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 areas: 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.

The following sections present highlights of several major programs and selected projects. A complete listing of NSF-funded Arctic projects can be obtained from the Office of Polar Programs, National Science Foundation, Arlington, VA 22230.

	Funding (thousands)	
	FY 04	FY 05
Arctic Res. and Policy Support	90	94
Arctic Res. Supp. and Logistics	36,565	35,047
Arctic Res. and Education	250	320
Arctic System Science Program	20,250	20,250
Arctic Social Sciences	2,455	2,415
Cyberinfrastructure and Sensors	1,240	924
Information and Advisory Serv.	90	90
Arctic Natural Sciences	12,258	12,900
Arctic Research Commission	1,556	1,190
Funds Reprog. to Coast Guard	0	2,400
OPP Total	74,753	75,630
Non-OPP	26,000*	26,000*
Grand Total	100,753	101,630

* Estimated

Arctic System Science

The Arctic System and the ARCSS Program

The Arctic is a complex system consisting of physical, biological, and social components that interact across a wide range of temporal and spatial scales. Sea ice, ice sheets, and permafrost are key features that distinguish the Arctic from lower latitude systems. The Arctic system behaves in ways that are not fully understood, and it has demonstrated the capacity for rapid, amplified, and unpredictable change with global implications. Because of the Arctic's pivotal role in the earth's climate, it is critical—perhaps even urgent—that we understand this system in light of abundant evidence that a set of linked and pervasive changes are underway. What do these changes mean for the future of both the Arctic and the earth? To address this question, ARCSS research focuses on understanding the fundamental characteristics, dynamics, and controlling principles of the Arctic system through integration and synthesis of knowledge from past and ongoing studies.

In 1989 the NSF established the Arctic System Science (ARCSS) program, an interdisciplinary program that strives 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. ARCSS works towards advancing the scientific understanding needed to predict environmental change on a decade-to-centuries time scale and to inform policymakers on 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, especially with NASA and NOAA on projects dealing with Arctic climate and ocean processes and modeling research. ARCSS research continues to contribute to the U.S. Global Change Research Program.

The ARCSS program adapts its structure and goals to the progress of its research. This adaptation is achieved through various mechanisms, including a scientific committee erected by the research community, that provides a community perspective on the overall coordination and integration of ARCSS. To ensure community participation, ARCSS has used various methods to develop new ideas and set priorities, including workshops and open meetings. Recently the program has sought to improve its facilitation of dialogue in the research community and improve the exchange of ideas between the program and its constituents. As outlined below, ARCSS is exploring new modes of pursuing its science and of interacting with the broader scientific community with the intent of engaging as many people as possible in a responsive planning process.

The guiding question for ARCSS at present is: What do changes in the Arctic system imply for the future?

Planning is focused on three science questions:

- How do the interconnected social, physical, chemical, and biological systems of the Arctic operate and interact to define and drive the Arctic system (broadly defined)?
- How does the Arctic system interact with the larger earth system?
- What is the trajectory of the Arctic system and the implications of that trajectory in the years and decades to come?

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.

To address these questions ARCSS must:

- Advance from a component understanding to a system understanding of the Arctic;
- Understand the behavior of the Arctic system, past, present, and future;
- Understand the role of the Arctic as a component of the global system; and
- Include society as an integral part of the Arctic system.

In recent years ARCSS focused on several disciplinary components: Ocean/Atmosphere/Ice Interactions; Land/Atmosphere/Ice Interactions; Human Dimensions of the Arctic System, and Paleoenvironmental Arctic Sciences (PARCS), under which research activities were developed. (PARCS proposals were considered within the Earth System History competition at NSF.) This disciplinary focus was necessary to build communities and knowledge bases for these disciplines. However, once that was achieved, the structure of the program began to evolve to one more amenable to its goal of understanding the Arctic as a system. Thus, most of these components have now been replaced by a more proactive ARCSS committee that guides the system-level thinking of the program, strives to develop more extensive connections to a broader array of disciplines for new ideas, and devotes considerable attention to fostering ARCSS research efforts during their full life cycle from inception of ideas through archival of data, synthesis of results, and communication of scientific knowledge to the research community and the public.

Shelf–Basin Interactions

A current example of a process-oriented ARCSS research activity is the Shelf–Basin Interactions (SBI) project, established to improve understanding of the role of the large continental shelf seas off Alaska in marine 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:

- 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.

The SBI project has finished most of its field activities and is now analyzing the results of its work and producing scientific summary documents. It is anticipated that it would eventually participate in a final phase in which SBI results are incorporated with other similar results and related to the functioning of the Arctic system.

Researchers retrieving a CTD (conductivity, temperature, depth profiler) rosette on the USCGC Healy *during the Shelf–Basin Interaction (SBI) study of the northern Bering Sea in 2005.*

Freshwater Cycle Integration Study

The first exercise in a new mode of ARCSS research, the Freshwater Cycle Integration Study, was developed as a thematic interdisciplinary approach that addressed a major part of the Arctic system. This research addresses the physical, chemical, and biogeochemical character of the Arctic freshwater system and its interactions with the polar ocean and subpolar seas. The 22 projects constituting the effort are not only engaged in field research on Arctic freshwater systems, but they have also begun formulating a series of united research perspectives and project outputs. The strategy has been to foster mechanisms to achieve a project synthesis by uniting available water system data streams, process studies, and modeling. The goals are to reveal processes, linkages, and causes of variability in the Arctic terrestrial, atmosphere, and upper-ocean hydrologic cycle through an integrated set of research activities focused on three science questions: Is the Arctic freshwater cycle intensifying; if so, why; and what are the implications? These questions span traditional land–ocean–atmosphere communities and have brought diverse communities into active cross-disciplinary dialogue.

