October 12, 1998

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Dr. Robert Corell, Assistant Director
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Dear Drs. Hunt and Corell,

Enclosed is *Opportunities in Arctic Research: Final Report*, prepared by ARCUS through support from the National Science Foundation (NSF) under Cooperative Agreement OPP-9727899. These recommendations were developed during Opportunities in Arctic Research, a community workshop held in Arlington, Virginia, on 3-4 September 1998. Twenty-eight scientists representing a wide spectrum of arctic research interests identified critical research questions and support requirements. These issues are described in the report, which was reviewed in draft form by the workshop participants and the core organizing group.

Although this report was developed over a limited period of time, it outlines current opportunities in arctic research and challenges in arctic research support needs. While it takes into account earlier planning exercises in arctic research, it also includes some ideas that have not been articulated previously. It incorporates the perspectives of broad range of disciplines, including the physical, biological, and the social sciences. We hope that it will be of assistance in your planning processes.

Workshop participants and ARCUS appreciated the opportunity to develop these recommendations for NSF. We also appreciated the information presented by Drs. Colwell, Hunt, and Pyle at the workshop that helped to clarify our charge and the context in which this planning process was conducted. NSF staff added much valuable information in the course of the workshop deliberation. The drafting of the report has benefited greatly from the contributions of the workshop participants and members of the core organizing group.

Again, thank you for the opportunity to contribute to this important arctic research community effort.

Sincerely,

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Enclosure

Opportunities in Arctic Research: Final Report

At the request of the National Science Foundation's Office of Polar Programs, the Arctic Research Consortium of the United States (ARCUS) organized a community workshop, "Opportunities in Arctic Research", which was held in Arlington, Virginia on 3-4 September 1998. Twenty-eight scientists participated in the workshop, representing a wide spectrum of arctic research interests. Participants identified critical research questions and support requirements. These issues are outlined in the accompanying report, which has been reviewed by the workshop participants and the core organizing group.

Workshop participants and ARCUS appreciated the opportunity to develop planning recommendations for NSF. We also appreciated the information presented by Drs. Colwell, Hunt, and Pyle that helped to clarify our charge and the context in which this planning process is being conducted. NSF staff added much valuable information in the course of the workshop deliberation.

INTRODUCTION: RESEARCH OPPORTUNITIES AND NEEDS IN THE ARCTIC

For the last few decades the scientific community has expressed concern about the vulnerability of the Arctic and its residents to environmental, social, and economic changes. For example, climate model studies indicate that the arctic environment may react particularly sensitively to global climate change. Now research results show that arctic climate and ecosystems are indeed changing substantially with impacts on people living in and outside the Arctic. Some changes appear to have begun as early as the 1970's, but many have only become significant in the 1990's. Moreover these changes and the processes that cause them appear to be linked to changes in the whole Northern Hemisphere, involving physical characteristics in the atmosphere, ocean, and on land.

Early indications suggest that the physical changes are also causing changes in the biosphere. Because many of the Arctic's human populations are tied to the natural environment, they are quite vulnerable to changing conditions. In fact, many arctic residents, particularly subsistence users, are already reporting ecosystem changes and believe that these changes are affecting their lives. Concern about the impacts of physical and biological change is heightened by new evidence that contaminants are spreading and accumulating in arctic ecosystems. Although the connections with the rest of the environment are not clear, there have been changes in the upper atmosphere as well. We know that many of the phenomena we study in the Arctic, from deepest oceans to space, are part of global processes that have effects on our citizens. Therefore, arctic research is of national and global importance. Expansion of current efforts (which are small in comparison to the region's size and global importance) would allow us to document and understand the changes that are already taking place, how they are impacting the human population, and how people living in the Arctic can adapt to the changes.

The Arctic is strongly coupled to the rest of the globe. Processes and impacts that occur in the Arctic have the potential to create cascading effects in lower latitudes. The Arctic has a significant impact on global climate through the freshwater cycle, thermohaline ocean circulation, albedo feedback, and greenhouse gas release. On the other hand, the impacts on climate caused by human activities around the world might be most readily detected in the polar regions due to the sensitivity of the high latitudes to global warming. In addition, the Arctic is exposed to contaminants produced at low latitudes that are transported to and trapped within the Arctic; effects of these contaminants and of additional environmental changes on arctic animals and residents must be anticipated.

