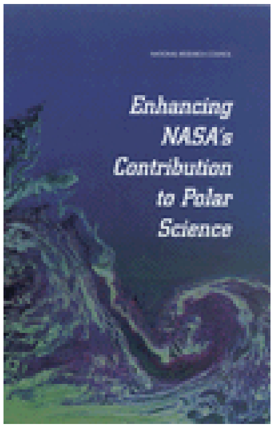

Enhancing NASA's Contributions to Polar Science: A Review of Polar Geophysical Data Sets

Committee to Review NASA's Polar Geophysical Data Sets, Polar Research Board, National Research Council

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A Review of Polar Geophysical Data Sets

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Polar Research Board
Division on Earth and Life Studies
National Research Council

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Cover: Space radar image of the Weddell Sea. The cover image shows two large ocean circulation features, called eddies, at the northernmost edge of the sea ice pack in the Weddell Sea, off Antarctica. The eddy processes in this region play an important role in the circulation of the global ocean and the transportation of heat toward the pole. The image was produced at NASA's Jet Propulsion Laboratory by the Alaska SAR Facility's ScanSAR processor system, using data obtained on October 5, 1994 during the second flight of the Spaceborne Imaging Radar S/X-Band Synthetic Aperture Radar (SIR-C/X-SAR) onboard the space shuttle Endeavour. The image has been reversed for purposes of this cover. In reality, the ocean eddies have a clockwise (or cyclonic) rotation. The dark areas are new ice and the lighter green areas are small sea-ice floes that are swept along by surface currents. First year seasonal ice is shown in the darker green area. The open ocean to the north is uniformly bright and appears blue. The small image inserted on the back cover shows the size of a standard space-borne radar image as a comparison to what can be created when the radar instrument is used in the ScanSAR mode (the main image). This image and many others are available at NASA's Visible Earth website, <http://visibleearth.nasa.gov>, which provides a central catalog of Earth science-related visualizations and images.

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Preface

When NASA first explained its hope that our committee could review its strategy for providing satellite-derived geophysical data sets to the polar science community and provide guidance to make future data sets more useful, the task seemed somewhat ambiguous and daunting. We could not look in depth at every available data set given the time and resources available, nor did it feel particularly useful to comment on what was right or wrong in past decisions. But as the committee met and gathered information, it became clear that our most useful contribution could lie in determining how a better match could be achieved between NASA's data sets and the needs of NASA's current strategic guide, the Earth Science Enterprise (ESE) program. By analyzing what information is needed to address the ESE questions from a cryospheric perspective and then mapping those needs against existing resources, we found a way to turn our review into concrete suggestions to guide future activities.

To support this approach, our report has a simple structure. After a brief introduction (Chapter 1), we provide an overview of existing geophysical data sets—describing what things are now measured by NASA and by others, identifying the resulting data sets, and gauging the experiences of users of these data sets (Chapter 2). Next, we cite the five key questions guiding the ESE and then recast each question into a cryospheric framework (Chapter 3). Thus the first ESE question, "How is the global Earth system changing?" becomes "Are changes occurring in the polar atmosphere, ice sheets, oceans, and terrestrial regime?" and for each of these we developed a series of polar-focused sub-questions. After much brainstorming and debate, we reduced these "science-driving questions" to those we consider most important. Then we developed a list of the measurements required to support research on those questions, in essence the high-latitude observations most needed to detect global change. This analysis appears in Chapter 3. In Chapter 4, we assess some of the specific polar observational programs and data sets that NASA has supported. This assessment, when related back to the science-driving questions, allows us to judge the adequacy of current data collection efforts from an ESE perspective and sets the stage for our advice on how to improve the agency's overall high-latitude program strategy. Finally, in Chapter 5 we provide conclusions and recommendations grouped in three areas: key gaps and measurement needs, general NASA strategy for supporting high-latitude research, and specific issues related to the effectiveness of the Distributed Active Archive Centers (DAACs). This report focuses on data sets of cryospheric importance, not all of geophysics, in an attempt to target our advice to be most useful to NASA's High Latitude Program.

Many people had a role in providing information to our committee as we prepared this report. In particular, the committee would like to thank Kim Partington, former manager for the High Latitude Program, at NASA Headquarters in Washington, D.C., for his leadership and assistance. We also appreciated the information provided by our DAAC liaisons: James Conner, DAAC manager, Alaska Synthetic Aperture Radar (SAR) Facility; Mark Parsons, DAAC manager, National Snow and Ice Data Center (NSIDC); David Bromwich, Ohio State University and member of the NSIDC Users Group; and Benjamin Holt, NASA Jet Propulsion Laboratory, California, and member of the Alaska SAR Users Group. We also wish to thank Drew Rothrock, Jamie Morison, and others who came to our meetings for face-to-face discussions and the more than 100 people who took the time to complete the questionnaire that we offered on the Polar Research Board's homepage. This survey, although anecdotal, gave the committee broad insights into how users perceive and use the available geophysical data sets, and helped us formulate our recommendations on the data archival and distribution system used by NASA.

On behalf of the entire committee, I want to express our appreciation to the Polar Research Board's supporting staff, Chris Elfring, Rob Greenway, and Ann Carlisle. Their guidance kept us on track, and their expertise and support, in too many ways to mention here, enabled the project to proceed far more efficiently than it would have without them. Finally, let me add a word of thanks to the committee's members. This was a highly talented and extremely hardworking group, and it showed

exceptional ability to work together as a team. I found it remarkable that individuals with so many other commitments were willing to volunteer the time and effort required to complete this activity on a relatively tight schedule.

JOHN WALSH, *Chair*
Committee to Review NASA's
Polar Geophysical Data Sets

Acknowledgment of Reviewers

The committee would like to express its appreciation to the people who served as reviewers for this report. These individuals were chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. This independent review provided candid and critical comments that assisted the authors and the NRC in making the published report as sound as possible and ensured that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remains confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Steve Ackerman, University of Wisconsin
Charles Bentley, University of Wisconsin
David Bromowich, Ohio State University
Jennifer Frances, James J. Howard Marine Laboratory
Lars-Otto Reiersen, Arctic Monitoring Assessment Program, Oslo, Norway
S. Fred Singer, Science and Environmental Policy Project
Patrick Webber, Michigan State University
E-an Zen, University of Maryland

While the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

Contents

Executive Summary

The high latitudes of the Arctic and Antarctic, together with some mountainous areas with glaciers and long-lasting snow, are sometimes called the cryosphere—defined as that portion of the planet where water is perennially or seasonally frozen as sea ice, snow cover, permafrost, ice sheets, and glaciers. Variations in the extent and characteristics of surface ice and snow in the high latitudes are of fundamental importance to global climate because of the amount of the sun's radiation that is reflected from these often white surfaces. Thus, the cryosphere is an important frontier for scientists seeking to understand past climate events, current weather, and climate variability. Obtaining the data necessary for such research requires the capability to observe and measure a variety of characteristics and processes exhibited by major ice sheets and large-scale patterns of snow and sea ice extent, and much of these data are gathered using satellites.

As part of its efforts to better support the researchers studying the cryosphere and climate, the National Aeronautics and Space Administration (NASA)—using sophisticated satellite technology—measures a range of variables from atmospheric temperature, cloud properties, and aerosol concentration to ice sheet elevation, snow cover on land, and ocean salinity. These raw data are compiled and processed into products, or data sets, useful to scientists. These so-called "polar geophysical data sets" can then be studied and interpreted to answer questions related to atmosphere and climate, ice sheets, terrestrial systems, sea ice, ocean processes, and many other phenomena in the cryosphere. The goal of this report is to provide a brief review of the strategy, scope, and quality of existing polar geophysical data sets and help NASA find ways to make these products and future polar data sets more useful to researchers, especially those working on the global change questions that lie at the heart of NASA's Earth Science Enterprise.

THE POLAR REGIONS AND NASA'S EARTH SCIENCE ENTERPRISE

NASA's Earth Science Enterprise (ESE) is one of four strategic enterprises being used to guide the agency's overall research direction. The ESE is dedicated to understanding the total Earth system and the effects of humans on the global environment. Within this enterprise, NASA works with inter-agency and international partners to understand patterns in climate that, ultimately, should allow the nation to predict and respond more quickly to environmental events such as floods and severe winters (NASA, 2000). ESE priorities are driven by five key science questions:

1. How is the global Earth system changing?
2. What are the primary forcings of the Earth system?
3. How does the Earth respond to natural and human-induced changes?
4. What are the consequences of change in the Earth system for human civilization?
5. How well can we predict the changes in the Earth system that will occur in the future?

These science questions drive current NASA research initiatives and thus help define the focus and scope of future data set needs.

In this report, the committee looks at these key science-driving questions from a cryospheric perspective and describes the most important research issues and the measurements required to address those issues. Thus, the first ESE question, "How is the global Earth system changing?," which addresses variability and trends in the climate and biosphere system, becomes "Are changes occurring in the polar atmosphere, ice sheets, oceans, and terrestrial regime?" and various sub-questions of relevance. The second question about primary forcing agents of the climate system becomes "What are the major fluxes of CO_2 and other trace gases from the polar land surfaces and oceans?" and "What are the spatial and temporal distributions and variability of aerosols in the polar atmosphere?"

The third question, focused on responses to change, breaks down into a number of important questions, such as "How will the atmospheric contribution to the mass balance of ice sheets change with the effects of global warming?," "How do the polar oceans respond to and affect global ocean circulation?," "How will the albedo-temperature feedback amplify future climate change?," and "How will land surface hydrology and energy exchanges be influenced by the climate-induced changes to vegetation structure and distribution across the polar regions?"

The fourth question, about consequences, is focused on understanding the possible effects of change on permafrost, shipping, offshore mineral extraction, commercial and subsistence fishing, storms and coastal erosion, water supplies, growing seasons, and changes in range of vegetation and animal species. Finally, the fifth question—pertaining to predictive capabilities—translates to improving capabilities for understanding climate variation in polar regions, defining and obtaining data sets needed by modelers, and improving model simulations of polar processes. The science-driving questions and the associated measurement requirements formulated by the committee are summarized in Table ES-1 and discussed in full in Chapter 3.

Discussion of whether existing data-sets provide the information needed to answer the science-driving questions and the committee's conclusions and recommendation follow Table ES-1, begining on page 9.

TABLE ES-1 Key Questions, Research Issues, and Associated Measurement Requirements

1. HOW ARE POLAR CLIMATE AND THE BIOSPHERE CHANGING?	
1.1. Are changes occurring in the polar troposhere?	
1.1a: Is an acceleration of the polar hydrologic cycle apparent in changes of polar precipitation rates in either hemisphere?	*Measurement Requirements 1.1a*: Rainfall and snowfall over land, ocean, continental ice and sea ice; profiles of atmospheric humidity, temperature, winds at synoptic time and space scale resolution.
1.1b: Is the radiation balance of the polar regions changing?	*Measurement Requirements 1.1b*: Atmospheric temperature and humidity profiles, aerosol abundances and properties, surface albedo and temperature, cloud horizontal/vertical extent and water content (also phase and particle sizes), surface radiation fluxes, top of atmsphere radiation fluxes.
1.2 Are changes occurring in the polar ice sheets?	
1.2a: Is the surface elevation of the ice sheets changing?	*Measurement Requirements 1.2a*: Ice sheet elevation time series.
1.2b: In coastal Greenland, are present-day changes in ice sheet mass due to changes in discharge rates, changes in accumulation, and/or changes in melt rates? How do the changes in ice sheet mass compare to past changes?	*Measurement Requirements 1.2b*: Time series of ice velocity and grounding line position, ice thickness distributions for outlet glaciers and drainage basins, surface energy balance, albedo, and ice-melt runoff.
1.2c: Are present day changes in the West Antarctic Ice Sheet due to local or global phenomena? Local warming appears to be independent of or decoupled from global trends and mass wasting of the West Antarctic Ice Sheet is believed to be occurring at an unprecedented rate. Is this related to human activities, local weather phenomena, or long-term climatic oscillations?	*Measurement Requirements 1.2c*: Time series observations of ice velocity and grounding line positions, the distribution and velocity of ice streams, ice thickness (topography and mass), surface energy balances, precipitation accumulation rates, melting rates (oceanic salinity) and rates (mass) of calving.