Two avenues of investigation have been pursued. One aims to synthesize existing quantitative information to construct a comprehensive freshwater budget linking fluxes and stocks through all major domains of the pan-Arctic system: atmosphere, land, ocean, and sea ice. The articulation of such a budget has highlighted several chal-

Scientist taking an ocean temperature and salinity profile at the side of a lead during field work.

lenges in establishing the "fundamentals" of the Arctic water system and has identified critical existing unknowns in data coverage, spatial and temporal harmony, and consistency across measurement campaigns. It has also shown the need for coherent strategies to address the subtleties associated with the inherent variability of the Arctic hydrological system. A second direction is the attempt to establish the consistency of changes across observational studies of paleo, historic, and contemporary water systems with simulated behaviors generated by Arctic and earth system models. This will allow us to assess our system understanding of observed changes and search for the attribution of such changes. To make these efforts relevant to the policy community, a new emphasis is on the implications and impacts of Arctic system change, specifically on ecosystems, on climate, and on humans living both in and outside of the Arctic.

Scientists on the Lena River in Siberia. After sampling the river at approximately 71°N, they disembarked at the village of Kyusyur to meet with the local hydrologist responsible for making Lena River discharge measurements. The Lena River, roughly equal in discharge to the Mississippi, has been monitored daily since 1936. Its discharge has increased substantially over the past several decades, likely in response to global warming.

Study of the Northern Alaskan Coastal System

Lying at the intersection of the land, ocean, and atmosphere, and the locus of much human activity, the coast is a critical interface in the Arctic system and was considered to be an ideal test bed for tackling the kinds of complex scientific issues required to develop a true systems approach to Arctic research. In early 2004, NSF released an announcement of opportunity for a Study of the Northern Alaska Coastal System, a second effort towards system-wide research, this time with a regional approach. The announcement defined the coastal system very broadly, as the region extending from the Brooks Range in Alaska to the ice edge at sea, and was open to all disciplines. Six projects were supported on subjects including bowhead whales and the marine ecosystem, carbon interconnections, organic carbon and eroding coastlines, halomethane gas exchange, synthesis and scaling, and the deposition and fate of mercury. Although it was not through any active steering or design, most of these projects focused their field activities in Barrow, Alaska, and this circumstance provided excellent opportunities for close collaboration with one another and with scientists from other agencies, as well as for outreach to the community. Although widely divergent in discipline and approach, these projects are working closely together and finding unexpected synergies in their research.

