a compass and ruler were used to measure the size and orientation of the connection, and natural and artificial tracers were used to determine flow direction and flow speed. Pressure variations were monitored for the rest of the summer season. High-frequency radar profiles of the glacier subsurface were conducted to image the hydrologic passages that were intercepted in the boreholes.

The results were surprising. Eighty percent of boreholes hydraulically connected to a water-bearing passage inside the glacier. The borehole camera revealed that instead of conduit features with semi-circular cross-sections, all the connections were crack-like features. Water flow in the cracks was quite slow and typically at laminar speeds. Under such conditions it is unlikely that the water produces sufficient heat to significantly alter the geometry of the passage. So instead of creating conduits through frictional heating, the water takes advantage of existing passages formed by cracks. These results profoundly change our way of thinking about how water moves through a glacier. Naturally formed conduits (which can be observed near the margins of a glacier) appear to be special features of the subsurface hydraulic system, and cracks accommodate the bulk of the water flow. With this in mind, the results and conclusions based on the past 30 years of subsurface hydrological measurements will have to be rethought. Cracks exist throughout the entire body of a glacier and are not limited to the more brittle glacier surface. How these fractures originated—through advection from surfaces higher on the glacier or in situ—is not clear. In any case, that such cracks exist at all is interesting and leads us to reconsider the mechanical strength of a glacier. This is important not only to the behavior of alpine glaciers but also to the stability of giant ice shelves around Antarctica, which can catastrophically fail under warming conditions.

Atmospheric Sciences

Atmospheric sciences research focuses on stratospheric and tropospheric processes, climate, and meteorology. Research on past climates and atmospheric gases preserved in snow and ice is encouraged. The program also supports research on atmosphere–sea and atmosphere–ice interactions. In upper atmosphere and space physics, research interests include auroral studies, atmospheric dynamics and chemistry, and magnetosphere–ionosphere coupling.

In the past few years there has been an explosion of scientific interest in the chemical reactions that happen in sunlit snow. Rather than simply acting as the final resting place for pollutants that deposit from the air, snow turns out to be one of the most photoreactive regions on earth. These sunlight-driven reactions in snow release a number of important pollutants to the lower atmosphere, including formaldehyde, nitrous acid, and reactive halogens. In turn, these pollutants alter the composition and chemistry in the lower atmosphere. One of the major effects of snow emissions is that they alter concentrations of atmospheric radicals, highly reactive chemicals that clean the atmosphere. Snow reactions and how they change the amount of pollutants and radicals in the Arctic atmosphere are being explored.

In addition to changing the composition of the atmosphere, these sunlight-initiated reactions also change the make-up of the snow itself and the ice that eventually forms from the snow. Understanding how photochemical reactions influence ice composition will help others use ice cores to reconstruct what the atmosphere used to be like.

There are five major parts of the project: measuring radicals, measuring chemicals that form radicals, characterizing sunlight in the snowpack, determining the physical structure of the snowpack, and putting it all together to create a model of photochemistry in the snowpack.

The northern North Atlantic winter atmosphere is one of the most synoptically active areas of the planet, characterized by frequent cyclone generation and intensification. One reason is that the region lies downstream of the primary eastern North American trough, which provides a favorable environment for storms. But there are important regional processes. Cyclone development is especially preferred in the lee of Greenland and along the sea ice margin, where there are strong horizontal temperature gradients (baroclinicity) that extend rather deep into the atmosphere. This seems to be fostered, in part, by very large heat fluxes from ice-free open waters just south of the sea ice margin, especially in the Norwegian Sea. Associated deep convection mixes heat and water vapor upwards.

Over much of the Arctic, mid-tropospheric temperatures rarely fall below about –45°C. This minimum temperature coincides with that predicted for moist adiabatic ascent of air over a sea surface near its salinity-adjusted freezing point. A primary source region of this heating appears to be winter convection in the Norwegian Sea. Single-column model experiments simulating convective warming of a cold air mass moving over open water and undergoing radiative cooling as it moves again over cold land or sea ice support the hypothesis that the –45°C threshold can be maintained for 10–14 days after the air is convectively warmed.

Cyclone development processes and how they impact the sea ice circulation are being studied in more detail. Initial studies indicate that cyclone variability near the ice margin has a significant impact on the freshwater budget of the Arctic Ocean by modulating the flux of sea ice through Fram Strait.