The arctic region includes some of the most extreme environments on the planet, where radical changes in photoperiod and excursions in temperature affect growing seasons alternately to constrain and stimulate terrestrial and marine ecosystems. People around the circumpolar North have coped successfully over millenia with this environment, accumulating an extensive body of environmental knowledge as well as keen awareness of ecosystem changes. Because the Arctic has many unique conditions, better understanding of the region will contribute to basic research with intrinsic interest. The Arctic's physical and biological systems are regulated by processes that offer numerous opportunities for advancing basic knowledge. Many of these processes are not well understood. Ice, snow, glaciers, tundra, permafrost, boreal forests, and peatlands are sensitive integrators and indicators of change; investigating these can also provide fundamental information about the interactions and processes which regulate them. The polar region is also unique in its direct electrodynamic coupling to the space environments through the geomagnetic field.

Rapid changes are also taking place in arctic societies, especially in political and economic systems, and these processes are more apparent and less affected by extraneous influences in the Arctic than many other areas of the world. From a high-level of self-sufficiency in the recent past, arctic peoples now are incorporated into national states and the global economy. In many places, such as Alaska, Greenland, and Canada (where the new territory of Nunavut is being formed), arctic peoples are gaining political and economic power. In other places, such as Russia, arctic residents are struggling to cope with massive political and economic changes. In the U.S., recent welfare reforms have implications for the viability of many arctic communities. Throughout the world, changes in markets for oil, minerals, forest products, and marine resources are having far-reaching consequences for subsistence and commercial activities. The ways in which these changes take place and the variations in the processes and outcomes need to be understood.

A balanced arctic research strategy of planning, coordinated measurements, and modeling will improve our present levels of understanding, predictive skill, and assessment. Among the key questions that have emerged are the following:

- How are the rapid social, political, economic, and environmental changes occurring in the Arctic today affecting the people there? How have similar changes affected arctic residents in the past?
- How close is the Arctic Ocean to a transition to an alternate state? Is natural variability, when superimposed on any greenhouse-related trends, sufficient to make an ice-free Arctic likely in the next 100 years?
- Are the observed trends of warming, thinning ice, etc., going to continue, or are they the result of a multi-decadal cycle? How have these changes varied around the Arctic?
- Are the large recent population changes of some arctic animal species linked to changes in climate, ice conditions, landscape cover, or human resource use?
- How will the distributions of arctic vegetation and permafrost change over the next decades to centuries?
- What are the origin and effects (at the surface) of recent arctic upper and lower-atmosphere changes, e.g., the increase of polar stratospheric clouds and Arctic Haze and the decrease of stratospheric ozone? Will these changes accelerate in the near future?

PLANNING FOR THE FUTURE: KEY RESEARCH ISSUES

The National Science Foundation has provided crucial leadership in addressing many complex and interconnected issues in arctic science. Significant progress has been made recently, perhaps most notably in several areas of global change research. However, the region as a whole and its relationship to the rest of the world remains largely unexamined, in part because of its sparse population and logistical difficulties in conducting research. The valuable findings of the past decade reveal the many gaps in our information as they demonstrate the urgency of the need for more data. For example, many locations have never been sampled, while sampled sites have records that are generally short or intermittent. Workshop participants identified several examples of multidisciplinary research which would advance our understanding of the Arctic:

1. Variability in the physical environment of the Arctic:

The polar regions are predicted to sustain early and significant changes associated with contemporary climate change. The past several decades have seen a substantial warming of the northern land areas, unexpected change in the distribution of Atlantic water in the Arctic Ocean, freshening of the upper water layer and a thinning of the halocline, higher incidence of extreme ice retreat during the summers of the 1990s, persistence of certain phases of key circulation patterns in the atmosphere (e.g., the North Atlantic and Arctic Oscillations), increased frequency of polar stratospheric clouds, and decreases in the concentrations of stratospheric ozone. These changes will affect the broader arctic system through physical feedbacks and through impacts on biological systems, including humans. Linkages between the various changes are known or suspected in some cases, but unknown in others. Perhaps more importantly, it is unknown whether these changes represent natural variability or shifts related to changes in external forcing and/or anthropogenic factors (Morison et al., 1998).

Conversely, events in the Arctic have global significance. The Arctic appears to have a potentially strong influence on the global climate system, for example through regulation of global thermohaline circulation, potential amplification of greenhouse gas release, and very active biogeochemical cycling in the region. Understanding how arctic processes connect into the climate system is essential to describing the working of the world’s climate and predicting future changes.