continued

TABLE ES-1 Continued

1.3 Are changes occurring in the polar oceans?	
1.3a: Are changes in high latitude precipitation and surface runoff influencing the Arctic Ocean's salinity, sea ice, and circulation structure?	*Measurement Requirements 1.3a*: Precipitation, river runoff, snow cover, glacial runoff, ocean circulation, temperature, and salinity.
1.3b: Are changes occurring in the thickness, coverage, and circulation of sea ice?	*Measurement Requirements 1.3b*: Sea ice thickness, concentration, and motion.
1.3c: Are significant changes occurring in ocean productivity?	*Measurement Requirements 1.3b*: Ocean color, sea ice concentration and thickness, river discharge, and chemical fluxes.
1.4 Are changes occurring in the polar terrestrial regime?	
1.4a: Is the distribution of permafrost and Arctic region freeze/thaw changing?	*Measurement Requirements 1.4a*: Permafrost extent, timing of freeze and thaw, vertical temperature profile, and thermokarst topography.
1.4b: Is the hydrology of Arctic terrestrial regions changing?	*Measurement Requirements 1.4b*: Precipitation, temperature, surface radiation parameters (roughness, albedo), winds, humidity, permafrost state, land cover, runoff, and river discharge.
1.4c: Are significant changes occurring in the distribution and productivity of high-latitude vegetation?	*Measurement Requirements 1.4c*: Vegetation characteristics (leaf area index, canopy density, albedo, structural composition, vegetation class), disturbance characteristics (type, timing, severity), wetlands extent, and nitrogen deposition.
2. PRIMARY FORCINGS OF THE POLAR CLIMATE SYSTEM	
2.1 What are the major fluxes of CO_2 and other trace gases from the polar land surfaces and oceans?	*Measurement Requirements 2.1*: Sea ice concentration and extent, evapotranspiration, soil moisture, surface temperature, permafrost characteristics, vegetation characteristics, disturbance characteristics, wetland extent, CO_2 and CH_4 fluxes, nitrogen deposition, river discharge, and chemistry.

continued

TABLE ES-1 Continued

2.2: What are the spatial/temporal distributions and variability of aerosols in the polar atmosphere?	*Measurement Requirements 2.2*: Aerosol concentration, size distribution, vertical distribution, and composition (index of refraction).
3. RESPONSES TO FORCING AND ASSOCIATED FEEDBACKS INVOLVING THE POLAR REGIONS	
3.1 How will the atmospheric contribution to the mass balance of the ice sheets (i.e., precipitation and energy fluxes) change with the effects of global warming?	*Measurement Requirements 3.1*: Precipitation and accumulation history, surface heat fluxes, surface temperature, inversion strength, snowpack structure, ice sheet elevation, ice sheet discharge and runoff.
3.2 How do the polar oceans respond to and affect global ocean circulation?	
3.2a: How sensitive are the polar oceans to changes in freshwater inputs and how does the outflow of sea ice and freshwater affect the global thermohaline circulation?	*Measurement Requirements 3.2a*: Sea ice concentration, thickness, velocity; precipitation, evaporation, river runoff, sea surface height, ocean temperature, salinity, and circulation.
3.2b: What is the relationship between polar ocean circulation and the large-scale interrannual/decadal modes of atmospheric variability (e.g., ENSO, AO, NAO, AAO)?	*Measurement Requirements 3.2b*: Surface pressure and temperature, vertical profiles of atmospheric winds, sea ice concentration, ocean temperature, salinity, and circulation.
3.2c: How will changes in ice sheets and polynyas affect water mass formation and circulation?	*Measurement Requirements 3.2c:* Glacier runoff and iceberg calving, sea ice concentration and thickness, sea surface height, ocean temperature, salinity, and circulation.
3.3 How will the albedo-temperature feedback amplify future climate change?	
3.3a: How is the albedo-temperature feedback affected by the physical characteristics of melting snow and ice?	*Measurement Requirements 3.3a:* Surface albedo, sea ice concentration and thickness, melt pond fraction, snow depth on sea ice, surface temperature.
3.3b: How is the albedo-temperature feedback affected by polar clouds and aerosols?	*Measurement Requirements 3.3b:* Atmospheric temperature and humidity profiles, aerosols, surface temperature and albedo, cloud horizontal/vertical extents and water contents (particle size and phase).

continued

TABLE ES-1 Continued

3.4 How do seasonal snow and ice cover interact with the modes of interdecadal variability in the Northern Hemisphere and the Southern Hemisphere?	*Measurement Requirements 3.4:* Snow cover and albedo, sea ice concentration and albedo, global surface temperature, precipitation, pressure.
3.5 Are changes in sea ice concentration influencing the amount of water vapor in the polar atmosphere?	*Measurement Requirements 3.5:* Surface temperature, surface evaporative flux (surface air humidity and winds), sea ice concentration, snow on sea ice.
3.6 How do atmospheric boundary layer processes under polar conditions influence the exchanges of heat and freshwater between the atmosphere and cryosphere?	*Measurement Requirements 3.6:* Atmospheric temperature and humidity profiles, cloud and vertical layer structure, wind profiles and advective fluxes, surface turbulent fluxes, surface temperature and salinity.
3.7 What role does the cryosphere play in determining the dependence of the large-scale atmospheric circulation on the global meridional temperature gradient?	*Measurement Requirements 3.7:* Profiles of atmospheric winds, temperature, humidity, clouds (layer structure and water content), surface and atmospheric radiative fluxes, precipitation.
3.8 How will land surface hydrology and energy exchanges be influenced by the climate-induced changes to vegetation structure and distribution across the polar regions?	*Measurement Requirements 3.8:* Profiles of atmospheric winds, temperature, humidity, clouds (layer structure and water content), surface and atmospheric radiative fluxes, precipitation.
3.9 How will ecosystems of the high latitudes change in response to CO_2 and trace gas loading of the atmosphere?	*Measurement Requirements 3.9:* Vegetation characteristics, albedo, snow characteristics, precipitation, evapotranspiration, disturbance characteristics, permafrost characteristics, soil moisture, river runoff, rainfall, snowfall, and snow cover.
4. CONSEQUENCES OF CHANGE IN THE POLAR REGIONS	
4.1 How does permafrost variability impact human infrastructure (roads, buildings) in high latitudes?	*Measurement Requirements 4.1:* Permafrost extent, thermokarst topography, soil temperature profile, land-surface temperature, snow characteristics, soil moisture, vegetation characteristics, disturbance characteristics, wetlands extent.

continued

TABLE ES-1 Continued

4.2 What changes will occur in water supplies from snow and snow-fed rivers as the climate changes?	*Measurement Requirements 4.2:* Precipitation, snow cover, ground water, river runoff.
4.3 How will shipping, offshore mineral extraction, commercial fishing, and subsistence fishing/hunting be affected by changes in coastal sea ice characteristics?	*Measurement Requirements 4.3:* Sea ice concentration, ice thickness distribution, surface winds, ocean productivity.
4.4 How will changes in coastal sea ice coverage and sea level rise impact storm surges, coastal erosion and inundation of the coastal fresh water supply?	*Measurement Requirements 4.4:* Sea level height, sea ice concentration, coastal erosion rates, coastal topography.
4.5 How will primary terrestrial productivity, vegetation, and higher organisms be impacted by changes in the Arctic's physical environment?	*Measurement Requirements 4.5:* Permafrost characteristics, vegetation characteristics, rainfall, snowfall, snow characteristics, disturbance characteristics, wetlands extent, soil moisture, land surface temperature, photosynthetically active radiation, evapotranspiration, vegetation characteristics, sea ice extent and thickness, sea surface temperature, salinity, and color, UV radiation.
5. PREDICTING CHANGES IN THE POLAR CLIMATE SYSTEM AND THEIR GLOBAL IMPACTS	
5.1 To what extent can transient climate variations in the polar regions be understood and predicted?	*Measurement Requirements 5.1:* Relevant models and supporting data as described in Chapter 3.
5.2 For the purposes of data assimilation by atmosphere and ocean/ice models, including numerical weather prediction models, is there a need for more and/or new observations from the polar regions?	*Measurement Requirements 5.2:* Relevant models and supporting data as described in Chapter 3.
5.3 What specific improvements to formulations of polar processes (e.g., sea ice, land surface energy exchanges) are necessary for the accurate simulation and prediction of climate and climate change?	*Measurement Requirements 5.3:* Relevant models and supporting data as described in Chapter 3.

DO EXISTING DATA SETS PROVIDE WHAT IS NEEDED TO ANSWER THE SCIENCE-DRIVING QUESTIONS?

The science-driving questions in Chapter 3 can be analyzed to lead to a clear set of research priorities. That is, by defining the measurements needed to study these questions, one can then evaluate whether NASA's existing polar geophysical data sets adequately meet these needs or whether additional measurements are needed. NASA and other organizations already support and collect data for many variables that are relevant to the polar science-driving questions, but the temporal and spatial coverage can be improved.

The committee's analysis identified the following priority measurement needs:

atmospheric profiles (including vertical profiles of atmospheric temperature, humidity, and wind)
cloud properties
aerosol properties
surface temperature
surface heat fluxes
surface albedo
precipitation
permafrost
land surface characteristics
evapotranspiration
soil moisture
terrestrial CO_2 and CH_4 flux
river runoff
ice sheet elevation
ice sheet dynamics
snow cover
sea ice concentration
sea ice thickness
sea ice velocity
ocean surface temperature and salinity
sea surface height
ocean productivity and CO_2 flux
wildlife habitat and migration

NASA makes significant contributions to the development, evaluation, and availability of many data sets of importance in addressing the science-driving questions. For instance, it has done well in supporting demonstration projects and field campaigns that have helped identify the potential applications of remote-sensing technologies to development of data sets addressing variables relevant to the terrestrial land surface (e.g., land surface characteristics, terrestrial CO_2 and CH_4 flux, freeze/thaw dynamics, snow cover, evapotranspiration and soil moisture). The agency also makes a valuable contribution in terms of ground-based monitoring for carbon fluxes.

NASA has also supported analysis of satellite data collected by other agencies, for instance to determine atmospheric temperature and humidity profiles enhanced for polar conditions, surface temperature and visible albedo, cloud properties, and surface radiative fluxes. NASA's work on mass change for the Greenland ice sheet, its contributions toward understanding ice mass balance in Antarctica, its contributions to understanding surface energy balance and local meteorology, and its high resolution mapping of ocean color also important for understanding climate changes and its potential societal impacts. Many other examples are discussed in Chapter 4.

CONCLUSIONS AND RECOMMENDATIONS

Based on its deliberations, the committee developed conclusions and recommendations in three categories:

- key data gaps and the highest priorities for measurements in the context of the polar variations of NASA's Earth Science Enterprise science-driving questions;
- the general NASA strategy for enhancing and providing relevant data sets to the polar science community; and
- issues relating to the effectiveness of the Distributed Active Archive Centers (DAACs) and their data distribution activities.

Data Gaps and Measurement Needs

The committee identified 10 high-priority measurements related to the cryosphere (i.e., surface characteristics) and the fluxes that determine cryospheric characteristics. Thus, the committee sees them as obstacles to progress on the fundamental science issues in the ESE. These high priority measurement needs are:

- polar precipitation,
- surface albedo,
- freshwater discharge from terrestrial regions,
- surface temperature,
- surface turbulent fluxes,
- permafrost extent,
- ocean surface salinity,
- ice sheet mass flux,
- land surface characteristics, and
- sea ice thickness.

For all variables, the need is for data sets sufficient to determine the spatial and temporal variations. For those variables deemed suitable for monitoring, temporal continuity across instruments must be a key consideration.

For polar precipitation the key need is to measure the space-time distribution of precipitation rates for moisture budget determinations. For surface albedo the key need is to capture the progression of melt and freeze-up over spatial and temporal scales adequate for surface energy budget evaluations and for testing and validation of models. Meeting this objective also requires surface temperature measurements with similar time and space resolution. Related to freshwater discharge from terrestrial regions, there is need for data on fluxes of freshwater to polar oceans from ice sheets and glaciers, as well as surface and sub-surface runoff from non-glaciated land area. With regard to surface temperature, the need for routine measurements under cloudy skies calls for multisensor analysis approaches that combine microwave, infrared, and radar measurements. For surface turbulent fluxes, the key need is to measure sensible and latent heat fluxes over all polar surfaces.

For permafrost, the key need is for measurements of the extent of permafrost, the depth of permafrost, vertical temperature profiles, and the timing of thaw and freeze-up of the active layer. Key needs with regard to polar ocean surface salinity are high- to moderate-resolution measurements of coastal and ice edge environments and improved accuracy in near-freezing temperatures. For ice sheet mass flux, the key need is for the continuation and interpretation of measurements to understand the variability introduced by accumulation and ablation, both temporally and spatially.

Needed measurements of land surface characteristics include leaf area index, wetlands extent and water storage, canopy density, structural composition of vegetation, and disturbance characteristics at appropriate time and space scales. Finally, for sea ice thickness the key need is for development of remote-sensing techniques (beyond those currently available for mapping ice age and type).

NASA's General Strategy on Polar Geophysical Data Sets

To improve NASA's general strategy for providing useful polar geophysical data sets the committee strongly believes that measurements should not be made in isolation, and that there is a need for across-sensor and across-variable evaluations to be an integral part of remote sensing activities. These themes are common to several of the following recommendations.