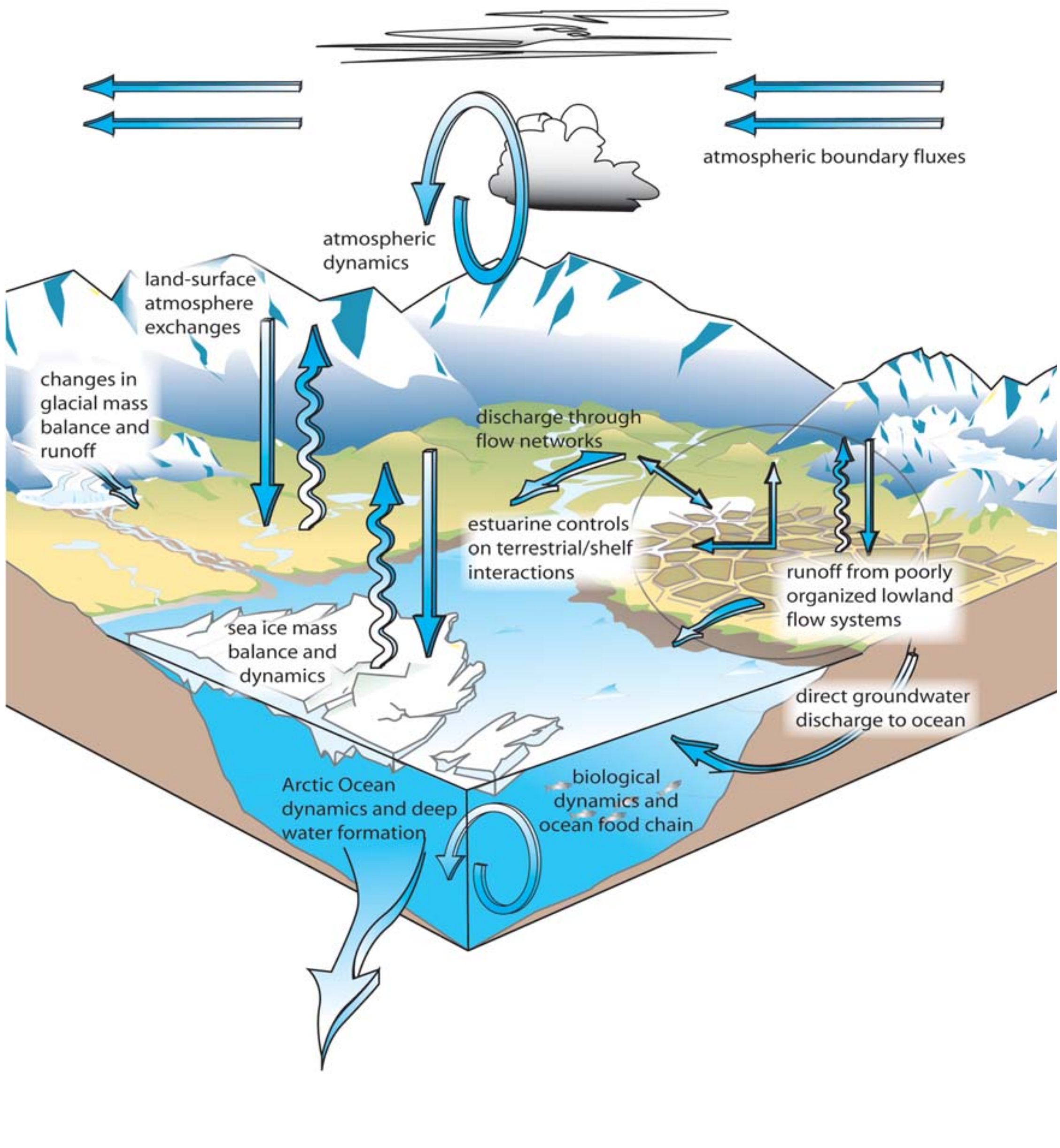
Human Dimensions of the Arctic System

Human Dimensions of the Arctic System (HARC) has been a collaborative effort with the Arctic Social Sciences Program to integrate natural and social sciences research that demonstrates 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. 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 and social sciences will increase policymakers' understanding of regional natural and social systems and build linkages among 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. This effort is still being fostered actively in ARCSS; the goal is not to establish a social science sub-program, but rather to make social science a part of the fabric of all ARCSS research. ARCSS has supported the HARC effort by funding several large collaborative projects. An example can be found in a large project funded in 2004 called The Intersection Between Climate Change, Water Resources and Humans in the Arctic. In this project, researchers in natural science, engineering, and social science are linking hydrological, cultural, and engineering studies in the Seward Peninsula of Alaska with the goal of understanding the vital role that fresh water plays in the lives of humans in the Arctic.