The arctic environment may be poised to change beyond the limits defined by recent records or human memory. Modeling will have a major role in assessing the implications of such environmental changes; models are required on all scales, from relatively simple and geographically focused process and population models to global-scale general circulation models (GCMs). Modern observational and process studies provide essential information for the models. Paleodata provide means to test the effectiveness of predictive models, to compare currently observed changes to magnitudes and trends of natural variations, and to help understand relevant processes. The only observational information on the extreme conditions that may occur in the future are paleo-environmental records at timescales up to 10^6 years. Effective synthesis of modeling and observational studies, both contemporary and paleo, is critical to answering questions such as those posed above.

2. Chemical cycling and contaminants:

The Arctic features vigorous natural cycling of chemical components thought to have an impact on the global scale. These include the carbon, sulfur, and nitrogen containing chemicals of importance to climate, atmospheric chemistry, and as nutrients for biota. Cycling of chemical constituents in the Arctic is often governed by processes that have lesser influences in the rest of the world: low temperatures, limited sunlight, vapor-liquid-ice phase changes, cold-trapping of semivolatiles, highly stratified atmospheric and marine environments. These processes, which tend to limit degradation and promote accumulation, are not fully understood because they has not been studied as comprehensively as have processes relevant to lower latitudes.

Contaminant sources have been identified both within and outside of the Arctic. In some regions of the Arctic, levels of contaminants such as PCBs, pesticides (DDT, chlordane, toxaphene, dieldrin), cadmium, and methyl mercury are high enough to raise concern about damage to animals' reproductive, neurological, renal, or immune systems. In certain cases contaminant cycling cannot be understood without investigating the natural cycle simultaneously; for example, natural marine production of DMS (which may be substantial in the Arctic) and fossil fuel combustion both ultimately contribute to SO_2 cloud condensation nuclei, which in turn affect the global heat balance. Within the ecosystem, contaminants such as persistent organic pollutants (POPs) accumulate in the highest levels of the food chain due to biomagnification. The concentration of contaminants is particularly important because of the high reliance of rural arctic residents on high trophic level foods (i.e., meat). Understanding contaminants' pathways and the processes that redistribute and transform them will help in assessing the dangers to human populations.

Contaminant trends are complex. Different contaminants have different sources, input functions, pathways, transformation and sequestration patterns. In addition, recent studies have documented a large degree of interannual variability in the Arctic which is likely to have shifted contaminant pathways (Toward An Arctic System Synthesis, ARCUS, 1998). Such shifts must be placed into the broader context of arctic environmental change.

3. Effects of change on biological resources:

Understanding arctic organisms and their unique adaptations to high latitude conditions is a major goal of arctic science. The wealth and variety of living organisms that depend on and influence the arctic physical environment comprise an essential resource and cultural base for people in and outside the Arctic. Biological resources, particularly land cover (vegetation), have strong feedbacks and controls to climate, soils, and permafrost, and thus understanding these resources is essential to understanding and predicting changes in these other parts of the system.

Changes in the arctic environment have led to changes in arctic plant and animal communities that threaten the health and biological diversity of the region and have adverse impacts on the human populations that depend on these resources. The productive but precarious arctic ecosystems support renewable resources, such as wildlife and fisheries, which are economically important to the people who live in and outside the Arctic. Some Alaskan salmon stocks have collapsed recently; populations of sea lions, fur seal pups, and birds have declined in arctic regions. In rural communities that rely on subsistence economies, arctic residents have documented changes in local animal and plant populations. The preservation of arctic animal populations remains spiritually important to people in the Arctic and nationwide.

Understanding of two major components of biological systems—higher trophic levels in terrestrial and marine systems and temporal dynamics of plant and animal systems—is ripe for advancement. Participants identified the following areas as having had little research attention while being critical to understanding biological resources in the Arctic:

Animals in arctic systems. The economic and cultural importance of harvestable animals in the Arctic mandates research targeted on these species. However, additional work is needed on the effects of accelerated ecosystem change on indicator species and on declining populations of animals. These population declines threaten biological diversity in the Arctic. Experimental approaches to processes regulating animal populations and physiological parameters are needed. Feedbacks to landscape level changes in habitat and effects of habitat change on animals must also be addressed. Integrated with results from work proposed below, better knowledge of animal systems will lead to building models to predict changes in plant and animal communities (10-100 yr).