- In several respects, polar data sets have been isolated from global data sets in the overall NASA data set framework. Examples are the global satellite-derived atmospheric termperature data sets and global sea surface temperature data sets versus the TOVS vertical profiles and the POLES surface air temperatures. **We recommend that NASA make efforts to integrate polar data sets and global data sets in the architecture of the NASA data distribution system.**

• The committee was struck by the multiplicity of data sets available for some polar variables. Cloud products, sea ice coverage, and sea ice motion are examples. **The committee recommends that NASA support systematic comparisons of different versions of the same product, including calibration and validation activities, the establishment of error bars, and the merger or consolidation of data sets depicting the same variables. This activity should include the determination of needs for (1) ground-based validation sites in addition to those planned for EOS, and (2) additional field campaigns directed at validation of remote-sensing products.**

• In general, satellite sensors and products have not been optimized for polar regions. Examples include those used for precipitation estimation, determination of cloud properties, and sea surface salinity. **The committee recommends that NASA give higher priority to sensor optimization for polar applications.**

• For some of the variables listed in the preceding sub-section, alternative measurement approaches may be more appropriate than reliance on satellite products. Alternative and complementary approaches could include aircraft (manned and unmanned), automated underwater vehicles, and other ground-based measurements. **The committee recommends that NASA explore such alternatives from a cost and benefit perspective in the planning and design of its polar programs.**

• There is a need for enhanced interaction and feedback between modelers and data providers. This interaction can occur to some extent through data assimilation activities; however, there is often a disconnect between modelers' needs for forcing and validation data sets and the products derived from remote sensing. **The committee recommends that NASA strengthen the connection between modeling and its remote sensing strategy for the polar regions.**

• **The committee recommends that NASA support research to determine optimum uses of polar remote sensing measurements in re-analyses so these measurements are better integrated into a global context, thereby enhancing their value to ESE and reducing their insularity.** For the broadest impact, this activity should entrain, in the earliest stages, the two leading global re-analysis centers, NOAA's National Centers for Environmental Prediction and European Center for Medium-range Weather Forecasts.

• Consistency within and among data sets is a necessary prerequisite for detecting, with a known degree of certainty, the effects of climate change on high-latitude systems. Such an effort would also enhance the interaction of modelers and data providers and constitute an important framework activity for developing and testing new sensor designs. **The committee recommends that NASA give high priority to fostering the development of spatially and temporally coherent, internally consistent polar geophysical data sets.**

• Finally, the continued use of satellite-derived data sets in intercomparison and synthesis activities, such as those described above, argues for the long-term archiving of satellite data sets within the NASA data distribution system. **The committee considers the DAACs to be the natural vehicles for long-term archival.**

Improving the Effectiveness of Distributed Active Archive Centers

As a result of its deliberations—including consideration of the 1998 National Research Council report, *Review of NASA's Distributed Active Archive Centers*, conversations with DAAC managers and representatives of associated user groups, and a survey of the science community—the committee learned much about the effectiveness of the polar-oriented DAACs. Unlike the recommendations in the two preceding sections, the following recommendations pertain specifically to the polar DAACs.

• *Redundancies*: **The committee recommends that NASA support quantitative evaluations of possibly redundant data sets to help provide a rational basis for decisions about discontinuing certain data sets.** The results of coordinated evaluations should be used by the DAACs to minimize redundancies in their holdings and their distribution responsibilities.

• *Outreach*: The survey responses showed a surprising lack of awareness of the availability of holdings of the DAACs. **The committee recommends that the DAACs increase the efforts to disseminate and publicize their holdings, particularly among investigators who are not involved in large NASA programs, as well as provide overview documentation of the broad spectrum of data sets available at a site.**

- *Links*: **With regard to the distribution of data products by the DAACs, the committee recommends that the DAACs install more extensive web links to other global products that contain polar data, with brief descriptions of the holdings in the sites.** These "pointers" should include available information about data sources, quality, and limitations specific to the polar regions. This information can be provided through literature references or through DAAC-initiated assessments.

- *Improvements in Tools*: **The committee recommends that data set providers better document their individual holdings as well as provide overview documentation of the broad spectrum of data sets available at their site.** The addition of browse products to data sets would help users unfamiliar with the data to judge the utility of the data set for their uses. To help overcome obstacles faced when trying to combine data sets from different sensors, data set providers should increase availability of user-friendly software tools to help with tasks such as converting from one format to another and among standard grid formats. Attention should also be given to the issue of changing technology so that archived data will remain readable with future technologies.

- *Feedback*: **The committee recommends that data set providers provide additional opportunity for community feedback via the creation of web bulletin boards where users may comment on their experience using data at that site.** This will encourage a more coherent user community where, for example, problems may be solved between users without direct intervention by the data site provider.

- *P-I Web Sites*: **The committee recommends creation of an archive of principal investigator-generated websites containing relevant data sets or information about these data sets.** This type of archive will complement the data distribution activities of the DAACs and will enhance their utility as information resources for the polar community.

- *Alaska SAR Facility*: While ASF received expressions of both praise and frustration from our survey respondents, the use of ASF products has been limited by data product availability, by costs, by ease of access, and by access and distribution restrictions. There has been some recent improvement in access to SAR products. Nevertheless, we share the concern of the 1998 DAAC review and reiterate the need to facilitate access to and utilization of ASF products. **In particular, the committee recommends that ASF become more proactive in the assembly of pan-Arctic data sets.**

1

Introduction

The Earth's cryosphere—that portion of the planet where water is perennially or seasonally frozen as sea ice, snow cover, permafrost, ice sheets, or glaciers—is especially sensitive to climate change. Thus, scientists often study the cryosphere to learn more about past climate events, understand current weather, and project future climatic changes. Understanding cryospheric processes requires the capability to observe, measure, and understand the variability exhibited by major ice sheets and hemispheric patterns of snow and sea ice extent. To diagnose and predict climate change, climate and hydrologic models need adequate representation of cryospheric processes (e.g., phase changes from solid to liquid) and interactions.

In the past, unprocessed satellite data of relevance were abundant, but little of the data was processed into useful geophysical data sets (products). To address this challenge, the National Aeronautics and Space Administration (NASA)—in partnership with the National Oceanic and Atmospheric Administration (NOAA), the United States Geological Survey (USGS), and the Environmental Protection Agency (EPA)—initiated the "Early Earth Observing System Pathfinder Data-Set Activity" in 1990. The Pathfinder Program was established to develop remote-sensing data sets to support global change research and to enable NASA to gain experience in reprocessing and transferring large data sets between national and international research facilities. Pathfinder data sets consist of long time series of global and regional data as well as higher-level data products generated by NASA and other federal agencies. Some of these products

BOX 1-1
POLAR PATHFINDER DATA SETS

There are three major NASA/NOAA Pathfinder data sets with significant relevance to the polar regions:

1. Advanced Very-High-Resolution Radiometer (AVHRR) Global Area Coverage, which measures global vegetation, radiance, sea-surface temperature, and clouds and aerosol data;

2. Television Infrared Observing Satellite Operational Vertical Sounder, which produces level-3 (gridded to 100 km boxes), daily-averaged atmospheric data, such as temperature and moisture profiles, surface skin temperature, cloud fraction and height, bulk boundary layer parameters, and surface pressure;

3. Special Sensor Microwave/Imager, which produces hydrology, ocean, snow, and ice data.

Other Pathfinder activities are the joint NASA/USGS/EPA LANDSAT Pathfinder, which includes land-cover data, and the NASA Scanning Multispectral Microwave Radiometer (SMMR). Each Pathfinder activity had a designated science working group responsible for identifying needed products, algorithms, and user services. Research teams coordinate all data sets based on a common map projection and use consistent file-naming conventions and validation methods.

have important significance for climate research in the polar region (Box 1-1).

Pathfinder data sets and derived products are made available to researchers through the Distributed Active Archive Centers (DAACs). The National Snow and Ice Data Center (NSIDC), a component of the DAACs, distributes the polar Pathfinder data sets to the scientific community as part of its many responsibilities related to cryospheric research. In parallel to the polar Pathfinder program, a related group of data sets is being developed through the Polar Exchange at the Sea Surface (POLES) and RADARSAT Geophysical Processing System (RGPS) projects.[1]

[1]The POLES project is an interdisciplinary effort to look at the polar processes that influence the global heat and hydrological cycles; it combines satellite and in situ data in collaboration with the polar Pathfinder Program to create a complementary data set to explore complex physical processes in the polar regions. The RGPS polar products measure geophysical quantities such as sea-ice motion and the thickness distribution of thin ice using Synthetic Aperture Radar archived at the Alaska SAR Facility.

Together, the Polar Pathfinder products, POLES products, and RGPS images are a significant source of satellite data for the polar research community.

The term "polar geophysical data sets" is used here to indicate any data set that has some special relevance to understanding the most important questions being addressed by current Earth system research in polar regions. Examples of such questions include: How are changes in polar ice sheets reflected in global sea level? How will changes in climate affect hydrologic processes at high latitudes and hence affect such features as ice sheet mass balance and thermohaline circulation? What will be the effects of changes in permafrost, Arctic tundra, boreal forest, and polar oceans on the concentrations and flux of radiatively active gases in the atmosphere? Figure 1-1 depicts the main systems of interest to polar scientists and the relationships among them.

The scope of the present review does not include geophysical problems in the solid earth nor in the upper atmosphere. The important ozone/UV issue, for example, is not addressed here. Our decision to narrow the scope in this way was based on the charge to the committee and on the need to focus our efforts on the primary thrusts of NASA's Polar Program.

PURPOSE OF THIS STUDY

NASA invests significant resources in collecting data sets that serve the science community, but those data sets can only be judged "successful" if scientists use them effectively. To assist in planning how data sets will support polar science in the future and how data products may best be tailored to support the Earth Science Enterprise program, NASA asked the National Academies for guidance. In response, the Committee to Review NASA's Polar Geophysical Data Sets was created to review NASA's strategy for providing derived geophysical data sets to the polar science community. This report provides a brief review of the strategy, scope, and quality of existing polar geophysical data sets; suggests ways to make these products and future polar data sets more useful to researchers; and considers whether the products are reaching the intended communities. Specifically, the committee was charged to:

1. assess the general scope and quality of the polar data sets and determine whether, as a whole, these support the needs of the polar research community.
2. evaluate the strategy NASA uses to develop and disseminate the polar data sets.
3. recommend improvements to NASA's strategy for providing data

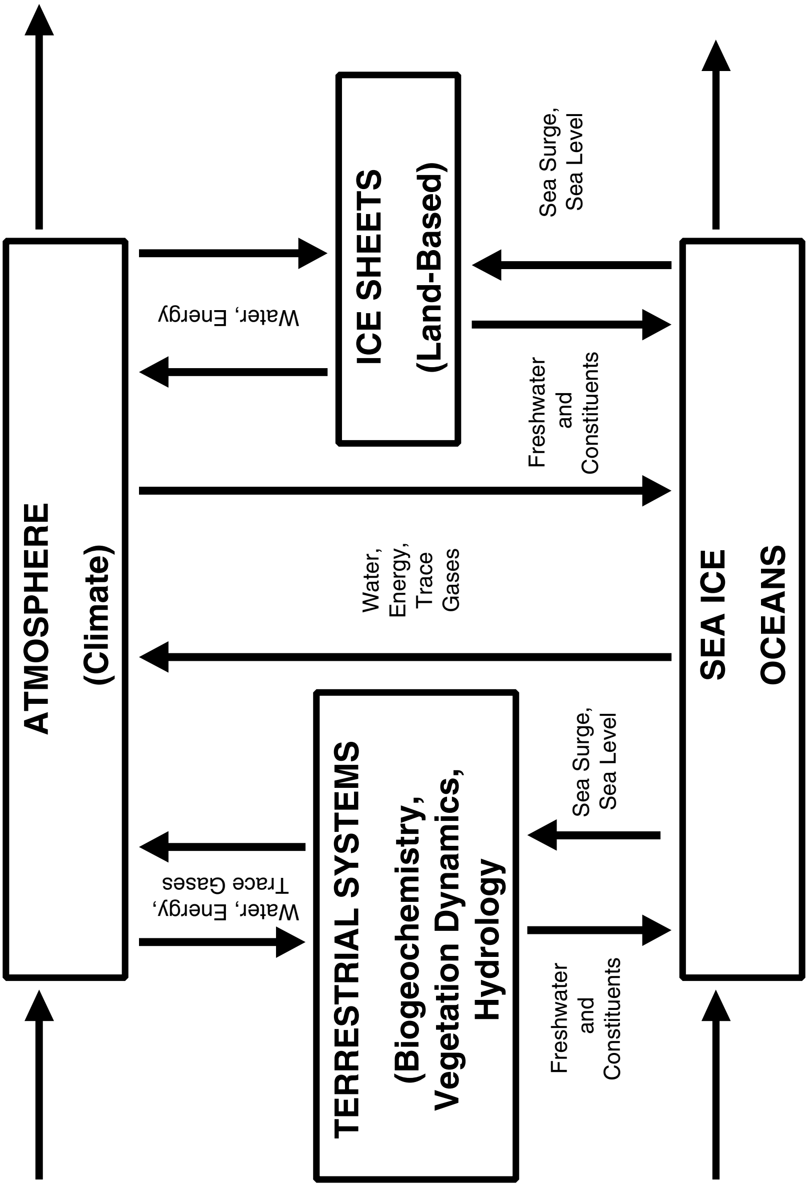

FIGURE 1-1 Main global systems where NASA geophysical data sets provide important information to polar scientists.

sets that support the goals of NASA's Earth Science Enterprise Program, taking into consideration current capabilities, existing infrastructure, and cost-effectiveness.

4. evaluate, as time and resources allow, individual polar data sets and products at the NSIDC and Alaskan SAR Facility to determine whether they can be improved or modified to better support the community.