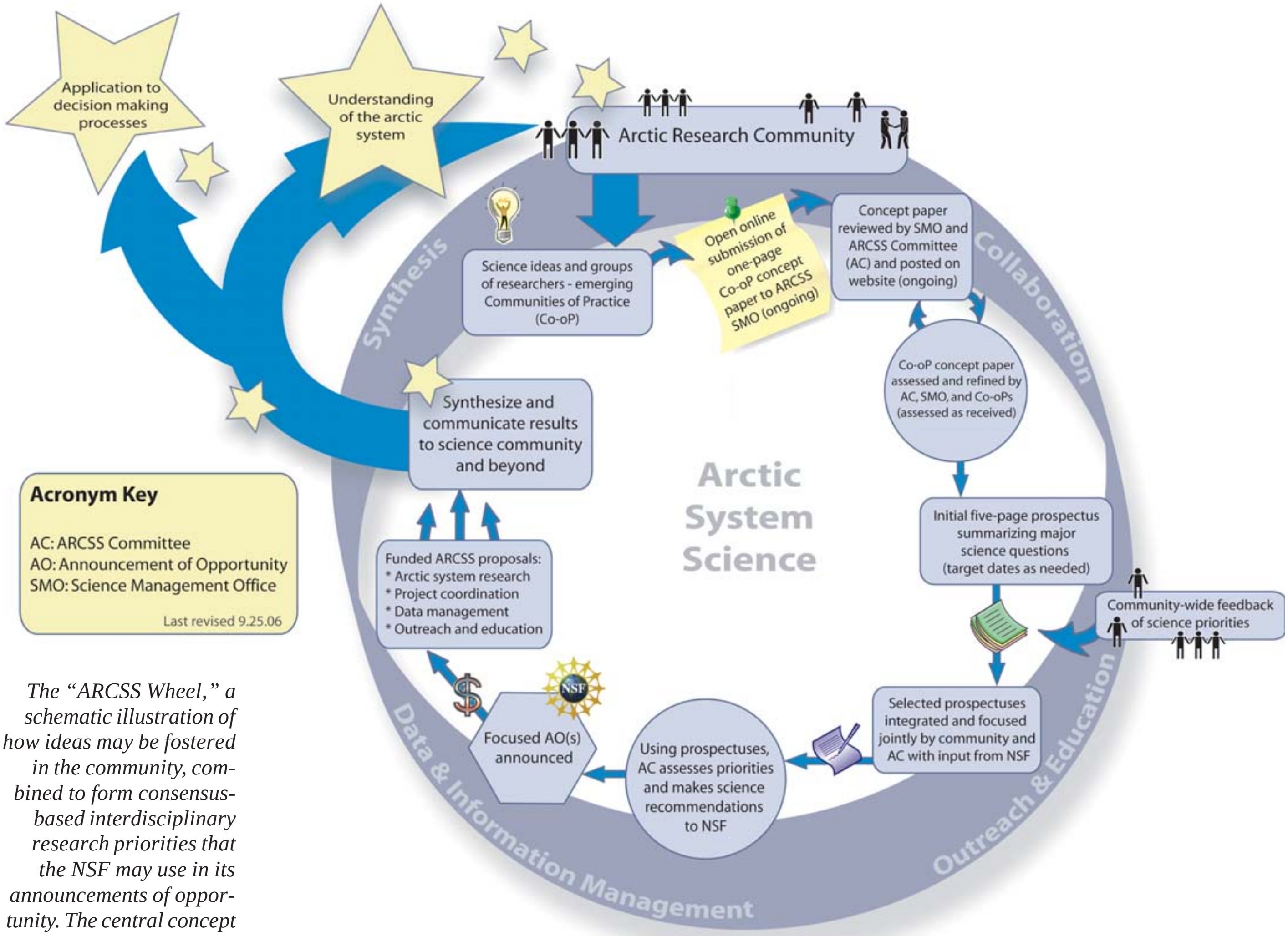
Synthesis in ARCSS

ARCSS has long supported the idea of integrating research results across components through a Synthesis, Integration and Modeling Studies (SIMS) effort. This activity is now achieving renewed prominence in the program. As ARCSS ventures into its first program-wide synthesis, the program is expanding on the existing data-oriented SIMS effort to synthesize knowledge of how the Arctic system works, with a major emphasis on understanding the linkages between parts of the system and better articulation of the implications for the future. “Synthesis,” as ARCSS has employed it, is essentially the juxtaposition of disparate ideas, facts, or data to gain unexpected insight. In essence it is the pursuit of surprise by design.

Although it was not widely called synthesis then, the process of synthesizing the community's collective knowledge of the Arctic system really began at an ARCSS All-Hands Workshop, with more than 300 ARCSS researchers participating. It continued formally with the Big Sky Synthesis Retreat (Big Sky, Montana) of a few dozen scientists in August 2003. The retreat’s goals were to analyze and then synthesize available knowledge into a system perspective of the Arctic. Scientists from a variety of disciplines investigating many components of the Arctic system attended, and most called it a tremendous learning experience in the form of an opportunity to discuss commonalities and linkages among researchers who rarely cross paths. Discussions centered on the interwoven complexity of recent Arctic change, how this



Schematic of the Arctic system, showing the areas of current ARCSS synthesis activity.



The "ARCSS Wheel," a schematic illustration of how ideas may be fostered in the community, combined to form consensus-based interdisciplinary research priorities that the NSF may use in its announcements of opportunity. The central concept is the sharing and managing of information throughout the cycle of inquiry, from conception of idea to publication and interpretation of research results, informing the public and policy makers, as well as feeding further idea development.

fabric of change is tied to the larger global system, how it will unfold in coming years, and what the implications for humans may be. This assembly of expertise led to the realization that Arctic change is pervasive, widespread, and dramatic, and hence to the "Big Sky Question," "Is the Arctic system moving to a new state outside the envelope of the natural glacial–interglacial cycle?" Throughout the week, the participants worked together, offering their own expertise and perspectives, to give their best determination of whether the Arctic is moving toward a new state. By the end of the week, participants reached near-unanimous agreement that the Arctic is likely moving outside the envelope of past experience, and possibly toward a new state, and that we do not yet understand the implications for the Arctic, the global climate system, or human society. Participants also agreed that a state change could include major surprises and non-linear responses of Arctic components and that the implications could be wide-ranging and substantial for humans.

An important product from the retreat was a paper (*EOS*, Vol. 86, No. 34, 23 August 2005, p. 309–316) describing the motivation for the synthesis approach, as well as new insights from discussions at the Big Sky gathering. Numerous other questions were raised at the retreat too; some were pursued in a second retreat a year later, and a group funded to synthesize the results of the paleoenvironmental efforts in ARCSS is examining others.

To engage the larger community in this effort, ARCSS held a special competition called Synthesis of Arctic System Science (SASS) in 2005, soliciting proposals to consider the Arctic as a system. There were nine successful projects supporting 44 investigators to explore various aspects of the system. A supplemental activity will engage these various projects in seeking synergies among their efforts and identifying how well their collective results describe the system.

ARCSS will likely continue to support efforts that synthesize knowledge of how the Arctic system works (including a focus on the linkages between parts of the system) and better articulation of the implications for the future. In general the program is trying to concentrate on understanding the relations among the components of the system and leaving the detailed studies at the subcomponent level to other, more disciplinary programs. ARCSS will also continue to conduct field research to address key questions but will use its ongoing synthesis to help identify the problems of highest priority to be pursued in the field.

Engaging the Community

ARCSS is both a program that funds research projects and a process to plan for future directions of its science. In the latter mode, it has moved deliberately away from a hierarchical array of committees that developed disciplinary projects, to experimenting with new ways of bringing ideas into the program. Most recently the program has engaged the community directly using electronic discussion groups. Thus, immediately after the most recent competition results were released, an open meeting was held with the community (an "e-town meeting") in which over 60 people discussed the results and considered directions of ARCSS synthesis. Other mechanisms will include sponsored Communities of Practice that will develop new ideas. The intent is that these communities will generate science ideas, and as they mature and are combined with other ideas, they will progress through a series of steps to feed into mature interdisciplinary research priorities that NSF may draw upon to develop new announcements of opportunity. This approach is very much in keeping with NSF's goal of listening to the community in order to respond quickly in developing research priorities, but it also allows these ideas to be focused to meet ARCSS goals. ARCSS will continue to explore new ways of engaging as many people as possible in its research agenda.