Ocean Sciences

Ocean science research is concerned with expanding knowledge about the structure of the Arctic Ocean and adjacent seas, their physical and biological interactions with the global hydrosphere, and the formation and persistence of sea ice cover.

The most important subsurface Arctic Ocean transport system is an anticlockwise boundary current, which carries Atlantic (warm, salty) waters and Pacific (fresh, nutrient-rich) waters along the continental slopes and major trans-Arctic ridges. The most complex obstacle the boundary current encounters on its circum-Arctic pathway is the Mendeleev Ridge/Chukchi Borderland. This region, some 350 km northwest of Barrow, is the crossroads for Pacific-origin waters from the south and Atlantic waters carried from the west with the boundary current. The existing data suggest that some of the boundary current and some of the Pacific waters are diverted out into the deep basin in this region and that over the last decade a warming signal is propagating through the area. However, because of the complexity of the region and the paucity of data, we have no clear understanding of the processes that determine the fate of these waters.

In a changing Arctic Ocean, both issues are highly relevant. The sea ice is protected from the warmth of the Atlantic layer by a cold, low-salinity layer originating from the Arctic shelves and from the Pacific, and changes in the pathways or quantities of these waters could thin the sea ice. Similarly, the course and final depth of the nutrient-rich Pacific waters affect the local biological productivity, with implications up the food chain. Changes in the Arctic system over the last decades (the thinner ice cover and the generally warmer climate over both land and ocean) indicate the importance of gaining a clearer understanding of the general Arctic Ocean circulation, especially in complex regions such as the Chukchi Borderland.

A three-year project is investigating the physical and chemical oceanography of this region. Preliminary results show the continued advance of the Atlantic temperature maximum and unexpectedly large variability in temperature structure in the Atlantic core. Temperature and tracer data indicate the spreading of Pacific halocline waters north across the Chukchi Plateau and Northwind Ridge. Water mass analysis also supports the hypothesis of a "Taylor Cap," an isolated circulation, over the Chukchi plateau. Mooring data reveal a more complex structure to the boundary current than hitherto expected. As the analysis continues, reference to historic data from the region should allow understanding not only of the Chukchi Borderland of today, but also a glimpse of how things have changed in the last decade at this Arctic Crossroads.

Heat and salt exchanges at the ice/ocean interface play a key role in the annual cycle of sea ice growth and ablation. Recent observations of significant change in the extent and thickness of the Arctic ice cover have focused attention on factors that control the mass balance, and treatment of ice/ocean exchanges in numerical models is becoming increasingly sophisticated. Direct measurements of turbulent heat flux under pack ice have shown that the exchange coefficient is an order of magnitude smaller than the corresponding exchange coefficient for momentum. This implies that, unlike momentum flux, heat flux at the interface is rate-limited by molecular processes in thin sublayers adjacent to the surface.

Earth Sciences

Research on earth sciences includes all subdisciplines of terrestrial and marine geology and geophysics. Of greatest interest is a better understanding of Arctic geological processes that are important for improving our ability to interpret the geologic record of environmental change in the polar regions. Also of interest is better understanding and reconstruction of the plate tectonic history of the Arctic Ocean.

Large igneous provinces (LIP) are massive outpourings of mafic igneous rocks that commonly cannot be related to normal plate tectonic processes. A LIP of Cretaceous age, represented by Alpha Ridge, is thought by many to occupy the central Arctic Ocean basin. Given the thick ice cover, remoteness, and sediment overburden, a direct study of Alpha Ridge represents one of the more logistically challenging earth science subjects for the future. However, much can be learned about the nature of this LIP through land-based studies because correlative volcanic rocks are preserved in the stratigraphic sequences of the high Canadian Arctic (specifically on Axel Heiberg and Ellesmere Islands). These sequences also represent a storehouse of geological and geophysical information on topics ranging from the nature of Earth's magnetic field to past Arctic climate.