METHODS

To gather the information needed to address these tasks, the committee's members relied on their own experiences working with geophysical data sets and input from a wide variety of others involved in either collecting, managing, or using polar data sets and products. The committee established liaisons with the DAACs and relevant user groups, and these representatives made presentations and provided information to the committee. An important aspect of this study was a Web-based survey that drew responses from more than 100 scientists (see Appendix B). The survey gathered opinions about the strategy, scope, and quality of existing polar geophysical data sets and ideas for improving future products. Respondents described their general areas of research and the data sets they used; noted if they did not use NASA data sets and why not; offered opinions on the quality and ease of access; and noted whether there were any data sets they wished were available. The committee considered this information as it wrote this report, and some comments on the responses appear in Appendix B.

The committee interpreted its charge as providing an assessment of current NASA polar geophysical data set products and recommendations to guide future decisions about the products. Rather than assess the details of specific data sets, the committee took a broad approach and based its assessment on the science questions outlined in the Earth System Enterprise program (NASA, 1988) adapted to focus on the cryosphere. Chapter 2 is an assessment of the status of polar geophysical data products, including results of the survey of data users. Chapter 3 develops a list of science questions, including the committee's assessment of the data required to address each science question. Chapter 4 assesses the adequacy of existing polar geophysical data products for addressing the science questions. Chapter 5 provides an assessment of major gaps in the polar data products, suggests improvements to the general strategy on polar data sets, and addresses the effectiveness of the DAACs.

While the ESE science-driving questions provide a framework for assessing what additional measurements are needed, a recurring theme of the report is the importance of mining as much information as possible from the existing record of satellite data, which extends back for 20 years for some sensors. Existing satellite data provide a powerful resource for understanding how and why the polar regions have experienced such large changes in recent decades. New EOS-era sensors will fill in some details, to be sure, but data records from these sensors for studying change will not be available for many years, if they indeed receive continued support for "long-term" monitoring. Various recommendations in Chapter 5 focus on the use of existing data sets in the more general contexts of ESE science and change detection, and also in the more specific context of NASA's DAACs and their provision of useful data sets to the science community.

2

Overview of NASA Data Sets

As a first step in assessing data sets with relevance to research in high latitudes, it is important to describe the broad context—that is, to introduce NASA's Earth Science Enterprise (ESE) and to provide examples to illustrate the great diversity of available and expected products. The ESE, formerly Mission to Planet Earth, uses space-, ground- and aircraft-based systems to measure relevant attributes of the Earth system and quantifies responses to natural and human-induced changes. The ESE also seeks to improve predictive capabilities for climate, weather, global air quality, and natural hazards. To accomplish these goals, the program seeks to describe how Earth-system components and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all relevant time scales. ESE is driven by recognition that the planetary environment has natural variability and that humans are no longer passive participants in the evolution of the Earth system; its research activities are important parts of the U.S. Global Change Research Program.

The fundamental question that ESE addresses is: "How is the Earth changing and what are the consequences for life on Earth?" Key research topics fall largely into three categories: forcings, responses, and the processes that link the two and provide feedback. The science strategy is guided by five fundamental questions, each of which can be addressed only by a range of cross-disciplinary research programs (NASA, 2000). These questions are discussed in detail in Chapter 3.

Many ESE research activities have a polar component. This chapter describes examples of some of the polar-specific activities funded by NASA, including POLar Exchange at the Sea Surface (POLES); RADARSAT Geophysical Processing System (RGPS) and the RADARSAT Antarctic Mapping Project; Snow and Hydrology Group; Program for Arctic Regional Climate Assessment (PARCA); and Polar Pathfinder products. These products, together with the detailed listings of data sets held at the National Snow and Ice Data Center (NSIDC) and the Alaska Synthetic Aperture Radar Facility (ASF), represent the data sets generally thought of as the "polar" data sets.

NASA's polar-relevant data holdings, however, are considerably larger than this list suggests. It is notable that in the survey discussed later, respondents frequently asked for atmospheric and cloud-radiation data sets, although most of the respondents study sea ice, snow, and ice sheets. Since such data sets exist elsewhere in NASA, this suggests the need for the polar parts of the data system to provide links and directions to all the polar-relevant data sets held by NASA, along with guidance about quality and usage (preferably by reference to the literature). A similar situation exists regarding international data sets and data sets held by other U.S. agencies, many of which NASA also archives.

EXAMPLES OF NASA-SUPPORTED ACTIVITIES

Polar Exchange at the Sea Surface

A component of NASA's Earth Observing System (EOS), POLES is an interdisciplinary project investigating the exchange of mass and energy at the polar air-ice-ocean interface. POLES is located at the Polar Science Center, Applied Physics Laboratory, University of Washington. Scientists from eight disciplines and four institutions have joined together to use the rich array of satellite data collected from polar regions. The data have been collected using a variety of satellite-based sensors, including passive microwave radiometers, the TIROS-N Operational Vertical Sounder (TOVS), Advanced Very High Resolution Radiometer (AVHRR), and synthetic aperture radar (SAR).

Historically, satellite data have been used for short-term weather forecasts. POLES scientists, however, are using the data to build an understanding of long-term patterns in the fluxes of heat, moisture, and momentum across the surface of the polar oceans. Their goal is to assimilate satellite (and some buoy) observations into polar ocean-atmosphere models that not only refine the treatment of surface exchange processes but also quantify the roles of horizontal transports, oceanic mixing, and deep convection. With better data use, researchers can move beyond present climatological descriptions and document interannual variability. For more information see <http://psc.apl.washington.edu/poles/>.

RADARSAT Geophysical Processing System Products

Polar products of the RGPS measure such variables as sea-ice motion and the thickness distribution of thin ice using SAR archived at the ASF. The scientific goal of the RGPS is to provide data sets that improve the current understanding of the impact of sea ice on climate. Interactions between sea ice, the ocean, and the atmosphere in the polar regions strongly affect the Earth's climate. Sea ice growth, movement, and decay affect energy and mass balance of the polar ocean system. The surface heat and brine fluxes associated with sea ice growth contribute significantly to convection of the ocean and thermohaline circulation. Snow-covered sea ice reflects most of the incident solar radiation back into space, while fresh water fluxes associated with melting ice retard vertical mixing and thus serve as stabilizing elements in the circulation of the North Atlantic waters. Processes along the ice margin and coastlines are important in water-mass formation, development of upwelling, convection, sediment transport, and other phenomena. Understanding and modeling these phenomena requires information on sea ice motion, thickness, and concentration.

The fundamental data set provided by the RGPS is ice motion obtained from tracking common features in successive SAR images. RGPS products (Box 2-1) include derived ice age and ice thickness histograms of the thin-ice fraction of the ice cover in the winter. In the summer, they also include an estimate for the open water fraction. The time of melt-onset in the spring and freeze-up in the late fall are estimated from changes in backscatter signature of the ice cover. These geophysical variables support model improvements and the development of climatologies of sea ice processes. Products are currently maintained by NASA's Jet Propulsion Laboratory (JPL) and will eventually be archived and distributed by the ASF; more information is available at <http://www-radar.jpl.nasa.gov/rgps/radarsat.html>.

RADARSAT Antarctic Mapping Project

The RADARSAT Antarctic Mapping Project (RAMP), a collaboration between the Canadian Space Agency and NASA, has created the first seamless, high-resolution-radar, map-quality mosaic of Antarctica (see Figure 2-1). The goal of the project is to use the map and resulting data products to study Antarctica's ice cover and its response to climate change.

BOX 2-1
RADARSAT GEOPHYSICAL PROCESSING SYSTEM PRODUCTS

Ice Motion (Lagrangian trajectories). A regular array of points is defined initially on the first image of a long time series of SAR images and an ice tracker finds the positions of those points in all subsequent images of the series. This product contains a record of the trajectories or an array of position measurements of the "ice particles" that are located on an initial grid which covers the entire Arctic Ocean. The sampling interval is determined by the available repeat coverage of these points by the SAR sensor (usually 3 days). The initial grid spacing is 10 km. The accuracy of the position measurements is typically 300m in areas with moderate deformation with higher uncertainties in areas with intense deformation.

Ice Deformation. The local deformation of the ice is computed using the velocity gradients at the vertices of the cells. The deformation fields characterize the opening, closing, and shear of the ice cover.

Ice Age Histogram. The ice age distribution of sea ice specifies the fractional area covered by ice in different age categories as a function of time. This ice age distribution is computed from the field of Lagrangian trajectories described above. The algorithm for determining ice age works only in the winter: the assumption is that there is ice growth in all new leads. It is initialized shortly after fall freeze-up and is operated until the onset of melt. The resolution of age is dependent on the sampling interval of the area of interest. The multiyear ice fraction is obtained with a backscatter-based ice classification algorithm. The accumulated freezing-degree days associated with each age class are tracked. The surface air temperatures for computing the freezing-degree days are extracted from analyzed air temperature fields. Closings are interpreted as ridging events and the amount of ice that participates in this processes is recorded. This product contains records of local ice age distributions and the accumulated freezing-degree days of each age category within the distributions, and the ridged ice area.

Ice Thickness Histogram. The ice thickness distribution specifies the fractional area covered by ice in different thickness ranges within a given region as a function of time. The ice thickness distribution is estimated from the ice age distribution using an empirical relationship between the accumulated freezing-degree days and ice thickness. The local age distributions are converted to ice thickness distributions and accumulated over large areas to provide regional scale products.

Open Water Fraction. Summer ice conditions are characterized by an open water fraction. The summer open water fraction in a Lagrangian cell (defined by line segments connecting the tiepoints) is estimated from kinematics and backscatter data.

Backscatter Histogram of Lagrangian Cells. The backscatter histograms of the Lagrangian cells are recorded in this product.

Date of Melt-onset in Spring/Freeze-up in Fall. There is a fairly well-defined change in the backscatter of the snow/ice to the onset of melt and freeze-up. The analysis algorithm will detect and estimate the date of this seasonal transition using the time series of backscatter product.

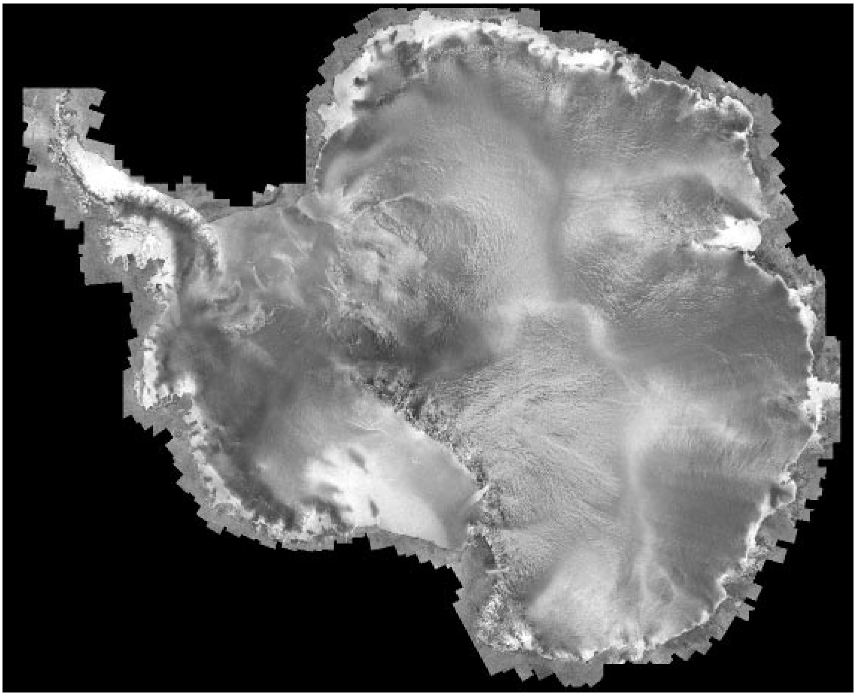

FIGURE 2-1 First complete seamless radar mosaic of Antarctica. Courtesy Canadian Space Agency, © Canadian Space Agency, 2000 (http://www-bprc.mps.ohio-state.edu/radarsat.html).

The first Antarctic imaging campaign was held during the fall of 1997, after the Canadian Space Agency successfully performed a difficult rotation maneuver that enabled the U.S.-launched RADARSAT to become the first SAR instrument capable of viewing the South Pole. Over 7,000 image frames were acquired as part of a mission plan devised by the JPL. Over 4,000 frames were processed to images by the ASF and provided to Ohio State University, which assembled the mosaic using a Vexcel-designed mapping system. The remaining frames were acquired after one repeat cycle of the satellite, and are suitable for interferometric analysis of ice sheet motion.