Arctic Natural Sciences

Arctic Natural Sciences (ANS) provides core support for disciplinary research addressing Arctic processes in the areas of cryospheric sciences, atmospheric sciences, ocean sciences, earth sciences, and biological sciences.

Cryospheric Sciences

Research in the cryospheric sciences focuses on the history and dynamics of all naturally occurring forms of snow and ice, including seasonal snow, glaciers, sea ice, permafrost, and the Greenland ice sheet. The program also supports studies of glacial geology.

A significant focus of glacial field research continues to be the collection of observations sufficient to develop theory and predictive models of glacial dynamics and mass balance, as well as the subsequent validation of those models. Observations of Helheim Glacier, in East Greenland, indicate rapid retreat associated with thinning of the glacier and acceleration of its seaward velocity. Lagged acceleration of tributary glaciers is also occurring. Comparison of these data with theory suggests that the acceleration and thinning are, predominantly, responses to the calving and retreat of the glacier front, rather than to thermal melting during summer. The potential for enhanced calving and retreat associated with a thinner glacier suggests that an important positive feedback mechanism is at work. In related studies of Bench Glacier, in the Chugach Mountains of Alaska, associations between the horizontal motion of the glacier and excess pressure at the base of the glacier suggest that increased subglacial connectivity of the water flow may result initially in increased velocity, but that rapid drainage then leads to increased friction and slower velocity for the glacier. Observations of Breiðamerkurjökull, Iceland, following liquid precipitation events support these suggestions. Two neighboring sections of the glacier sat on rough bedrock and smoother till, respectively. Excess pressure at the bed diminished following the precipitation and initial drainage events, allowing the ice over rough bedrock to settle back onto the bottom features, the water connectivity to diminish, and the ice velocity to decrease. Over the smoother till, connectivity was maintained, even after the initial drainage event, and high ice velocities persisted. The fact that high velocity leads to further bed erosion again suggests significant potential feedback mechanisms on the glacier's dynamics.

Atmospheric Sciences

Research in the atmospheric sciences focuses on stratospheric and tropospheric processes, climate, and meteorology. Upper atmosphere and space physics concerns include auroral studies, atmospheric dynamics and chemistry, and magnetosphere–ionosphere coupling. These efforts are often supported jointly by the Division of Atmospheric Sciences and the Antarctic Aeronomy and Astrophysics Program. The difficulties associated with obtaining the direct observations necessary for structuring model development and then for model–data comparison continue to argue for significant resources being devoted to observational programs in these latter disciplines.

A large international collaboration recently has completed a comprehensive campaign that directly measured the size and composition of particles forming polar stratospheric clouds. These data clearly define the importance of nitric acid trihydrate in such clouds.

Observations continue to indicate initial cooling of the Arctic mesopause approximately two days prior to a stratospheric warming event, thus offering the possibility of early warning of such an event. This seems to be associated with intense planetary wave oscillations of the mesopause–lower thermosphere region at least four weeks earlier. The observations suggest that the planetary waves alter the structure of the atmosphere, lowering the regions where upward-propagating gravity waves break and causing the associated warming to occur in the stratosphere rather than in the mesopause.

Numerous ground-based observation systems observe the dynamics and consequences of space weather. Recent observations suggest that substorm initiation does not require plasma sheet changes as intense as previously thought. They also suggest that a majority of substorms with well-defined onsets are associated with a reduction of large-scale convection.

Space weather studies have been hampered by the inconsistent definition of the polar cap index, a proxy for various measures of the coupling between the solar wind and the magnetosphere, in the northern and southern hemispheres. Ongoing development of a more accurate and objective technique for deriving these indices is anticipated to facilitate the use of extensive data sets being collected in both polar regions.

Ocean Sciences

Research in the ocean sciences is focused on understanding and predicting the structure and dynamics 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. This last topic involves close linkages with the cryospheric sciences.

An important aspect of the Arctic Ocean transport system is an anticlockwise boundary current, which carries Atlantic (warm, salty) waters and Pacific (fresher, nutrient-rich) waters along the continental slopes and major trans-Arctic ridges. This current system is undersampled in both time and space. Detailed numerical modeling is being applied to study three regions of the system where the topography is believed to be particularly important: St. Anna Trough, where the two inflowing branches of Atlantic Water, each having been modified by atmospheric cooling and/or ice melt, converge and interact to produce a single current; Lomonosov Ridge, where the current system bifurcates, with part flowing north along the ridge and the rest continuing into the Canadian Basin; and the Mendeleyev Ridge/Chukchi Borderland, where the remainder of the current system that passed the Lomonosov Ridge encounters particularly tortuous topography. As an extension of these studies, rotating stratified hydraulic theory has been applied to the deepest pass through the Lomonosov Ridge. The resultant flow rates have been used to estimate the age of the deep water in the Canadian Basin. The theory suggests water ages roughly 150 years older than in the Eurasian Basin, in good agreement with the 200-year age difference previously estimated from carbon-14 dating.