Dynamics of riparian systems: Considerable work has been done on fundamental process and pattern in both terrestrial and aquatic arctic ecosystems. Riparian systems, however, which link these major landscape units, have had less attention. Particularly important are studies of dynamics of riparian plant and animal populations and biogeochemical links between terrestrial and aquatic systems. Linking modern and paleo data would be particularly valuable in the study of these systems. In particular, where watersheds include lakes, longer-term dynamics can be addressed using paleo techniques.

Predicting land cover change: Recent advances in understanding spatial variability in arctic land cover and in how vegetation interacts with climate, snowpack features, soils, and permafrost indicate that the strong interaction among these systems is a unique characteristic of the Arctic. Combined process studies and models to predict changes to vegetation cover on annual to decadal time scales are needed to provide key information for studies of higher trophic levels, climate change, and human use of the Arctic.

Arctic marine ecosystems: Primary and secondary productivity on the shelves, slopes and basins of the Arctic Ocean may be altered by global change. For example, global warming and sea ice retreat may have profound effects on the pelagic and benthic food chains and subsequent harvestable resources. Year-to-year variations in ice cover provide a natural experiment for evaluating the qualitative and quantitative effects on both lower and higher trophic level processes and interactions. Long-term observation programs and process studies can then lead to models which provide regional predictions of the extent and concentration of sea ice, productivity, and the cascade of trophic dynamics.

Adaptational and organismal biology. Organisms' evolutionary adaptations to the arctic environment are important from a fundamental science perspective. Predicting ecosystem responses to global change scenarios requires understanding controls over structure and function of individual species, many of which are not well investigated. Specific examples include: identification of molecular, physiological, and behavioral traits associated with adaptation to high latitude environments (extremes in photo-period, temperature, short breeding seasons, and overwintering conditions), linking individual variation in these traits to differences in survivorship and measures of fecundity, and building towards predicting population response to environmental change.

4. Upper atmosphere and space weather studies:

Upper atmosphere: Important issues in arctic upper-atmosphere research include the recent increase in noctilucent clouds (NLCs), ozone depletion, and the coupling among the upper atmosphere, the lower atmosphere, and the surface. Reports of NLCs, primarily from high latitudes, have increased several-fold during the past few decades. NLCs may be a visual indicator of long-term global change (1996 CEDAR Report). Recent advances in their detectability with lidar have set the stage for the modeling of NLCs in order to understand their formation, their latitudinal migration and any links to the solar cycle.

Arctic stratospheric ozone has recently experienced several documented depletion events that were regional in scale and several days in duration. In addition, there has been a general downward trend of arctic ozone concentrations: average values were 10% lower in the 1990s than in the 1970s (Arctic Monitoring and Assessment Program, 1997). The associated increase in UV radiation reaching the surface is compounded by the presence of a highly reflective snow cover. Disruptions of marine food webs are likely if the increased UV radiation damages plankton, plants, and animals that normally survive in shallow water. Issues that need to be addressed include the clarification of the mechanisms (dynamic, chemical) responsible for the recent ozone anomalies in the Arctic, probable changes in the effects of these mechanisms under plausible scenarios of climate change, and assessments of impacts on arctic marine and terrestrial ecosystems, including humans.

The coupling between the upper and lower atmosphere (and the surface) is a central issue in long-term and short-term climate change. The recently identified Arctic Oscillation has been speculated to have stratospheric ties. Any solar-weather relationships must involve a coupling between atmospheric regions. Perhaps more importantly in the global context, the middle atmosphere is sensitive to lower-atmosphere and surface emissions of chemicals such as CFCs, CO_2 and CH_4. The Arctic's role as a potentially significant source of CO_2 and CH_4 implies that trace gas fluxes in the Arctic may have global consequences through the radiative budget of the middle and upper atmosphere. In turn, upper-atmosphere changes can impact the arctic surface through changes in ozone concentrations and UV fluxes and consequently photochemistry of the troposphere. The chemical and associated dynamic linkages between the Arctic and the upper atmosphere represent potentially important avenues for arctic-global interactions. Atmospheric chemistry studies should include both extended time-series sampling of this unique environment and targeted field studies for process-oriented understanding of coupling of the lower atmosphere with the surface and upper atmosphere