In a multidisciplinary study of these rocks, it was established that the major pulse of volcanism, which is similar to that typical of continental flood basalt provinces elsewhere, occurred at approximately 95 Ma. However, this volcanism was followed by a less-voluminous episode at 83 Ma (or younger). These ages rely on plume and non-plume models to explain the magmatism. Paleomagnetic studies indicate that the sites of eruption in the Canadian Arctic archipelago (at approximately 71°N) were contiguous with the North American craton, resolving debate concerning potential tectonic motions. Freshwater sediments overlying the volcanic rocks have been found to contain an important fossil fauna, including turtles and champsosaurs (extinct crocodile-like vertebrates). These fossils indicate extreme polar warmth during Late Cretaceous (Turonian) times.

The Arctic region is of special significance for understanding the nature and history of the geodynamo because of its proximity to the tangent cylinder, the imaginary cylinder that is tangent to the solid inner core. Numerical models of the geodynamo have shown that this region is critical in defining the nature of the field. Directional and paleointensity measurements of the Cretaceous Arctic lavas to date show that the field was dipolar, stable, and strong, suggesting that the basic features of the geomagnetic field are intrinsically linked. This conclusion has important implications for our understanding of the past, present, and future geomagnetic field.

Contaminants

ANS supports research in the area of persistent organic pollutant (POP) fate in the Arctic. These compounds are lipid soluble and can bioaccumulate in organisms that are ultimately harvested by the indigenous peoples of the Arctic. These "country" foods constitute a high percentage of the diet of many Native Americans, and as a consequence high levels of POPs may pose a long-term public health threat in the Arctic.

Much of the research conducted to date on POPs in the Arctic have focused on monitoring, i.e., measuring specific levels of POPs in environmental compartments (air, water, soil, biota), but little is known about POP fate in this environment. Recent research supported by ANS has focused on the photochemical transformation of POPs in Arctic surface waters. Many of the lakes, rivers, and nearshore marine environments contain significant quantities of dissolved organic matter (DOM), which are naturally derived and ubiquitous substances that are able to act as catalysts (photosensitizers) in the presence of sunlight. Photo-excited DOM releases a number of reactive species that can in turn react with POPS and transform them into other products, a process known as indirect photolysis. Because the Arctic experiences significant irradiance during the boreal summer, indirect POP photolysis maybe an important transformation pathway in waters that contain significant amounts of DOM.

Recent studies at Toolik Lake LTER in the Alaskan Arctic have shown that selective transformation of POPs can occur in sunlit Arctic surface waters. Hexachlorobenzene, a relatively ubiquitous Arctic POP, degrades readily in the presence of DOM and sunlight, while lindane, another commonly detected Arctic POP, does not. These studies demonstrate that in certain water bodies some POPs may be transformed, while others will be conserved and potentially accumulate. Thus, the fate of certain POPs in the Arctic will depend on their structure and the amount of DOM present in the surface waters. Ongoing studies at Toolik Lake will focus on other classes of POPs, such as polychlorinated biphenyls (PCBs), pesticides, and polychlorinated napththalenes (PCNs). All these substances have been detected in the Arctic and can potentially bioaccumulate in the food chain.

Biological Sciences

Biological science research emphasizes understanding the adaptation of organisms; freshwater, marine, and terrestrial biology; organismal biology; ecology; microbiology; ecosystem structure and processes; and the consequences of ultraviolet radiation.

Muskoxen are a relict of the Ice Age. Animals physically identical to modern muskoxen roamed the Arctic along with mammoths, horses, camels, and large cats. Yet muskoxen are one of the few large mammals that survived the end of the Pleistocene and continue to inhabit Arctic regions. Modern muskoxen were close to extinction around 1900 as a result of climate fluctuations and hunting pressure, but they have since recovered, with healthy native populations in Canada and Greenland and re-established populations in Alaska and Siberia. However, these current animals have low levels of genetic variability, which may limit their ability to adapt to future changes in their environment. Numerous Pleistocene-era muskox bones have been collected from the North Slope of Alaska, cataloged, and ^{14}C-dated by the Bureau of Land Management. These ancient bones, which have been frozen in the permafrost for thousands of years, are a good source of DNA for analysis of genetic change over time. DNA from the ancient muskox bones is being investigated to determine whether patterns of genetic change over time can be related to climate change. All DNA from the muskox bones more than 35,00 years old is very similar to that of modern muskoxen, suggesting that muskoxen have lacked significant genetic variability for a long time. Preliminary analysis indicates there is some genetic discontinuity between the muskoxen more than 35,000 years old and all the more recent muskoxen. Genetic analysis of the muskox bones is ongoing to fill in gaps in segments of DNA among individuals and to try to define the genetic change that occurred after 35,000 years ago. NSF and BLM jointly supported this project.