Processes within this boundary current system have been implicated in the transport of shelf water into the subsurface interior of the Arctic Ocean (ventilation). Arctic Ocean 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 result in thinning of the sea ice. Furthermore, the course and final depth of the nutrient-rich Pacific waters entering the Canadian Basin from the Chukchi Sea affect the local biological productivity, with implications up the food chain. These ventilation processes are also being modeled numerically in an effort to understand controls on the exchange processes. Initial results from a stratified model of Chukchi Sea dynamics confirm the main flow features anticipated from sparse observations and earlier non-stratified modeling results. They also suggest a significant role for local atmospheric forcing within the Chukchi Sea in controlling the water mass characteristics of those waters ultimately advected into the Canadian Basin.

An intriguing situation arises when one performs a model–data comparison of flow within the Atlantic Water layer of the Arctic Ocean. The Arctic Ocean Model Intercomparison Project

(AOMIP), an international consortium that compares Arctic Ocean models by driving them with identical forcing fields, finds that its model results can be separated into two groups with almost exactly opposite patterns; among 11 model results posted in their web site, 6 are counterclockwise and 5 are clockwise, while observations suggest a counterclockwise circulation. Theoretical studies of the circulation of the Arctic Ocean suggest that modeled circulation fields are sensitive to the circulation structure (potential vorticity) at the inflow through Fram Strait, requiring great care in accurate depiction of this condition in realistic models.

Earth Sciences

Research in the earth sciences includes all subdisciplines of terrestrial and marine geology and geophysics. Of particular interest are studies leading to an improved understanding of Arctic geological processes that enhance our ability to interpret the geologic record of environmental change in the polar regions and to reconstruct the plate tectonic history of the Arctic Ocean.

Warming of the northern latitudes during the Middle Miocene is particularly clear in the north Pacific region. Recent collections of bivalves and gastropods have been used to document, contrast, and compare this climate change and its impact in Alaska and Kamchatka, Russia. The principal samples were derived from Kodiak Island and regions near the Bay of Korf. At the beginning of the Middle Miocene Climatic Optimum (14.5–17 Ma BP), these regions suffered a molluscan community shift from cool- and cold-water mollusks to warm-water species. Analyses of $\delta^{18}O$ within the mollusk shells indicate seasonal temperature ranges of 8–22°C in the Bay of Korf samples and 14.7–28.7°C in the Kodiak Island samples, similar to present-day ranges from much lower latitudes. In contrast, samples from the Sea of Okhotsk, at the same latitude as the Bay of Korf, suggest temperature ranges of 0.5–5.9°C, similar to the range that exists today. Both the faunal and the isotopic data further suggest that the climatic changes in the region occurred as a series of events that perturbed a cooler water background, potentially because of warm water advection into the region, in contrast to the situation at lower latitudes, where the Middle Miocene Climatic Optimum is seen as a single event.

Existing theories of the timing and extent of the Eurasian/Fennoscandian ice sheet over the Barents Sea are conflicting. The lack of glacial geomorphic depositional features exacerbates the situation. Recent ^{26}Al and ^{10}Be ages of common glacially eroded bedrock quartz veins and granitic glacial erratics are beginning to shed light on the history of the region. The observed $^{26}Al/^{10}Be$ ratios suggest long prior burial (greater than 200,000 years) and minimal erosion (less than half a meter) during the last glacial maximum. Related work over the East Greenland shelf recently has used seismic and core data to document the retreat of the Greenland ice sheet from the shelf break in the Denmark Strait to the present coast during the period from 17 to 11.5 ka BP. In related studies, a major meltwater pulse from the Greenland ice sheet has been documented to have begun during the Allerod chron and intensified at the onset of the Younger Dryas period. The relationship of this meltwater pulse to the timing of the Younger Dryas remains to be clarified, but theoretical work has suggested that freshwater pulses that alter the thermohaline circulation of the North Atlantic Ocean presage the onset of cold climatic periods. Other work has long suggested a relationship between the commencement of the Younger Dryas and the draining of Lake Agassiz. Recent theoretical and modeling work, though, notes that freshwater pulses from Lake Agassiz would be confined to the shelf/slope regions at least as far south as the Tail of the Grand Banks. This is consistent with the lowered $\delta^{18}O$ in shelf cores and the lack of such a signal in the Nordic Seas. These findings raise questions concerning the role of Lake Agassiz disharge in modifying deep convection in the Nordic Seas and, consequently, driving the Younger Dryas cold period.

Biological Sciences

Research in the biological science emphasizes understanding ecosystem processes and the adaptation of organisms to Arctic conditions.