Space weather: The sun's atmosphere explodes away from its surface, flowing at supersonic velocity through the solar system. The Earth's magnetic field forms a cavity in the flowing solar wind gas called the magnetosphere. Interactions between the solar wind and magnetosphere produce variations in the magnetosphere, often described as space weather, which have profound consequences for various space- and ground-based technologies. The Arctic is fundamental to these interactions because the magnetic field lines at high latitudes often connect directly to the solar wind, and manifestation of the energy coupling can be measured in the high latitude ionosphere. Societal vulnerability to space weather has accelerated in recent years due to the increased sophistication of technology and the increased use of space technology for navigation, communication, and remote sensing. The recent widespread interruption of satellite telecommunications points to a need for improved prediction of space weather. Space weather prediction must rely upon models, which, in turn require data for development and validation as well as for direct assimilation into operational forecast simulations. Particular types of data needed for models include multi-instrument suites of observations at high spatial and temporal resolution, including data on ionospheric convection, temperature, density, electrical currents, optical emissions, and plasma waves. Essential to obtaining this data is a Polar Cap Observatory to be located near the magnetic pole with instrumentation suited to obtain these measurements, which are presently lacking from this important region.

5. Dynamics of human systems in the Arctic:

Humans are integral to the arctic ecosystem, both affecting the arctic environment and being influenced by physical and biological processes (People and the Arctic, ARCUS 1997). The linkages among economic, political, cultural, social, and knowledge systems in the circumpolar North have tremendous impacts on life in the Arctic. Temporal and regional variations in these processes influence the ways in which humans react and adapt to their environment, with implications for international relations and the futures of arctic communities. Research opportunities in arctic social sciences have been identified recently (Arctic Social Science: Opportunities in Arctic Research, ARCUS, 1998).

Many types of changes that occurred over centuries—or centuries ago—in other regions were compressed into the last few generations in the North. Thus, historical records and oral traditions of indigenous residents of the Arctic offer richer documentation of the processes of social, economic, and cultural change than are available for most other regions. Archaeological sites in most sectors of the Arctic are also better preserved and more easily found than sites in more temperate areas and are often linked directly to current populations. These prehistoric arctic sites supply a unique source of data on both former environmental changes and past human responses to climate fluctuations, shifts in ice-weather regimes, dynamics of biological resources, etc. This nexus of environmental and historical conditions often allows researchers to elucidate past processes of social change more clearly in the Arctic than in other areas.

Social, political and economic changes have affected and have been generated by arctic communities. Arctic residents (through social, economic, political, and cultural power or policies) are now actively involved in arctic environmental change. Human populations are expanding, putting additional pressure on an often fragile balance between declining arctic resources and growing need for these resources. Hunting and fishing rights, international whaling laws, and land use policies, for example, can affect the availability of biological and other resources. The effects of these policies and practices which differ in different areas of the Arctic and therefore have varying impacts, also need to be understood.

Relatively recent shifts from a high level of self-sufficiency among arctic communities to their incorporation into national states and the global economy have challenged cultures that have coped successfully with severe environmental conditions over millennia. Social scientists need to identify responses to social, economic, and environmental change by social systems and seek models for optimizing these responses.

Challenges to the survival of distinct local cultures and traditions throughout the Arctic need to be understood and addressed. The recent opening of Russia to the West offers researchers unprecedented opportunities to work with Russian colleagues and in Russian northern communities. The Russian North has especially pressing needs for research to address social and economic problems that residents are currently facing.

While human behavior drives change in arctic systems, many arctic residents remain highly dependent on local resources economically, culturally, and spiritually. Therefore, changes in arctic ecosystems are major issues of immediate concern. Three venues are critical to address these new challenges:

Historical and temporal variations in human-environmental systems. Modern research has revealed the dynamism of social, cultural, and economic models throughout the circumpolar North. This new dimension has profoundly changed the way we now think about the Arctic and its indigenous peoples. Still, our knowledge of human diversity in the Arctic and of variability of the past and present human responses to environmental changes is highly inadequate. Physical, biological, and social components in multidisciplinary research are in urgent need of integration, and many arctic areas have huge gaps in organized records on the present and prehistoric human-environmental systems. The new focus on documenting and modelling changes and interactions (rather than existing conditions) is, thus, key to research advancement

Interaction between local knowledge and academic science: People living in the Arctic have accumulated outstanding bodies of data on the various aspects of arctic environment, including sophisticated local indicators of ecosystem change. Integrating local knowledge and building venues to include arctic residents as respected partners in new cooperative projects will be a critical link to successful interdisciplinary opportunities in arctic research.