On arrival in the Arctic, migrant birds must adjust their physiology and behavior to unpredictable snow cover, weather, food sources, and predator pressure. In other words, they must cope with environmental perturbations (stress) so that they can migrate to their tundra nesting areas and settle on territories. Breeding must begin immediately when environmental conditions become favorable. They do this partly by using microhabitats where snow depth is low and patches of tundra melt out rapidly (especially near willows). Ground temperatures increase dramatically within hours after exposure to sun, and invertebrate activity begins simultaneously. Wind speeds are attenuated almost completely within 10 cm of the ground in willows and tussock tundra. The combination of these conditions provides an ideal refuge, especially for passerine migrants in early spring. However, if conditions worsen, they can leave. There are adjustments of the adrenocortical responses to stress because Arctic conditions in spring are potentially severe, at least compared with wintering grounds to the south. Secretion of corticosterone in response to acute stress is enhanced at arrival in males, accompanied by a decrease in sensitivity to negative feedback and a change in responsiveness of the adrenal cortex cells to adrenocorticotropin. There is also an increase in corticosterone-binding globulin levels so that the actions of corticosterone are buffered according to the severity of environmental conditions. Regulation at the level of genomic receptors, particularly the low-affinity type-2 receptor for corticosterone in the brain and liver, may be important, and non-genomic actions of corticosterone may play a major role. In other words, the hormone–behavior system associated with arrival biology is highly flexible.

After arrival on the tundra, migrant birds then begin establishing territories and attracting mates. At this time, circulating levels of testosterone are markedly higher than their congenors at lower latitudes, and adrenocortical responses to stress remain high, especially in populations at the northern edge of their range. Mating, nest building, and egg laying begins quickly, and within days incubation is underway. At this time the adrenocortical response to stress declines rapidly, and birds become resistant to acute stress. It is likely that once Arctic breeding birds commit to reproduction and are on eggs, they become resistant to stresses such as inclement weather because the breeding season is so short and no second nestings are likely. Additionally, these birds become resistant to the effects of high corticosterone levels typical of a stress response. Mechanisms underlying this modulation of the adrenocortical response to acute stress are under investigation.

Another change that occurs as the parental phase of breeding begins is a decline in circulating testosterone, including decreased sensitivity to this steroid hormone. Most songbirds apparently become refractory to testosterone, possibly as a mechanism to avoid distraction from parental care by male–male competition as seen in congenors at lower latitudes. This insensitivity to testosterone is accompanied by a decline in androgen receptor gene expression and reduced levels of aromatase, an enzyme that converts testosterone to an active form (estradiol) in the brain.

Future studies will continue to investigate the cellular and molecular bases of the behavioral ecology of Arctic breeding birds. One promising new area is the regulation of departure from the Arctic breeding grounds, a process about which we know essentially nothing.

In a study on protein conservation and the effects of diet quality, researchers used isotope kinetics to measure changes in the body composition and metabolism of female caribou and reindeer in winter.

Caribou consuming low-energy intakes in late winter apparently recycle carbon from body fat to membranes in other tissues because ^{13}C enrichment of red blood cells increases through winter. A similar redistribution of body protein is probably used to produce a fetus, even when intakes of nitrogen are less than 30% of predicted maintenance requirements for temperate species of deer. The role of dietary nitrogen in fetal growth is not clear because reindeer fed high protein diets during winter gain maternal lean mass as well as fetal tissue even as fat is lost. A close association between the enrichment of ^{15}N in urinary N and that of the diet in caribou suggests that dietary N may be preferentially oxidized over endogenous sources such as muscle. The apparent discrimination between stored and dietary N is unexpected, but it may be a novel adaptation to conserve maternal protein for fetal growth.