A study of muco-polysaccharide produced and excreted (exopolymeric substances, EPSs) by microorganims living in Arctic sea ice concluded that EPSs protect microbial communities from encroaching ice crystals through alteration of their microhabitat. The research has yielded a number of interesting results that are of relevance well beyond the original aims of the study. Apart from finding EPS throughout the ice cover in copious amounts, more was learned about its little-known contribution to organic carbon cycling in sea ice. Furthermore, the polysaccharide slime matrix appears to be important in allowing diatoms and other microorganisms to survive and remain viable at temperatures below –10°C. The study was able to show that a large fraction of the algal population in Arctic sea ice is enveloped in a slimy matrix of EPS, which creates a transparent and flexible physical barrier between the organism and its environment. Since EPS modifies the shape and connectivity of pore space in the ice as fluid inclusions containing microalgae shrink with dropping temperatures, work has begun to investigate other impacts of EPS on the physical properties of ice, leading to interesting insights concerning potential industrial applications of EPS and related classes of polymer compounds that modulate the physical properties of ice. In related studies of bacteria in sea ice, extracellular enzyme activity was clearly recorded at –12°C and indications of activity were recorded at –18°C, a record low temperature for natural samples, while viral activity was recorded as low as –12°C, another record low temperature observation.

Another adaptation to cold environments is the production of anti-freeze proteins (AFPs). A comparative study of beetle larvae in Alaska and Indiana provided insights into polar adaptations. While larvae from both produce similar levels of AFP, the Alaskan larvae develop extreme dehydration during the winter, enhancing the concentration of AFP during winter. This allows their observed mean supercooling point to be as low as –42°C in January 2003, with some individuals having supercooling points as low as –50°C. In the laboratory, some individuals did not freeze at temperatures of –130°C, well below anything that would be observed in the natural environment! Larvae supercooled to below –98°C are vitrified (glassy). Associated studies suggest AFP production, not previously observed, in 19 species of insect and 3 species of spider.

Recent studies have shown that lichens available to caribou and reindeer in Alaska are low in the nitrogen (N) and sulfur (S) required for maintenance and production of lean body tissues. The preferred lichens in the diet of these animals are below the dietary requirement of the animals, although less preferred lichens exceed the requirement. Reindeer and caribou fed low-N diets, similar to lichen and winter forages, do not gain N in late winter, even though lean mass is gained on diets high in N and energy. Lean mass is lost over winter in reindeer and maintained in caribou. Studies of ^{15}N indicate that reindeer and caribou deposit a store of N in autumn and early winter, which is extensively recycled through late winter and spring. Tolerance of low-N diets is therefore due to the mobilization of body protein stores in late winter and spring, especially when calves are born before the resumption of plant growth.

Arctic Social Sciences

The Arctic Social Sciences Program was established at NSF in 1990 and is in the middle of its second decade providing support for social science research across the Arctic. The program is unique at NSF in its support for a diverse portfolio of research projects from many social science disciplines, including anthropology, sociology, economics, political science, geography, 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. Other ways in which the program has increased Arctic social science research is by collaborating with other NSF directorates and other science funding agencies. Currently the program is collaborating with the NSF Directorate for Social, Behavioral, and Economic Sciences on a joint NSF/NEH program called Documenting Endangered Languages. FY 2005 is the first year that Arctic-relevant social science full research projects have been funded through the Biocomplexity in the Environment: Coupled Natural and Human Systems competition. Two projects represented a total of $3.9 million to northern social science research. In addition, the Arctic Social Sciences Program is the first NSF program to cooperate with the EUROCORES initiative at the European Science Foundation to fund Arctic social science research through the Programme BOREAS: Histories from the North—Environments, Movements, Narratives.

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

Pedagogical Grammar of Gwich'in

This research project was funded collaboratively by the Linguistics Program in the SBE Directorate and the Arctic Social Sciences Program through the Documenting Endangered Languages Program of the NSF and National Endowment for the Humanities. This award funds a Gwich'in scholar who is creating a pedagogical grammar text for use in teaching Gwich'in to students and community members. The Gwich'in language is one of the largest and most unusual of the Northern Athabascan language family. Although the language is severely endangered, there is enormous interest in language revitalization within the Gwich'in community. However, in spite of a rich history of linguistic documentation of Gwich'in, it has no accessible reference or pedagogical grammar. The grammar created by this project will serve as a key component of the developing Gwich'in language curriculum at the Alaska Native Language Center. In addition, it will provide a primary scholarly resource documenting the structure of a typologically unusual language. The grammar will be accompanied by a curriculum guide to aid in the teaching of Gwich'in. This guide may serve as a model that may be adapted for other languages. In addition, interested K–12 language teachers and language learners may find the model beneficial for their own use.

Yatsushiro Research Materials Repatriation

This award provided the resources for the preservation and repatriation of research materials collected by Dr. Toshio Yatsushiro in his 1959–1960 field season in the Arctic indigenous communities in the Nunavut Territory, Canada. Dr. Yatsushiro, now 87 years old, agreed to have the materials preserved and repatriated, including his field notes, household surveys, more than 80 ft of analog tapes of interviews and origin stories, genealogies, maps, over 500 black and white photographs, and more than 600 ft of 16 mm black and white film. Included in the project are contemporary interviews with Yatsushiro about the collection and his field work in Nunavut. The materials will be repatrated to the archives in Iqaluit, the capitol of Nunavut, and copies will be distributed to other interested organizations, such as schools, museums, and colleges. This is an unprecedented act by a social scientist and will not only comply with the communities' wishes for the return of the materials but will also include research among the current residents on the context of memory and history among Arctic indigenous peoples.