RAMP has produced some notable scientific accomplishments, such as identifying the southward extent of the East Antarctic Ice Streams and measuring the extent of physical properties of snow dunes and their contributions to mass transport. It is worth special note that in completing the radar imaging of Antarctica (see Figure 2-1), RADARSAT completed radar imaging of the entire Earth. Participants in the RADARSAT Antarctic Mapping Project activity were the Canadian Space Agency, NASA, The Ohio State University, Jet Propulsion Laboratory, Alaska SAR Facility, Vexcel Corporation, Goddard Space Flight Center, Canadian Center for Remote Sensing, Environmental Research Institute of Michigan, and RADARSAT International. The project received scientific and technical support from many organizations in a wide range of nations: British Antarctic Survey (Cambridge), International Center for Antarctic Research (New Zealand), Institute for Glaciology (Argentina), Institute for Geodesy (Germany), Antarctic Cooperative Research Center (Australia), National Institute for Polar Research (Japan), U.S. National Science Foundation, U.S. National Imagery and Mapping Agency, U.S. National Snow and Ice Data Center, and the Scientific Committee on Antarctic Research. More information on the data-set needs of Antarctic scientists is in Box 2-2. The RAMP mosaic and individual SAR images that comprise the mosaic are available from the ASF. The RAMP digital elevation model is available from NSIDC.

BOX 2-2
POLAR GEOPHYSICAL DATA SETS: AN ANTARCTIC PERSPECTIVE

The needs of Antarctic scientists for geophyscial data sets are similar to those of their Arctic counterparts. In particular, just as the NASA ESE objectives can be cast with an Arctic perspective, there are corollary objectives related to ice and snow mass, the lateral and vertical distribution of snow and ice, precipitation patterns, and how these attributes change over time in the southern cryosphere. Use of Antarctic geophysical data sets relates primarily to sea ice and ice sheet measurements. The most obvious distinction between the two polar regions are that Arctic water and ice dynamics primarily relate to floating sea ice whereas the bulk of ice and snow in the southern hemisphere is grounded on land. This basic difference provides challenges for detection systems and for the collection of relevant quantitative data on the mass and thickness of Antarctic ice sheets. Floating sea ice is a seasonally significant feature of the southern oceans as well. A second major difference is that Antarctica has no indigenous populations, whereas the Arctic has a human population that interacts with changes in the environment, not only responding to change but in some instances inducing change. In Antarctica, the major forces affecting climate and the environment are global and generally not locally derived. Antarctica is seen as providing a bellwether of future global changes. The dynamic ebb and flow among the major reservoirs of water, snow, and ice that reside in the southern polar regions are a sensitive barometer of climatic change.

Antarctica is a major consideration in any global inventories of water retained in ice and snow. Antarctic research focuses on the (1) air-sea-ice interactions from both a local and a global perspective; (2) ice sheet processes; and (3) ice shelf mapping. Air-sea-ice interactions are monitored using ice motion data sets and measurement of sea ice distribution and thickness. Studies of changes in the extent and dynamics of glaciers are important research areas for Antarctic glaciologists. Challenges in providing high quality quantitative data to support these programs include the development of common reference data and precise measurements of elevation over time. Accurate and dense topographic coverage of the vast Antarctic ice sheets is needed for glaciological research, including numerical modeling of ice dynamics, with particular reference to mapping and quantifying ice drainage basins, ice shelf grounding lines, ice divides, sub-glacial lakes, ice shelf fronts, and ice rises. Studies are under way to map the extent and concentration of sea ice; ice motion; estimate ice thickness; map sea ice surface temperatures, and map albedo and cloud cover. The data sets typically support (in conjunction with in situ measurements) studies of ice flux; brine production; heat flux; seasonal, interannual, and decadal variability; and validation of models.

Long-time series altimetry data have been provided by the NASA Pathfinder Program. Satellite radar imagery has been used in the southern hemisphere to quantify, map, and monitor: the boundaries of glaciers and ice sheets; the location of surface features such as crevasses, flow lines, moraines, ice streams; snow properties; ice temperature; snow facies; glacial ice motion; and the size, density, and rate of iceberg production. The data sets typically support studies of interannual and decadal variability of the transitions of the snow facies, timing of melt, glacial ice motion and grounding lines for mass balance analyses based on the flux method, and ice sheet elevation changes as an indicator of mass balance changes.

The primary satellites are DMSP with SSM/I microwave radiometer; LANDSAT, the ERS-2 and Canadian RADARSAT with synthetic aperture radar, and the ERS-2 altimeter. The suite of sensors available are not adequate to address all the important climatology issues. Improvements and enhancements in current products would include better coverage of the southern ocean using high resolution radar for ice motion measurement, a better understanding of the retrieved quantities, and coordination of efforts to map ice sheet and sea ice motion. In general, the data used to support Antarctic research are readily available, but issues related to the cost of managing ever-larger data sets and how the community is provided access to this data remain a challenge.

Program for Arctic Regional Climate Assessment

The Program for Arctic Regional Climate Assessment (PARCA) is a NASA project with the goal of measuring and understanding the mass balance of the Greenland ice sheet. The program began in 1993, but significantly increased in scope starting in 1995 when a number of investigations were brought together under one coordinated program. The program includes a mix of satellite and aircraft remote-sensing and in situ measurements from about 25 investigations that address different components of the problem.

The prime PARCA tool has been aircraft laser altimetry, which measures directly the rate of surface elevation change, and ice thickness along all flight lines. Field measurements include shallow to intermediate coring (for average accumulation rates and their temporal and spatial variability), velocity measurements around the ice-sheet perimeter at an elevation of about 2,000 m, local measurements of ice thickening and thinning rates, and climatological observations from automatic weather stations. Data from various satellite sensors are also used: elevation change from satellite radar altimetry; mapping of snow facies and zones of summer melt from passive and active microwave; ice velocities from interferometric SAR and from repeat high-resolution visible and SAR imagery; and mapping surface and 10-m temperatures, accumulation rates, and surface albedo from microwave and AVHRR data.

PARCA is making significant contributions to our understanding of the mass balance of the Greenland ice sheet, proving a baseline set of measurements that will be compared with precise surface-elevation measurements to be provided by NASA's Geoscience Laser Altimeter System (GLAS), to be launched aboard ICESAT in late 2001. Data products are in various stages of completion and many of the source satellite data that PARCA uses are available from the NSIDC and the ASF DAACs. Satellite radar-altimeter data can be obtained from the Pathfinder activity at the Goddard Space Flight Center. Satellite scatterometer data are available from the physical oceanography DAAC (PO.DAAC) at the JPL. LANDSAT imagery is available from the EROS Data Center and SPOT imagery is available through commercial purchase. Data from the recently declassified Defense Intelligence Satellite Program dating back to the 1960s are also available from the EROS Data Center.

Polar Scatterometer Pathfinder Products

Scatterometers offer the longest continuous synoptic microwave record of the globe other than the ongoing Defense Meteorological Satellite Program (DMSP) series of Special Sensor Microwave/Imager (SSM/I) instruments. This NASA Pathfinder uses precisely calibrated non-ocean data streams from the SeaWinds scatterometer instruments on board QuikScat (QSCAT) and ADEOS-II, the NASA Scatterometer (NSCAT) onboard ADEOS-I, and the European Remote Sensing Satellite scatterometer (EScat), and SEASAT scatterometer (SASS) scatterometer instruments to cover both terrestrial and polar ice-covered ocean surfaces.

Innovative techniques will generate products from presently underused scatterometer measurements to maximize their scientific returns for seasonal to interannual and long-term climate change research. These data address a direct scientific requirement in the Earth science community for active microwave data with improved resolution and equivalent time and space coverage to existing passive microwave data. Data that might be analyzed to provide useful geophysical products include:

- Ku-band SEASAT SASS (August–October 1978 [limited images available]);
- Ku-band NSCAT (September 1996–June 1997, daily);
- C-band ERS-1 and ERS-2 (1991 to the present, daily); distribution of derived products must be cleared with ESA.
- Ku-band SeaWinds onboard QSCAT (ongoing from July 1999 at daily intervals).

Consistent polar stereographic image data records are expected to be available by mid-2001 for each of the above instruments for the Arctic (generally between 52 and 90 degrees latitude through the JPL PO-DAAC).

NASA'S DISTRIBUTED ACTIVE ARCHIVE CENTERS

As noted earlier, the objective of NASA's Earth Science Enterprise is to obtain a broad-based understanding of the functioning of the Earth as a system, with particular reference to global environmental change. The data needed to study these processes are necessarily diverse, comprising observations from a wide variety of remote sensing and in situ instruments and experiments collected by several government agencies and academic institutions at different temporal and spatial scales (NRC, 1998). To integrate disparate data types and allow more comprehensive analyses NASA established the Earth Observing System Data and Information System (EOSDIS).

One element of this system is the Distributed Active Archive Centers (DAACs). Seven DAACs[1] process and disseminate remote sensing and in situ data and data products related to the Earth system and provide services primarily to scientists and agency partners. According to a recent review, each DAAC has an individual role in some part of the overall

[1]Goddard Space Flight Center DAAC, Langley Research Center DAAC, Eros Data Center DAAC, Alaska SAR Facility DAAC, Physical Oceanography DAAC, National Snow and Ice Center DAAC, and Oak Ridge National Laboratory DAAC. See NRC (1998) for descriptions and reviews of each. Information about the Alaska SAR Facility DAAC and National Snow and Ice Center DAAC in this section is taken largely from that report.

enterprise, with little overlap or redundancy, although "for the DAACs effectively to fulfill the expectations for them, EOSDIS will need inspired leadership to create a practical network of information centers that truly enables scientific discovery and assessment. . . ." (NRC, 1998). Data sets most relevant to polar regions are managed at the Alaska SAR Facility DAAC and the National Snow and Ice Center DAAC. Both have holdings of relevance to global, Arctic, and Antarctic observations.

Alaska Synthetic Aperture Radar Facility

The Alaska Synthetic Aperture Radar Facility DAAC is located at the Geophysical Institute, University of Alaska, Fairbanks. It was established in 1986 to process, distribute, and archive SAR data collected exclusively by foreign spacecraft: the European Remote Sensing Satellites 1 and 2; the Japanese Earth Remote-Sensing Satellite-1; and the Canadian RADARSAT-1 (Box 2-3). As specified in an international memorandum of understanding (IMOU) between NASA and the foreign space agencies, only limited quantities of data are acquired by ASF and distributed to NASA-approved researchers. The data that are the most accessible are largely from the Alaska and McMurdo Station, Antarctica, masks. The data, acquired and distributed since 1991, are useful for applications ranging from sea-ice dynamics and volcanology to permafrost and glacial loss and ecosystem change. The user community is relatively small but growing, albeit hindered by data restrictions in the IMOU. There were about 400 users in fiscal year (FY) 1997. The international character of this DAAC is unique within the EOSDIS system.

National Snow and Ice Data Center

The National Snow and Ice Data Center DAAC is hosted by the Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, and includes the DAAC, the NSIDC itself, and the World Data Center (WDC) for Glaciology. This DAAC, which manages data related to snow and ice, climate, and the cryosphere, was created by NASA in 1991, although its roots go back to 1957 when the World Data Center for Glaciology was established at the American Geographical Society in New York.

All three NSIDC centers serve the cryospheric and polar science communities, and data are available on snow cover, freshwater ice, sea ice, glaciers, ice sheets, and ground ice (Box 2-4). NSIDC provides access to EOS satellite data, ancillary in situ measurements, and necessary baseline data, model results, and relevant algorithms relating to cryospheric and polar processes. Although the operations and staff are commingled, the

BOX 2-3
ALASKA SAR FACILITY DAAC HOLDINGS

European Remote-Sensing Satellites (ERS-1 and -2): Complex Synthetic Aperture Radar (SAR) data (10-m resolution), full-resolution SAR images (30-m resolution), and low-resolution SAR images (240-m resolution) from 3,000-km-radius circles centered over Fairbanks, Alaska, and McMurdo Station, Antarctica. Data are available beginning August 1991 from the Alaska mask and October 1995 from the McMurdo mask.

Japanese Earth Remote-Sensing Satellite: Complex SAR data (10-m resolution), full-resolution SAR images (30-m resolution), and low-resolution SAR images (240-m resolution) from a 2,600-km-radius circle centered over Fairbanks, Alaska, and other limited areas. Data are available from May 1992 to October 1998.

RADARSAT-1: Complex SAR data (10-m resolution), standard beams; full-resolution SAR images (25-m resolution); low-resolutions SAR images (150-m resolution); full-, medium-, and low-resolution (50, 100, and 400 m, respectively) ScanSAR wide (500-km-swath width); and full-, medium-, and low-resolution (50, 100, and 400 m, respectively) ScanSAR narrow (300-km-swath width) data from 3,000-km-radius circles centered over Fairbanks, Alaska, and McMurdo Station, Antarctica. Significant coverage outside these masks is also available. Data are available from February 1996 to present.

RADARSAT-1: Antarctic Mapping Mission-1 (25-m resolution) RAMP Data (October 1997)

RADARSAT-1: Modified Antarctic Mapping Mission-2 (25-m resolution) RAMP Data (October to December 2000)

RAMP Antarctic mosaic and individual SAR images that comprise the mosaic, obtained September through October 1997.

Source: NASA, 1998.

DAAC holdings are distinct from the other two centers. Current DAAC holdings include passive microwave and AVHRR products, altimetry and elevation data, and remotely sensed and in situ polar atmospheric science data.