Arctic Social Sciences

The Arctic Social Sciences Program was established at NSF in 1990 and is starting a second decade of providing support for social science research across the Arctic. In the last three years, NSF has increased funding to the Arctic Social Sciences Program by 30% to its current level of $3 million, including research support and logistics. The program is unique at NSF in its support for a diverse portfolio of research projects from many social science disciplines, including anthropology, sociology, political science, linguistics, traditional knowledge, archaeology, and interdisciplinary research. In addition, the Arctic Social Sciences Program is unique within the Office of Polar Programs in its funding of stand-alone dissertation research projects. The program is committed to increasing the number of social science researchers from underrepresented groups, particularly rural Arctic Native residents. This commitment is realized by providing funds for unique education projects and workshops, supporting participation of Arctic Native peoples in science forums, and administering a cooperative agreement between NSF and the Alaska Native Science Commission (www.nativescience.org).

The following are highlights of the diversity of Arctic social sciences projects supported by NSF through the Office of Polar Programs in FY 03.

Alaska Natives in Geosciences

Alaska Natives in Geosciences is a project that broadens the participation of Alaska Natives in the geosciences at both the professional level and the community level by increasing geoscience literacy amongst the next generation of Alaska Native leaders. A college-level, field-intensive, introductory geoscience course is designed specifically for the high school juniors and seniors enrolled at the Rural Alaska Honors Institute (RAHI). This is followed by a community-based one-week field course open to RAHI graduates, as well as other Alaska Native geoscience students. Both classes will introduce Alaska Native students to the geologic issues and concerns relevant to Alaska Natives and their communities.

Alaska Native Science Commission

The Alaska Native Science Commission (ANSC) is funded in part through a cooperative agreement with NSF. ANSC is made up of Alaska Native scholars and scientists who facilitate the connections between rural Arctic communities and NSF-supported research. Through workshops, personal contacts, meetings, and research projects, ANSC has assisted scientists in making contact with Alaska Native communities and facilitated Native peoples' voices in Arctic science. By partnering in this way, scientific research can meet both research goals and the needs of Alaskan rural communities. In addition, ANSC maintains an internship program for Alaska Native students that helps increase the exposure of students to the many disciplines of science and engineering. ANSC publishes a quarterly newsletter to inform Alaskan communities about NSF science projects in their regions and provides a critical link between science, education, and local community concerns.

Northern Science Education Program

The Northern Science Education Program is the continuation of a Research Experience for Undergraduates site that provides a unique science education for urban undergraduate minority (53% of the participating students are women and 33% are from underrepresented minority groups) and nonminority students in Iceland by working on an early human settlement and historical landscape project. Based on the curriculum of interdisciplinary science (e.g., archaeology, zooarchaeology, human osteology, marine mammal necropsy, soil science, geographic information systems, and climate change), the students define and carry out their own research projects under the careful guidance of graduate student mentors and professors.

Dena'ina Archiving, Training, and Access

DATA is a cooperative project between the Alaska Native Language Center at the University of Alaska and the LINGUIST List program at Eastern Michigan University to preserve Arctic languages. The project digitizes existing collections of Dena'ina documentation using the standards and software developed by The LINGUIST List as part of the E-Meld project. The E-Meld project develops and implements recommendations of digital best practice for linguistics data. Through E-Meld the DATA project will create long-lasting archival formats and standardize linguistic data digitization of Dena'ina. In addition, both Native and non-Native students are being trained in linguistic research practices, applied computational linguistics, and linguistic analysis for the future preservation and revitalization of Dena'ina. This project is not only facilitating the preservation of Dena'ina for community members but is also standardizing the linguistics information so as to make it accessible and useful for scientific computational analyses.

Reducing Land Use Conflict in Arctic Wilderness Areas

This research project is examining public policy and cultural values of stakeholders in land use policy for Arctic wilderness areas. The researcher is comparing three case studies of wilderness areas in Finnish Lapland, Alaska, and the Yukon Territories of Canada in order to understand and explain the variation in conflict between local and non-local groups in these regions. The research will bring a comparative perspective of conflict resolution in cross-cultural as well as national contexts. In addition, it will inform the debate over contested meanings of wilderness between indigenous land users, land managers, and environmental groups.

Education

Objectives for education and outreach at NSF include the broader impacts that researchers perform as part of their projects as well as targeted projects aimed at improving education in science, technology, engineering, and mathematics (STEM). The Arctic Research and Education program, with an FY 04 budget of $250K, supports projects that bridge scientific research with education and public outreach, with emphasis on those that increase participation of underrepresented minorities in science. The approach of the program is to support projects that involve each level along the education continuum from K-12 through graduate school and the public at large. Awards are made as grants, supplements to existing awards, and co-funding to projects receiving primary funding from other directorates.