Indigenous Knowledge about Arctic Climate Change

This award to the Tapestry Institute, an American Indian institute, is to make indigenous knowledge about Arctic climate change widely available for research and education. The project is to develop a Digital Library of Indigenous Science using materials collected by Snowchange, a non-profit organization located in Finland, working with Arctic indigenous communities in Russia. The Snowchange data consist of audio, video, photographs, indigenous artwork, diary text, and research notes, all on climate change observations from Arctic communities. This project will develop a database in a standardized format, utilizing best practices, to digitize the primary data, produce the metadata that can be utilized by researchers, and develop a format that will be accessible to indigenous, academic, and education communities.
In addition, the project is in close cooperation with local indigenous organizations and includes widening the participation of indigenous people in the digital science library effort, as well as disseminating materials to indigenous communities and schools.

Historical Ethnography of Tuberculosis Among Yup'ik Peoples of Southwestern Alaska

This award funds an integrated, medical anthropological research project, drawing on ethnographic, oral history, and archival research methods to examine the complex relationship between Alaska Native culture and contemporary western medicine. Based on the specific case of tuberculosis among the Yup'ik of southwest Alaska, this project will provide insights on how the structures of power and historical processes interacted with Alaska Native experiences. The focus on the Yup'ik experience of the 1930s to the 1990s through the lens of tuberculosis will help shed light on the complexities of radical social and cultural change. There will be extensive local participation, both as researchers and as formal advisors to the project.

Northern Science Education Program

The Northern Science Education Program is the continuation of a Research Experience for Undergraduates grant that provides a unique science education for urban undergraduate minority and non-minority students in Iceland by working on an early human settlement and historical landscape project. Based on the curriculum of interdisciplinary science (such as 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.

Biocomplexity of Sanak Island

The Office of Polar Programs has participated in the Biocomplexity in the Environment priority area since its conception. The Sanak Island project was one of two Arctic-relevant social science research projects funded this year through this program, the other studying the paleobiogeography of Kuril Island. The Sanak Island project will investigate the complex interactions among natural and human systems on and around Sanak Island in the Aleutian chain of Alaska. An interdisciplinary research team will study humans as part of the northern ecosystem. The investigators will examine interrelationships among the modern and prehistoric, terrestrial and marine, and local and regional systems, including both empirical and theoretical explorations. The project will incorporate indigenous knowledge, local history, and direct community participation in data collection, and it will give residents a voice in the scientific process through both collaboration and the analysis of marine policy that directly affects their daily lives.

Arctic Research and Education

Involving students and the broader public in Arctic research is an important goal of the Arctic Sciences Section. The Arctic is a naturally intriguing region, and NSF projects in the Arctic provide a natural hook for science, technology, engineering, and mathematics education. It is also important to provide opportunities for people who live in the Arctic to be involved in the science that NSF supports there. The fund for Arctic Research and Education accomplishes these goals by supporting researchers and educators who integrate research with education through effective and imaginative means.

Arctic Research and Education supports Teachers and Researchers Exploring and Collaborating (TREC), an effort that sends teachers to the Arctic to work with research teams. The TREC program provides hands-on research and professional development experiences for teachers, who then engage their students and colleagues in experience-based learning in the sciences. In two years, over 15 teachers representing over 10 states have been involved in Arctic research. These teachers continue to work together and with other teachers as a learning community of experts who mentor their students and peers in current polar research.

Researchers have also found ways that residents of the Arctic can be integral contributors to their research projects. Arctic residents can enrich projects by sharing traditional ecological knowledge and improving data quality by virtue of being located near field sites year-round. Two funded research projects are benefiting by involving communities and schools in the Arctic. Teachers who are trained by the researchers on data collection protocols lead their students in field data collection of lake snow and ice or river water sampling for large scientific research projects. The teachers receive mentorship from the researchers, the students gain hands-on research experience, and the researchers gain access to time series data with a spatial coverage that they would not be able to obtain without the participation of Arctic communities. The collaboration has other rewards as well, through the cultural exchange taking place among the participants.

Many of the projects supported by Arctic Research and Education are co-funded with other parts of NSF, including programs in the Education and Human Resources (EHR) Directorate, the Geosciences Education program and the Environmental Research and Education program. Other examples of innovative projects sponsored by Arctic Research and Education are:

- Science journalists working on Arctic field research projects to gain a better understanding of the process of science;
- Education and outreach conducted during a dogsled expedition in the Arctic to collect natural and social science data on Arctic environmental change;
- Development of an undergraduate research and education program for interdisciplinary studies of the sustainability and resilience of Arctic communities;
- Graduate student support as part of a Graduate Fellowship in K–12 Education project through EHR;
- Planning workshops for polar science education and outreach; and
- Graduate student travel to scientific workshops and conferences.

These projects and others supported by Arctic Research and Education are part of the effort to ensure the broader impacts of NSF research, to increase diversity in the sciences, and to develop the next generation of scientists and engineers.

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 Congress in 2005. This revision to the U.S. Arctic Research Plan included two major sections. The first of these presented the Special Focus Interagency Research Programs:

- The International Polar Year;
- Arctic Environmental Change;
- Bering Sea Research;
- Arctic Health Research;
- Resource Evaluation; and
- Civil Infrastructure.

The second major section was Agency Programs, which represents the objectives of Federal agencies, focusing on the period covered by this revision (2006–2010). 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
- Education, Training, and Outreach.

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;
- Development of technology and instruments;
- 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 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 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.