All other NASA DAACs hold global data sets that are directly relevant to polar studies, but NASA and polar researchers do not think of them in this light. Two examples are particularly notable because the need for them is frequently mentioned in both the science-driving ques-

BOX 2-4
NASA-FUNDED DATA SETS AT THE NATIONAL SNOW AND ICE DATA CENTER

The National Snow and Ice Data Center (NSIDC) maintains a large number of relevant polar geophysical data sets, among its other holdings. A list of many of the most significant appears below, and more information can be obtained at <http://nsidc.org/NSIDC/GUIDE/index.html>. Information can also be obtained from NSIDC User Services, Campus Box 449, University of Colorado, Boulder, CO 80309-0449 USA, 303-492-6199, fax: 303-492-2468, or email: nsidc@kryos.colorado.edu. See Appendix A for a list of acronym descriptions.

BRIGHTNESS TEMPERATURE DATA SETS

DMSP SSM/I Pathfinder Daily EASE-Grid Brightness Temperatures
DMSP SSM/I Daily Polar Gridded Brightness Temperatures
Near Real-Time DMSP SSM/I Daily Polar Gridded Brightness Temperatures
AVHRR Leads-ARI Polar Gridded Brightness Temperatures
Nimbus-5 ESMR Polar Gridded Brightness Temperatures, Revision 1
Nimbus-7 SMMR Antenna Temperatures
Nimbus-7 SMMR Pathfinder Brightness Temperatures
NOAA/NASA SSM/I Pathfinder Antenna Temperatures
NOAA/NASA SSM/I Pathfinder Level 2 and Level 3 Land Surface Products
DMSP Special Sensor Microwave/Imager (SSM/I) F8 and F10 Wentz Antenna Temperatures

SEA ICE DATA SETS

Nimbus-7 SMMR Polar Radiances and Arctic and Antarctic Sea Ice Concentrations
DMSP SSM/I Daily and Monthly Sea Ice Concentration Grids for the Polar Regions
Near Real-Time DMSP SSM/I Daily Polar Sea Ice Concentrations
Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I Passive Microwave Data
DMSP-F8 SSM/I Pathfinder Global Level 2 Sea Ice Concentrations
Navy/NOAA National Ice Center Weekly Sea Ice Concentration and Extent, Arctic and Antarctic
Arctic Ocean Drift Tracks from Ships, Buoys, and Manned Research Stations
IABP Drifting Buoy Gridded Pressure, Temperature, Position, and Interpolated Ice Velocity
Nimbus-5 ESMR Polar Gridded Sea Ice Concentrations

SNOW COVER AND PRECIPITATION DATA SETS

Historical Soviet Daily Snow Depth Version 2 (HSDSD)
Nimbus-7 SMMR Derived Global Snow Cover and Snow Depth 1978-1987
Former Soviet Union Monthly Precipitation Archive, 1891-1993

COMBINED SEA ICE AND SNOW COVER DATA SETS

Northern Hemisphere EASE-Grid Weekly Snow Cover and Sea Ice Extent
Near Real-Time SSM/I EASE-Grid Daily Global Ice Concentration and Snow Extent

ICE SHEET AND ELEVATION DATA SETS

Digital SAR Mosaic and Elevation Map of the Greenland Ice Sheet
SEASAT and GEOSAT Altimetry Data for the Antarctic and Greenland Ice Sheets
GEOSAT Radar Altimeter DEM Atlas of Antarctica North of 72.1 Degrees South
Antarctic Ice Velocity Data

POLAR ATMOSPHERE DATA SETS

Arctic Water Vapor Characteristics from Rawinsondes
Comprehensive Ocean-Atmosphere Data Set LMRF Arctic Sub-set
Coordinated Eastern Arctic Experiment (CEAREX), Volume 1
Daily Arctic Ocean Rawinsonde Data from Soviet Drifting Ice Stations
Historical Arctic Rawinsonde Archive (HARA)
NCEP/NCAR Arctic Marine Rawinsonde Archive
TOVS Pathfinder Path-P Daily Arctic Gridded Atmospheric Parameters

OTHER DATA SETS

Polar Pathfinder Sampler: Combined AVHRR, SMMR-SSM/I, and TOVS Time Series and Full-Resolution Samples
AVHRR Polar 1 km Level 1b Data Set
Global Annual Freezing and Thawing Indices
State of the Cryosphere

EXPECTED DATA SETS[a]

Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I
ERS-1 Altimeter Digital Terrain Ice Model of Antarctica
ERS-1 and GEOSAT Altimetry Data for the Antarctic and Greenland Ice Sheets
Antarctic Ice Sheet Digital Elevation Model
RAMP (RADARSAT Antarctic Mapping Project) Digital Elevation Model
RADARSAT Antarctic Mapping Project (RAMP)
Canadian Monthly Precipitation
AVHRR Polar Pathfinder 1.25 KM Data Set
AVHRR Polar Pathfinder 5 KM Data Set
MODIS Terra Snow Cover Products
MODIS Terra Sea Ice Extent Products

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[a]Some of these data sets may be available by the time this report is published. We supply this list only to illustrate the types of products expected within a reasonable timeframe.

tions and in the survey of polar researchers. The first example is surface radiation, which is controlled by the properties of the polar atmosphere, particularly its clouds. The most extensive global data set that contains polar cloud information is produced by the International Satellite Cloud Climatology Project (ISCCP), which is archived at the NASA Langley DAAC. Two other NASA projects are now producing systematic and global surface radiative flux data sets based on this project and other data products, which are being archived at NASA Langley. Many satellite sensors are sensitive to surface temperature and albedo, including the sensors used to determine cloud properties. The ISCCP data set also contains global surface temperature and visible reflectance information; however, insufficient attention has been paid to examining the quality of these and other satellite determinations of surface temperature and albedo in the polar regions. As a second example, we note that land vegetation properties have been characterized by a number of sensors that could also be studied in the polar regions. Such data products and the satellite data sets from which they are produced are archived at NASA Goddard DAAC and the EROS DAAC. The NASA terrestrial biosphere program supports the analysis of many of these satellite data sets, but they need to be more thoroughly evaluated for polar conditions. There is also a need for improvement in how satellite remote sensing is used for biological oceanography (Box 2-5).

OTHER AGENCY DATA SETS

NASA is not the sole provider of data sets related to polar regions. NOAA, the Department of Defense, and the National Science Foundation also provide related information, and thus must be considered when judging NASA's strategy for providing such data, particularly in terms of identifying gaps and redundancies in the nation's overall capabilities.

The National Science Foundation's Arctic System Science Program,[2] which consists of the following sub-programs, is especially relevant:

- Land-Atmosphere-Ice Interactions (LAII)[3]
- Ocean-Atmosphere-Ice Interactions (OAII)[4]
- Synthesis, Integration, and Modeling Studies, and Paleoenvironments of the Arctic System, (which combine the Paleoclimates of Arctic Lakes and Estuaries [PALE],[5] the Greenland Ice Sheet Project 2

[2]http://arcss.colorado.edu/projects/
[3]http://www.laii.uaf.edu/
[4]http://arcss-oaii.hpl.umces.edu/
[5]http://www.ngdc.noaa.gov/paleo/pale/index.html

BOX 2-5
SATELLITE REMOTE SENSING FOR BIOLOGICAL OCEANOGRAPHIC INVESTIGATIONS

Because primary production depends mostly on the availability of light and nutrients and photosynthetically derived material supports the entire marine food web, biological oceanographers need to know as much as possible about factors that influence key environmental variables. For example, clouds, snow cover, and sea ice have a large impact on albedo and the transmission of light into the ocean. Nutrient fluxes depend on the degree of stratification and mixing so winds, ice melt and movement, currents, fronts, etc. are all of interest.

Satellites offer a way to monitor many forms of biological activity in the vast and inhospitable polar oceans. They provide data about photosynthetically available radiation, phytoplankton chlorophyll, clouds, sea ice, sea surface temperature, surface albedo, winds and data telemetry capabilities for instrumentation packages. However, the coverage and resolution for various sensors and products are very different and software to manipulate, replot, and analyze these disparate data sets are not readily available. Improved resolution (~100 m) coverage (several overpasses per day or an innovative higher-latitude quasi-geostationary approach), and inexpensive software/hardware to analyze imagery within standard coordinate systems would provide a better understanding of biological variability over time, from hours to interannual scales. New and improved algorithms to understand phytoplankton biomass, primary production, and colored dissolved organic material are also needed.

When using remote sensing to study biological oceanography in polar regions, direct satellite observation can be constrained because clouds are a ubiquitous problem. In addition, sea ice—whether snow-covered or not—is a bright target that saturates highly sensitive marine sensors.

Based on the dominant primary producers, marine ecosystems in polar regions can be characterized into two types: those closely associated with sea ice and seasonal, open water communities. The transition area between ice and open water is the marginal ice zone (MIZ), which advances and retreats seasonally. Open water areas rely on phytoplankton production, whereas ice-associated foodwebs are supported by ice algae attached to sea ice or by adjacent phytoplankton blooms in the MIZ. The MIZ is a well-known locus for high primary production, but the proximity to ice can limit useful imagery and distort retrievals. There is a seasonal progression between these two types of ecosystems in regions covered by annual ice versus those under perennial pack ice. By virtue of their increased mobility, larger organisms such as birds and mammals can exploit both ecosystems. Many of these larger organisms move to leads and ice edges to exploit elevated prey concentrations and breathing access. Satellite tracking transmissions of “tagged” marine mammals is common in open water but is challenging beneath heavy ice cover.

Biologists have a critical need to assess environmental conditions and food web structure to better understand interactions between physical, chemical, and biological processes. Open waters are directly accessible to visible sensors to estimate the biomass of primary producers, but the dynamics of under-ice communities must be modeled with surface inputs. Knowledge of photosynthetically available radiation, clouds, snow and ice cover are necessary to predict light transmission accurately.

SOURCE: G. Cota, Research Professor, Dalhousie University, private communication, 2000.

[GISP 2],[6] and the Human Dimensions of the Arctic System Science Program [HARC][7]).

Similarly, NOAA produces significant data of relevance to high latitudes and the ESE questions. For example, the science-driving questions and responses to this committee's survey both highlight the need for measurements of polar atmospheric properties (temperature, humidity, winds), even though these data are routinely produced by NOAA to support global weather forecasting activity. Moreover, NOAA also produces global analyses that integrate satellite and conventional observations of these quantities into global data products, which can also be used as a source of this information. NOAA supports this activity by producing sea surface temperature (SST) and vegetation index data from the same sensors. Note that the polar Pathfinders have produced special versions of some of these data products for the Arctic; a similar analysis should be conducted for the Antarctic.

A number of NASA principal investigators (PIs) distribute data sets from Web sites specific to their projects. Examples include meteorological data, data from aircraft and surface measurements as part of field campaigns, and other data sets that may be the subject of active research or processing efforts, and so continue to be updated. There are many reasons why university and PI-based Web sites are not suitable for long-term storage and distribution; it is, therefore, important that these data sets be placed in permanent archives. The committee believes that the DAACs should be the permanent archives for satellite-derived data sets to which NASA has been the dominant contributor, for example, the 22-year record of sea ice concentrations from passive microwave sensors.

INTERNATIONAL DATA SETS

To appreciate NASA's contribution to satellite data sets, it is necessary to consider the international context because there are a number of relevant satellite missions by other nations, as well as various projects with significant international components. For instance, valuable international satellite projects include the joint French/German/Russian mission called ScaRab, which measured the top-of-atmosphere radiation budget (like the Earth Radiation Budget Experiment) and its products cover

[6]http://arcss.colorado.edu/Projects/gisp2.html and http://arcss.colorado.edu/Gispgrip/index.html
[7]http://arcss.colorado.edu/Projects/harc.html

the period March 1994 through February 1995. (For further information, contact <scarab@cst.cnes.fr>). Another international satellite is the Japanese experimental satellite ADEOS-I, which operated for eight months between November 1996 and June 1997 and which will have a follow-on mission in 2001. The payload is expected to include a number of important instruments, including an Ocean Color and Temperature Scanner, an Advanced Visible and Near-Infrared Radiometer, a NASA Scatterometer to measure ocean surface winds (for information see <http://winds.jpl.nasa.gov/missions/nscat/nscatindex.html>), and a Total Ozone Mapping Spectrometer <http://jwocky.gsfc.nasa.gov/adeos/adeos.html>. Another international satellite project of importance is the European Earth Remote Sensing (ERS) satellite mission. ERS-1 and -2 are research satellites that carry a combined wind scatterometer (also useful for land and ice surface characterization) and SAR, a radar altimeter, an infrared and microwave atmospheric sounder; an ozone radiometer (ERS-2 only); an imager (the Along-Track Scanning Radiometer is like AVHRR but with two look angles). However, researchers have noted many difficulties in obtaining data from these satellites, especially ERS-1.