Communication of scientific knowledge and data to arctic communities: Arctic residents seek to document environmental change in the North, including depletion of biological resources, contamination of food-webs, increased UV radiation, and global warming. Local communities are pursuing ways to be more informed on the outcomes and data of academic research. Educated and politically powerful arctic residents can be a vocal constituency to advocate for academic research in the Arctic. New patterns of dissemination of research goals and results to communities, including electronic communication, public and visual programs, and distance education will boost public awareness and benefit scientific research.

RESEARCH SUPPORT NEEDS

A relatively meager observational infrastructure in the Arctic combined with the spatial scale and topical breadth of the reseach issues identified here presents the research community with new challenges. If we are to understand the implications and effects of the changes in the Arctic, we must first of all track them into the future by establishing long-term, systematic observation programs. Second, in order to understand the connections between the changes we are seeing, we will need to perform intensive, process studies. Finally, we will need theoretical and modeling studies to synthesize the long-term measurements and process-oriented information, and to predict the future course and impact of the changes. Process studies and modeling are needed to extrapolate to the regional and panarctic scales. Participants concurred that research support initiatives should develop through close links with science issues in the Arctic Section of OPP.

While monitoring activities have traditionally been outside the purview of NSF, we believe that the value of time series as a vehicle for increasing understanding adds to the priority of a carefully designed and coordinated observing system in the

Arctic. In view of NSF's role as the interagency leader in arctic research, NSF must assume a more prominent role in the systematic measurement of variables central to arctic change. Traditional long-term observational activities by other agencies are being scaled back; these measurement series were and are the underpinning for the sort of studies traditionally funded by NSF. Therefore, while not a traditional pursuit of NSF, the undertaking of long-term observations is necessary in order to realize the full potential of a wide range of other funded studies related to arctic change.

For example, system model development requires data on snow cover for validation. Alaska contains only 40 sites that telemeter snow data each winter; a comparable area of the western states contains over 600 such sites. Each data point collected in the Arctic can thus reasonably be expected to deliver a greater return on investment than elsewhere, while issues of logistics, representativeness, scaling, etc. assume even greater urgency. Tools to facilitate spatial extrapolation, interpolation, and scale transformations (GIS, remote sensing, spatial statistics) have become available in recent decades, but there can be no substitute for carefully developed sampling programs to optimize efficiency.

The workshop participants concurred with the recent U.S. Arctic Research Commission/NSF Report, "Logistics Recommendations for an Improved U.S. Arctic Research Capability" (ARCUS, 1997). In addition to the recommendations summarized in that report, participants outlined ways in which a network of environmental observatories could facilitate many of the arctic research community's support needs, reflecting an observational strategy to measure the important time and space scales of changes in the Arctic. The following emerged as priorities of the workshop participants:

1. Long-term observations and integration with remote sensing and paleo records:

The reality of recent arctic changes – climatic, contaminant, UV, biological, social, economic, political – adds urgency to the need for scientific understanding that will permit meaningful prediction, adaptation to and mitigation of the changes. Systematic observation and elucidation of the linkages within the system are essential if anticipation and proaction, not reaction, are to drive our policy toward the arctic environment. Strategies to promote these ends include:

Environmental observatories: Participants endorsed the coordinated development of a set of strategically placed facilities, each of which is equipped for on-site research into processes that span arctic science and for collection of year-round comprehensive suites of observations. These might develop rather easily from systematic enhancements of existing facilities, including Summit, Thule (or Sønderstrøm), Resolute–Polar Cap, Barrow and Toolik Lake. The systematic development of arctic environmental observatories is likely to spur technological advances in automated and remote sensing technology. Enhancement of local centers/research sites/facilities, including cultural and social science centers, community museums, etc., should also be considered to include spatial sampling, social science data gathering, and community involvement. Observatories could also serve as bases for support of field work in surrounding areas. Where observatories are not practical, many researchers' work could be facilitated by "virtual centers" in particular disciplines to aid communication with colleagues, data management, and logistics coordination.

The social sciences should be a key part of the recommended network of Arctic Environmental Observatories. For example, geospatial information could be linked to local placenames, where appropriate, or interactive net labs could be included to study cultural differences in decision making. A commitment to such an effort would permit integration of social science research with other ongoing studies, improving communication among arctic social scientists and providing access to diverse cultures across geographical areas.