The programs Teachers Experiencing Antarctica and the Arctic (TEA; 1997–2003) and Teachers and Researchers Exploring and Collaborating (TREC; 2004) provide field research experiences for K-12 teachers to become members of field expeditions as engaged members of the field team. The nearly 40 teachers representing over 20 states who have been part of these programs have brought inquiry-based science to their classrooms, colleagues, and communities. The teachers have networked into a learning community that continues to be involved in polar research.

High school, undergraduate, and graduate students have been supported by the program to participate in research projects, receive mentoring, and participate in workshops and conferences. Through these experiences and the ensuing connection with STEM fields, new generations of scientists and engineers are developed who are familiar with Arctic research. Journalists convey information about science to perhaps the broadest audience through print and visual media. A project providing journalists with Arctic research experience in the lab and field is an important contribution to ensuring that research is reported on by journalists who understand the scientific process. While the scale of the program is small, its reach is increased by involving a broad cross-section of society in Arctic research and through its partnerships with other programs at NSF.

Arctic Research Coordination

NSF supported a program of polar information and advisory services; provided support for the Interagency Arctic Research Policy Committee; provided funds for the Arctic Research Commission; and supported conferences, workshops, and studies to further develop and implement Arctic research planning and policy.

As required by the Arctic Research and Policy Act of 1984, a comprehensive U.S. Arctic Research Plan was prepared by the Interagency Arctic Research Policy Committee and submitted to the President in 2003. The eighth revision to the U.S. Arctic Research Plan included two major sections. The first of these presented the Special Focus Interagency Research Programs:

- Arctic Environmental Change;
- Bering Sea Research and Assessment; and
- Arctic Health Research.

The second major section was Agency Programs, which represents the objectives of Federal agencies, focusing on the period covered by this revision (2004–2008). They were presented in seven major categories:

- Arctic Ocean and Marginal Seas;
- Atmosphere and Climate;
- Land and Offshore Resources;
- Land–Atmosphere–Water Interactions;
- Engineering and Technology;
- Social Sciences; and
- Health.

The Interagency Plan also addressed issues related to logistics support for Arctic research and new opportunities for Arctic research. The biennial revision of the U.S. Arctic Research Plan serves as guidance for planning by individual agencies and for coordinating and implementing mutually beneficial national and international research programs.

NSF supports many other interagency planning and coordinating activities. Coordination with global change programs is an integral part of Arctic program development and implementation. Improved communication at all levels is encouraged through newsletters and journals.

Engineering and Technology

The Engineering, Geosciences, and Mathematical and Physical Sciences Directorates support research in engineering, material sciences, and permafrost. Research has included studies of the mechanical properties of ice, the hydraulic conductivity of frozen soils, metamorphism of dry snowpacks, and three-dimensional analyses of ice.

Research Support and Logistics

NSF is using new resources targeted for Arctic logistics to enhance the U.S. leadership role in Arctic research. The focus on logistics entails:

- Establishment, development, and maintenance of national Environmental Observatories;
- Technology and instrument development;
- Expansion of marine platforms and aircraft support capabilities;
- Integration of research, education, and Arctic community interests; and
- Further international collaboration in the support of research.

The use of the new resources is guided by the Arctic Research Commission's report *Logistics Recommendations for an Improved U.S. Arctic Research Capability* [available from the Arctic Research Consortium of the United States (ARCUS) at http://www.arcus.org]. The general recommendations of the report are:

- Ensure access to the Arctic over the entire year;
- Increase the availability and use of remote/autonomous instruments;
- Protect the health and safety of people conducting research in the Arctic;
- Improve communications and collaboration between Arctic people and the research community; and
- Seek interagency, international, and bilateral logistics arrangements.

Planning is carried out in partnership with Native groups and other advisory bodies and responds to merit-reviewed proposals.

Another major logistics issue in the Arctic is developing full access and capability to conduct research on all aspects of the Arctic Ocean. NSF facilitates this by funding research use of the new Coast Guard icebreaker *Healy* and supports improved sensors for the Arctic drifting buoy program, moorings, and autonomous underwater vehicles. For both marine and terrestrial research, NSF works to improve basic health and safety by providing access to a pool of emergency beacons, satellite phones, and GPS receivers.