A good example of a U.S.-led activity with important international components is the project Surface Heat Budget of the Arctic Ocean (SHEBA). SHEBA's field program included an ice camp experiment investigating sea ice and upper ocean and atmosphere interactions for one annual cycle in the Beaufort Sea as part of an investigation of the role of Arctic climate in global change (see <http://sheba.apl.washington.edu>). The primary goals are: To determine the ocean-ice-atmosphere processes that control the surface albedo and cloud-radiation feedback mechanisms over Arctic pack ice, to use this information to improve models of Arctic ocean-atmosphere-ice interactive processes; and to develop and implement models that improve the simulation of the present Arctic climate, including its variability, using coupled global climate models. SHEBA is scheduled to run from 1995 until 2002. The primary sponsor is the National Science Foundation (Office of Polar Programs, Division of Ocean Sciences, and Division of Atmospheric Sciences), with significant direct funding provided by the Office of Naval Research (High Latitude Dynamics Program). Additional support has been provided by SHEBA partners, including: Japan Marine Science and Technology Center (JAMSTEC), Department of Energy (Atmospheric Radiation Measurement Program - ARM), National Aeronautics and Space Administration (First ISCCP Regional Experiment III Arctic Cloud Experiment - FIRE ACE); RADARSAT Geophysical Processing System - RGPS, Alaska SAR Facility (ASF), the Department of Fisheries and Oceans Canada (Canadian Coast Guard), and the Scientific Ice Expeditions (SCICEX - U.S. Navy and National Science Foundation).

Finally, an excellent example of a broad international activity with many components is the World Climate Research Programme (WCRP). Some of these elements are described below in some detail to illustrate the complexity of activities and thus the need for careful planning to ensure that duplication is minimized and opportunities pursued.

World Climate Research Programme

The World Climate Research Programme (WCRP) was established in 1980 under the joint sponsorship of the International Council for Science, the World Meteorological Organization, and since 1993 the Intergovernmental Oceanographic Commission of UNESCO. The program seeks to develop a fundamental scientific understanding of the physical climate system and climate processes needed to determine the extent to which climate can be predicted and the extent of human influence on climate. The program encompasses studies of the global atmosphere, oceans, sea and land ice, and the land surface that together constitute the Earth's physical climate system. Studies are directed to provide scientifically founded quantitative answers to the questions being raised on climate and the range of natural climate variability, as well as to establish the basis for predictions of global and regional climatic variations and of changes in the frequency and severity of extreme events. The cryospheric component of the WCRP is known as Climate and the Cryosphere (CliC), which is an outgrowth of WCRP's Arctic Climate System Study (see below).

Global Energy and Water Cycle Experiment

The WCRP initiated the Global Energy and Water Cycle Experiment (GEWEX) in 1988 to observe and model the hydrologic cycle and energy fluxes in the atmosphere, at the land surface and in the upper oceans. An integrated program of research, observations, and science activities, GEWEX will ultimately allow the prediction of global and regional climate change. GEWEX has contributed significant data and data sets to scientists addressing ESE questions and the polar science-driving questions of interest in this study. For information on how to obtain these data sets, see <http://www.gewex.com>.

International Satellite Cloud Climatology Project

The International Satellite Cloud Climatology Project was established in 1982 as part of the WCRP to collect and analyze satellite radiance measurements to infer the global distribution of clouds, their properties, and their diurnal, seasonal, and interannual variations (e.g., cloud cover, optical thickness, top temperature/pressure). Data collection began in July 1983 and is planned to continue through June 2005. The resulting data sets and analysis products are being used to improve understanding and modeling of the role of clouds in climate, with the focus on understanding the effects of clouds on the radiation balance.

Three products contain information with different space-time resolutions: 30 km and 3 hr, 280 km and 3 hr, and 280 km and monthly. Data processing is ongoing. Note that clouds are particularly difficult to detect and measure over the colder and brighter surfaces occurring in the polar regions; however, a revision of the processing specifically focused on these problems has somewhat reduced the errors. For more information, see <http://isccp.giss.nasa.gov>.

Surface Radiation Budget/Baseline Surface Radiation Network

The Surface Radiation Budget (SRB) produces a global data set providing upward, downward, shortwave, and longwave radiative fluxes at the surface, calculated from satellite determinations of atmosphere, cloud, and surface properties (mainly from the ISCCP). Currently, a monthly average shortwave product with a 280-km resolution is available covering the period July 1983 through June 1991. Another prototype product containing monthly averages of all flux components is also available covering the same period. The complete product with 3-hr and 110-km resolution should begin to appear in 2001. The Baseline Surface Radiation Network (BSRN) provides validation data sets by direct high-quality measurements of all flux components, with ancillary atmospheric and surface property information. Note that calculation of radiative fluxes under the severe conditions in polar regions is difficult. The main problems are accurate determination of cloud optical thicknesses, which affect shortwave fluxes the most, and proper determination of lower atmosphere temperature inversions and surface temperature, which affect longwave fluxes the most. For more information, see <http://agni.larc.nasa.gov/SRB_homepage.html and http://bsrn.ethz.ch>.

Global Precipitation Climatology Project

A global data set providing monthly average precipitation amounts covering the period from January 1988 through December 1996 is a merged analysis of surface gauge measurements and satellite microwave and infrared radiance measurements. A new product with 110-km and daily resolution is planned. Note that neither satellite analysis actually produces reliable results at high latitudes when precipitation is in the solid phase, so that all information available in this data set at these latitudes is from surface gauges, which have well-known difficulties with snow. For more information, see <http://orbit-net.nesdis.noaa.gov/arad/gpcp>.

International Satellite Land Surface Climatology Project

The International Satellite Land Surface Climatology Project (ISLSCP) has produced a global collection (Initiative I) of surface and atmospheric data suitable for forcing land hydrology models. The collection is a mix of satellite analyses, surface measurements, survey results (mainly for specifying surface physical properties, including topography and vegetation) and weather model output (mainly for meteorological information), all placed in a common 1-degree map grid. Time-dependent data cover the period from January 1987 through December 1988. A new version (Initiative II) is to be produced in 2001 covering a 10-year period with a 0.5-degree grid. The quality and completeness of the data for polar conditions is not known. See <http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/ISLSCP/islscp_i1.html>.

Global Water Vapor Project

The Global Water Vapor Project is a new activity proposed as part of the GEWEX. Water vapor plays a vital role in shaping weather and climate, and this project is intended to improve understanding of fundamental aspects of the atmospheric system, including radiative heating, precipitation, cloud formation, and horizontal and vertical moisture transport and convergence. This project seeks to improve the accuracy and availability of global water vapor data through the development of a global water vapor data set, establish reference stations, and conduct intercomparison of studies among the existing water vapor data sets. Although in its early stages, this project has produced a prototype global water vapor data set (called NVAP) that reports daily and monthly profiles of tropospheric water vapor covering the period January 1988 through December 1996 with 110-km resolution. The product is produced by merging rawinsonde results, where available, with satellite sounder products (NOAA operational), the latter modified to be consistent with a microwave (SSM/I) analysis over oceans.

Arctic Climate System Study

Another WCRP-associated program is the Arctic Climate System Study (ACSYS) <http://www.npolar.no/oelke/adis.html>. The ACSYS project is to ascertain the role of the Arctic in global climate by answering questions such as: What are the global consequences of natural or human-invoked change in the Arctic climate system? Is the Arctic climate system as sensitive to increased greenhouse gases as climate models suggest?

This study is now evolving into an expanded program called the Climate and Cryosphere Initiative, which is intended to investigate the role of the entire cryosphere for global climate and as an early indicator of change. It will integrate studies of the impact and response of the cryosphere in the global climate system and the use of cryospheric change indicators for climate change detection. All elements of the seasonal and perennial cryosphere are included, as are their interactions with the atmosphere and ocean on a global scale, and between the atmosphere, snow/ice, and land; between land ice and sea level; and between sea ice, oceans, and the atmosphere. The Arctic Climate System Study (ACSYS) produces the RADARSAT Eulerian ice motion data set for Surface Heat Budget of the Arctic project (SHEBA).

World Ocean Circulation Experiment

The World Ocean Circulation Experiment (WOCE) <http://www.soc.soton.ac.uk/OTHERS/woceipo/data.html> is a fundamental element of the WCRP scientific strategy to understand and predict changes in the world ocean circulation, volume, and heat storage that might result from changes in atmospheric climate and net radiation. It uses a combination of in situ oceanographic measurements, observations from space, and global ocean modelling, as well as the Topex-Poseidon Sea Surface (height) Anomaly data set (see <http://podac.jpl.nasa.gov/toppos>).

Oceans Pathfinder Data Sets

The NOAA/NASA AVHRR Oceans Pathfinder data sets < http://podaac.jpl.nasa.gov/sst> are derived from the 5-channel AVHRR onboard the NOAA-7, -9, -11, and -14 polar-orbiting satellites. Daily, 8-day, and monthly averaged data for both the ascending pass (daytime) and descending pass (nighttime) are available on equal-angle grids of 4096 pixels/360 degrees (nominally referred to as the 9 km resolution), 2048 pixels/360 degrees (nominally referred to as the 18 km resolution), and 720 pixels/360 degrees (nominally referred to as the 54 km resolution or 0.5-degree resolution). Data in different spatial and temporal resolutions are available from 1985 to 1999 (November 20). Global files are available through the PO.DAAC Internet ftp or order form and desired regions are available through the AVHRR Pathfinder sub-setting system.

Baltic Sea Experiment

The Baltic Sea Experiment (BALTEX) is a hydrology-meteorology-oceanography experiment covering the Baltic Sea and its drainage basin. This experiment, which is a continental-scale investigation associated with GEWEX, is designed to explore and model the various mechanisms determining the space and time variability of energy and water budgets of the Baltic Sea area and its interactions with surrounding regions; to relate these mechanisms to the large-scale circulation systems in the atmosphere and oceans over the globe; and to develop transportable methodologies in order to contribute to basic needs of climate, climate impact, and environmental research in other regions of the world.

BALTEX comprises both meteorological and hydrological research and it has a strong oceanographic research component, at present a unique feature among the GEWEX regional projects. Designed to assess the total heat and water flux divergence of the Baltic Sea area, program includes numerical modeling, data assimilation, experimental and numerical process studies, re-analysis of existing data sets, and application of remote sensing (see <http://w3.gkss.de/baltex/baltex_home.html>).

Mackenzie GEWEX Study

The Mackenzie GEWEX (MAGS) Study is a hydrology-meteorology investigation of the water and energy cycles of a northern river system, the Mackenzie River drainage basin in Canada. This study, which is also associated with GEWEX, includes a series of large-scale hydrological and related atmospheric and land-atmosphere studies. Within this region, there are many important cold-region phenomena, such as snow and ice processes, permafrost, and arctic clouds and radiation interactions that are essential components of any global climate system model. The Mackenzie basin and an associated similar initiative in the Mississippi River basin taken together provide a true continental area in which to test and validate macro-scale coupled hydrological and other models (see <http://www1.tor.ec.gc.ca/GEWEX/MAGS.html>).

Future International Satellite Missions

There are a number of potentially significant international satellite missions planned for the near-future that should provide data important to polar scientists. For example, ADEOS-II is a Japanese follow-on mission to ADEOS-I. Its instrument payload will include the Advanced Microwave Scanning Radiometer, Global Imager, Improved Limb Atmospheric

Spectrometer (ILAS), Seawinds (scatterometer), and Polarization and Directionality of Earth's Reflectances (POLDER).

Another planned mission is Envisat, a European research satellite scheduled for launch in 2001; its instrument payload will include a SAR, an ozone spectrometer, an infrared sounder, a multiwavelength imaging radiometer, a microwave imager, an infrared spectrometer, and a lightning sensor.

A European technology-experiment satellite, called Project for On-Board Autonomy (PROBA), carries a high-resolution imaging spectrometer (visible and near-infrared wavelengths).

The Aqua satellite, to be launched in 2001, will provide information on several key variables discussed in this report. For example, Aqua will carry an Advanced Microwave Sounding Unit (AMSU) for atmospheric temperature profiles as well as cloud and aerosol properties; an Advanced Microwave Scanning Radiometer for EOS (AMSR-E) for precipitation, columnar water vapor and cloud water, aerosol properties, sea surface wind speed, snow depth on sea ice, and snow water equivalent; a Moderate-Resolution Imaging Spectroradiometer (MODIS) for atmospheric profiles, land surface characteristics, ocean primary productivity, and snow and ice albedo; and a Clouds and the Earth Radiant Energy System (CERES) for radiative fluxes and cloud-radiative interactions.

Although only in the early stages of its product assessment and utilization, the recently (December 1999) launched Terra satellite carries MODIS and CERES instruments as well as an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), a Multi-angle Imaging Spectral Radiometer (MISR), and an instrument for Measurements of Pollution in the Troposphere (MOPITT). Applications of the Terra are directed toward aerosols characterization, changes in global cloudiness, changes in the global land surface, and the roles of the ocean in global change.

3

Science-Driving Questions: The Polar Regions in the Context of NASA's Earth Science Enterprise

Five key science questions drive NASA's Earth Science Enterprise (ESE):

1. How is the global Earth system changing?
2. What are the primary forcings of the Earth system?
3. How does the Earth system respond to natural and human-induced changes?
4. What are the consequences of change in the Earth system for human civilization?
5. How well can we predict the changes in the Earth system that will occur in the future?