Sustained Off-site Observations: Examples of target field activities not directly tied to specific environmental observatories include moorings, drifting and land-based automated sampling stations, regular hydrographic surveys, long-term observations on timing of animal reproduction, hibernation, and migration, permafrost and ice sheet monitoring, submarine surveys of ice thickness and distribution, expanded measurements of terrestrial and oceanic weather, increased radiosondes, snow-on-ground measurements, and the use of carefully targeted IOPs (Intensive Observing Periods) for PI-driven research.

Regular hydrographic surveys, such as those using the *Healy*, are essential long-term ocean observations and will require stable funding to avoid forcing PIs to secure operational funds; funding by a variety of agencies and sources, including foreign, will be scientifically most cost-effective. An ice-capable research vessel of medium size is needed to work in the western Arctic in all seasons, including the Bering Sea in winter (Arctic Marine Science Plan, in press)

Technology development and increased utility of remote sensing: Carefully designed campaigns of in situ field measurements are needed to improve our ability to use remote sensing. Collaboration with NASA, particularly in instrument design and algorithm development, will clearly be necessary. Related needs include the technical development of miniaturized, remote automated sensing devices, and the support of PI-class instrumental and development deployment to achieve better spatial and temporal coverage.

Integration of paleo data: We require the most detailed records possible about the recent past (past 100-1000 years) to provide a context for the currently observed changes and an estimate of recent variability in the Arctic. On longer timescales, paleo records tell us about the Arctic when it was very different from present. For example, the last time the Arctic Ocean may have been ice-free was probably the last interglacial, ca 130,000 years ago. Thus an ice-free Arctic Ocean is something unprecedented in human experience. To provide the most effective, high-resolution records of past environments in the Arctic, support is needed for not only the collection and analysis of data, but the effective dating of paleoenvironmental records. Accurate and precise dating of terrestrial paleorecords (at levels currently standard in the paleoceanographic community) is required to define high-frequency variation and to provide correctly dated paleoclimate scenarios for comparison with climate-model simulations of past arctic climates.

Year-round safe access: Regardless of discipline researchers share a need for access to the Arctic, including access to remote locations to facilitate unbiased sampling programs (including winter work); access by plane or helicopter to land surface sites, including the observatories; drilling capabilities on land; logistical costs at field stations should be directly supported.

Communications: Needs include basic phone communication with field sites; capability to send and receive data from remote sites and communities; and new technologies to support the distribution of information to remote sites and communities (distance learning, education, outreach, teleconferencing).

2. Development of modeling and a predictive capability

A fusion of modeling and observational efforts is required to effectively focus modeling on critical science questions raised earlier in the report, and data collection, where possible, should be relevant to the modeling effort. We need to develop and improve models of the arctic system, including the components of atmosphere, ocean, sea ice, glaciers, permafrost, tundra, forests, runoff, ecosystems, and human behavior. Enhanced computing facilities are needed to support complex and extended high-resolution arctic-specific simulations. Data-model comparisons for paleoclimates are an essential component of data-model integration. Syntheses of data, often across international boundaries, should also receive support.

3. Synthesizing local and academic knowledge on Arctic Change:

Venues need to be developed to improve cooperation and sharing of knowledge, information, and research data between academic scholars and arctic residents, including indigenous northern communities and local experts. Strategies to promote these include:

Joint locally-based meetings: Regional meetings and workshops to bring together academic researchers and local/native scientists and elders from arctic communities should be organized with the goals of building partnerships for joint research, sharing data, and identifying future research needs.

Active dissemination of research data via electronic means: Distance education, community outreach, cultural heritage, and other public-oriented programs could benefit greatly from dissemination via the Internet and other new forms of electronic communication available to arctic residents. New research and outreach programs should be advanced as a logical extension of academic-Native scientific collaboration.

4. International cooperation/collaboration:

Cooperation with the international community is required to achieve better global coverage and the needed mix of instrumentation and facilities efficiently. International collaboration is essential for the effectiveness of the hydrographic surveys and of large-scale comparative social science research, for example. A formal mechanism, above the PI level, is needed for handling issues of scientific access (especially to Russia).

While such coordination issues clearly extend beyong NSF, the opportunity for a leveraging of NSF resources adds to the priority of an active NSF/OPP involvement in international arctic science programs. Mechanisms for defining and achieving an optimum level of NSF/OPP involvement internationally merit further attention.

Opportunities in Arctic Research: References and Relevant Reports

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OPPORTUNITIES IN ARCTIC RESEARCH

A Community Workshop

3–4 September 1998
Arlington Hilton Hotel, Gallery I

Final Agenda

Thursday, 3 September 1998

9:00 a.m. Welcome and Introductions — Peter Schlosser, John Walsh
Workshop co-chairs

9:15 a.m. The National Science Foundation's Role in the Arctic — Rita Colwell
Director, National Science Foundation

9:45 a.m. Expectations from the community workshop — John B. Hunt
Interim Director, Office of Polar Programs

10:00 a.m. Opportunities in Arctic research — Thomas Pyle
Arctic Sciences Section, Office of Polar Programs

10:15 a.m. Summary of strategic issues and the context for the planning process
Peter Schlosser, John Walsh

Strategic Questions:

- What are the most important Arctic science issues to be addressed during the next 3 to 5 years and which of them will have the largest impacts if they can be solved?
- Are we positioned to study these issues effectively? How can the situation be improved by NSF?
- What is the best way to establish long-term programs needed for studies of variability and trends?
- How much coupling of Arctic research to global programs is needed? Where should we keep arctic research 'discrete' to be effective? Should NSF/OPP support international programs? If so, how?
- What are the optimal interfaces between NSF and other agencies and national and international research programs?

- How can we keep presently active long-term programs flexible and open to the input of a broad community to accommodate the need for incorporation of new research directions?

10:45 a.m. BREAK

11:15 a.m. **Presentations on the state of knowledge in Arctic science**
(There are many important interactions and linkages in regionally based research; Presentations on Arctic research cannot easily be divided into disciplinary, programmatic, or governmental categories or physical realms. For the purposes of achieving an overview, we have divided presentations into the following somewhat simplistic categories. Lead presenters will draw upon workshop participants and their broad community for information and recommendations.)

PHYSICAL SYSTEMS (five 15-minute presentations)

- Atmospheric Research — Robert Clauer
- Hydrological System: Ice Sheets, Glaciers, Snow, Permafrost — Matthew Sturm
- Ocean, Sea Ice, and Sea Floor — Kelly Falkner
- Climate Modeling — Bert Semtner
- Contaminants/Arctic Environmental Concerns — Stephanie Pfirman

12:30 p.m. LUNCH

1:45 p.m. Presentations on the state of knowledge in Arctic science (continued)

BIOLOGICAL SYSTEMS (three 15-minute presentations)

- Terrestrial Ecology — Mary Edwards
- Basic Biological Research — Brian Barnes
- Resource Biology — Mike Castellini

2:30 p.m. HUMAN SYSTEMS (two 15-minute presentations)

- Arctic Social Sciences — Carole Seyfrit
- Arctic Indigenous Peoples — Dolly Garza

3:00 p.m. Summary and plenary discussion to synthesize key issues
Schlosser, Walsh & workshop participants

- consequential scientific questions
- scientific readiness

- interdisciplinary linkages
- major gaps in understanding
- potential collaborations (international, interagency, inter-program)
- logistical and other impediments

3:30 p.m.	BREAK	
4:00 p.m.	Session for working group participants	
4:30 p.m.	Break into small working groups	
6:00 p.m.	Adjourn for the day	

Friday, 4 September 1998

9:00 a.m.	Welcome and summary of progress	Schlosser & Walsh
9:15 a.m.	Reports from small working groups (15-minute presentations) • WG 1 • WG 2 • WG 3	 Rapporteurs
10:00 a.m.	Review key issues/major changes in direction or scope	Schlosser, Walsh & workshop participants
10:30 a.m.	BREAK	
10:45 a.m.	Reconvene in small working groups potentially reconfigured to address multi-disciplinary science and logistics issues	
12:30 p.m.	LUNCH	
1:30 p.m.	Reports from small working groups (three 5-minute presentations) • WG 1 • WG 2 • WG 3	 Rapporteurs
2:45 p.m.	Discuss and integrate recommendations in outline form	Schlosser, Walsh & workshop participants

3:15 p.m.	Summarize progress, timeline, and plan for developing recommendations to be forwarded to NSF	Schlosser & Walsh
3:30 p.m.	Adjourn workshop	
3:30 p.m.- 4:00 p.m.	Organizing Committee Meeting	