The committee organized its discussion around these five questions that define the scope of the ESE program, but adapted them to focus on the cryosphere. In essence, the committee wishes to determine whether NASA-supported data sets contribute the information needed to address the cryospheric elements of the ESE. Specific, measurable biogeophysical phenomena are the focus; for example, to understand climate variability over land, researchers must be able to characterize individual elements of the Arctic water cycle such as seasonal variations in permafrost, soil moisture, evapotranspiration, precipitation minus evaporation, surface temperature, runoff, and snow cover.

Each of the five ESE science questions is addressed in a section below. In each case, the committee outlines what it believes to be the primary and related research questions that need to be addressed to support the ESE, and does so with sufficient specificity to allow an assessment of the supporting measurements.

The scope of the science questions considered here is affected by how "cryosphere" is defined. The committee elected to begin with the definition used by the WCRP's Climate and Cryosphere Program, which defines the cryosphere as that portion of the Earth containing sea ice, snow cover, permafrost, ice sheets, and glaciers (WCRP, 2000). The committee also included critical processes that influence surface energy, freshwater fluxes in the cryosphere, and carbon and trace gas exchanges at the atmospheric interface.

The committee wishes to emphasize that we did not create the basic science questions, but took the global science questions presented in the NASA ESE Science Plan and focused them on polar regions. The following science planning documents relevant to the polar regions were also used:

- Science Plan for the WCRP Arctic Climate System Study (WCRP, 1994)
- Science Plan for the WCRP Climate and the Cryosphere Programme (WCRP, 2000)
- Science Plan for the NSF ARCSS Human Dimensions of the Arctic System (ARCUS, 1997)

The IPCC Working Group I and II contributions to the Second Assessment Report were also consulted (Houghton et al., 1996). The committee found that several cryosphere issues that we judged relevant to this study were not thoroughly addressed by the three science plans or IPCC reports. For these issues, we have formulated a few new subsidiary science questions, but these are still organized within the basic ESE framework. For each ESE question, a set of polar-specific questions, a rationale for the importance of studying the relevant phenomenon, and a short list of required measurements are given.

1 Issue No. 1: How are Polar Climate and the Biosphere System Changing?

1.1 *Are changes occurring in the polar troposphere?*

1.1a Is an acceleration or deceleration of the polar hydrologic cycle apparent in changes of polar precipitation rates in either hemisphere?

The spatial and temporal patterns of rainfall and snowfall define the fundamental character of water availability over the poles. Precipitation is the first step in a chain of events that defines the distribution and dynamics of ice sheet, glacier, and sea ice mass; soil moisture; evapotranspiration; runoff and river discharge; vegetation distribution; primary production and trace gas production. Models of contemporary climate change show increases in high latitude precipitation, shifts in the predominance of snow and rain, and possible increases in the occurrence of severe events. A contemporary and historical assessment of the spatial and temporal distribution of precipitation provides a critical benchmark for future change.

One important aspect of the debate on climate change centers around the presumed intensification of the global water cycle through which excess energy trapped as a consequence of the greenhouse effect is transformed into an increase in the poleward delivery of water vapor and heat by atmospheric transport. Recent observational evidence shows an increase of storm tracks across the polar front and changes in precipitation patterns associated with the North Atlantic Oscillation (NAO). The impact of recent climate variability and ultimately greenhouse-induced circulation changes needs to be better monitored and understood.

Measurement Requirements: Rainfall and snowfall over land, ocean, continental ice, and sea ice; profiles of atmospheric humidity, temperature, and winds resolved at synoptic time and space scale.

1.1b Is the radiation balance of the polar regions changing?

The primary radiative energy exchange in the polar regions is the loss of energy to space, mostly from the atmosphere. This loss is regulated by clouds and water vapor: loss rate depends on the atmospheric temperature and the vertical distribution of clouds. In a changing climate, atmospheric advection of warmer and moister air into the polar regions will probably alter the vertical distribution of clouds. Tracks and frequency of storms might change. The precise interaction of the changing atmospheric and cloud properties will determine the consequent changes of the polar radiation balance. The secondary radiative exchange of energy is between the relatively warmer atmosphere and the colder sea-ice-covered ocean; this exchange regulates the heat content of the polar oceans. Clouds regulate the solar heating of the surface, usually melting ice in summertime, and the heating by terrestrial radiation, primarily in wintertime. These interactions among the atmosphere, clouds, and sea ice is central to determining the sensitivity of the polar climate.

Measurement Requirements: Atmospheric temperature and humidity profiles, aerosol abundances and properties, surface albedo and temperature, cloud horizontal and vertical extent and water content (also phase and particle sizes), surface radiation fluxes, and top of atmosphere radiation fluxes.

1.2 *Are changes occurring in the polar ice sheets?*

1.2a Is the surface elevation of the ice sheets changing?

An important concern regarding the impact of climate change across the high latitudes is the potential release of the huge quantities of water stored in the cryosphere. Measurements of changes in ice sheet elevation are not of themselves diagnostic of the processes that are producing change, but the measurements are nearly directly translatable into a component of present sea level rise. Recent NASA PARCA results showing a decrease in the overall mass of the Greenland ice sheet over the last five years is the first reliable indication of the impact of the ice sheets on global sea level rise, there is a clear need to continue this time series and provide similar information for the Antarctic.

Measurement Requirements: Ice sheet elevation time series.

1.2b In coastal Greenland, are present-day changes in ice sheet mass due to changes in discharge rates, changes in accumulation, and/or changes in melt rates? How do the changes in ice sheet mass compare to past changes?

Ice sheet mass discharge varies over both space (often locally) and time, and accumulation and melt patterns are affected by changes in atmospheric circulation; it is critical to understand these variations in order to provide a predictive understanding of the change. The societal impacts of ice-sheet-generated sea level rise will come from an acceleration of these processes. Melting has been identified as a causative factor in ice mass changes in Greenland and has been suggested as a cause of ice shelf changes in Antarctica as well. Ice melt is dependent on the surface energy balance, and this makes an understanding of surface albedo and radiative forcing particularly important, especially at the ice margins. In order to determine if accelerated melting, reduced accumulation, or ice dynamics are responsible, it will be necessary to collect time series data allowing the determination of the energy available for melting, the amount of runoff, accumulation variability, and changes in ice flow. Ice core measurements of past accumulation variation are required to place modern measurements into a longer-term context.

Measurement Requirements: Time series observations of ice velocity and grounding-line position, ice thickness distributions for outlet glaciers and drainage basins, surface energy balance, albedo, precipitation, and ice-melt runoff.

1.2c In West Antarctica, are the present local imbalances, caused by flow variations in large outlet glaciers and ice streams and possibly by local accumulation variations, consistent with long-term retreat or possible instability?

Rapid ice discharge in large outlet glaciers and ice streams carries much of the mass lost from the large ice sheets. In West Antarctica, intensive study of ice streams discharging into the Ross Ice Shelf has revealed a complex history of variably flow rates caused by basal conditions such as soft, deforming sediments and the presence of water at high pressure. The record shows a substantial retreat of the ice over the last twelve thousand years; however, the size of the region involved in the rapid flow has made detailed understanding of present conditions difficult. Satellite data used by both NASA and NSF funded research are changing our understanding of ice flow patterns continent-wide, revealing new sites of rapid variations in ice flow and ice thickness. These types of observations will indicate the scale of ongoing change and provide the foundation for a predictive understanding of the processes involved.

Measurement Requirements: Time series observations of ice velocity and grounding-line positions, the distribution and velocity of ice streams, ice thickness (topography and mass), surface energy bal-

ances, albedo, precipitation accumulation rates, melting rates (oceanic salinity), and rates (mass) of calving.

1.3 ***Are changes occurring in the polar oceans?***

1.3a Are changes in high-latitude precipitation and surface runoff influencing the Arctic Ocean's salinity, sea ice, and circulation structure?

Simulations of future climate change indicate an increase of high-latitude precipitation and related changes in surface runoff. This will likely have a strong influence on the freshwater budget of the Arctic Ocean as direct input to the sea surface and a delayed input via snow melt from ice and land. Each of these inputs has a distinctive geographic and seasonal signature that may change in response to changes in high-latitude precipitation. The resultant freshening might influence the strength and location of deep water formation in the North Atlantic Ocean.

Measurement Requirements: *Precipitation, river runoff, snow cover, glacial runoff, ocean circulation, temperature, and salinity.*

1.3b Are changes occurring in the thickness, coverage, and circulation of sea ice?

The spatial and temporal distribution of sea ice is a fundamental property of the high-latitude oceans. Concentration and thickness of sea ice reflect the state of ocean circulation and heat fluxes. These variables may also provide an important feedback to the larger Earth system by regulating planetary heat balance and the formation of deep ocean water, producing global consequences. It is important to monitor and understand changes in the character of sea ice, since it serves as a sensitive indicator of climate change while being an important physical control on important oceanic processes.

Together with its concentration and thickness, the dynamic properties of sea ice are an important characteristic of the Arctic Ocean. Improving our knowledge of contemporary sea ice flow fields will improve our understanding of how climate variations (e.g., response to NAO) and progressive climate change will influence ocean circulation. Monitoring sea ice concentrations and thickness, together with flow fields out of the Arctic Ocean will provide important estimates of ice mass—and hence freshwater—transport from the Arctic Ocean to the Atlantic Ocean. There are similar and equally important issues to be addressed in the Southern Ocean.

Measurement Requirements: Sea ice thickness, concentration, and motion.

1.3c Are significant changes occurring in ocean productivity?

The physics and nutrient chemistry of the high latitude oceans define patterns of primary productivity and open-water CO_2 exchange. Ice edge productivity is a primary source of productivity in the polar oceans that is particularly sensitive to warming. Projected reductions in sea ice concentration, enhanced light availability, and increased water temperatures can increase algal productivity. At the same time a possible reduction in upwelling associated with a weakening of the ocean conveyor belt could reduce nutrient inputs from deep ocean and thereby limit production and uptake of carbon. Linkages from the Arctic land mass to the Arctic Ocean are also important because Arctic coastal ecosystems are highly dependent on the sediments and nutrients delivered from land masses. These issues are important not only to Earth system analysis but to society as well since the high-latitude oceans provide important fisheries resources that depend directly on primary productivity.

Measurement Requirements: Ocean color, sea ice concentration and thickness, river discharge, and chemical fluxes.

1.4 *Are changes occurring in the polar terrestrial regime?*

1.4a Is the distribution of permafrost and Arctic region freeze and thaw changing?

The seasonal freezing and thawing of the Arctic land surface is a key trigger for virtually all the major land-based hydrological, biophysical, and biogeochemical processes. Seasonal snow pack represents both potential recharge to soils and groundwater, and delayed runoff, and, at larger scales, discharge to the Arctic Ocean. The phenology of higher plants is keyed to active layer dynamics. Plant growth, evapotranspiration, and exchange of carbon commence during the thaw period. Trace gases are also liberated by microbial processes activated by temperatures above freezing. The distribution of permafrost has recently been digitized by piecing together former paper map products having contrasting spatial resolutions and classification schemes, and without quantitative information on active layer dynamics. Modeling experiments under greenhouse warming show an important redistribution of permafrost, suggesting that a major improvement in the state of the art describing permafrost is urgently needed.

Measurement Requirements: Permafrost extent, timing of freeze and thaw, vertical temperature profile, and thermokarst topography.

1.4b Is the hydrology of Arctic terrestrial regions changing?

Drainage basins provide a useful organizing framework for tracking water, energy, and biogeochemical fluxes associated with the terrestrial hydrological cycle. When the Arctic is considered from the standpoint of a contributing drainage area to the Arctic Ocean, it constitutes the most land-dominated of all ocean basins with the greatest impact from freshwater discharge. Some Arctic drainage basins extend well south of 50º N, meaning that it constitutes an enormously complex landscape composed of many non-tundra, non-boreal forested ecosystems, including temperate grass and agricultural lands and deciduous forest. The dynamics of the local water cycle define the quantities and timing of the runoff, that moves water horizontally into sequentially larger channels and ultimately to the Arctic Ocean. Water is delayed or diverted with passage through floodplains and through ice dams on rivers. Seasonal ponding of water and resulting sheet flows are important in low-relief areas in many parts of the Arctic. The timing of ice-out in rivers and lakes also affects terrestrial ecosystems by affecting aquatic biology, biogeochemistry and water fluxes through drainage basins aquatic biology, biogeochemistry, and water fluxes through drainage basins.

Measurement Requirements: Precipitation, temperature, surface radiation parameters (roughness, albedo), winds, humidity, permafrost state, land cover, runoff, and river discharge.

1.4c Are significant changes occurring in the distribution and productivity of high-latitude vegetation?

Changes in high-latitude vegetation may influence climate through effects of vegetation structure and function on surface energy balance and on trace gas concentrations in the atmosphere. High-latitude vegetation may change in response to changes in climate, climate variability, and disturbance regimes. Disturbance is an important agent of change because it can cause abrupt changes in vegetation structure and function. Major disturbance types in high latitudes include insect infestations and fire. It is important to monitor the characteristics of these disturbance regimes for information on the type, the timing, the extent, and the severity of the alteration. In the context of this study, pollution of the terrestrial landscape encompasses atmospheric deposition, which can supply nutrients that are potentially limiting to plant productivity (such as inorganic nitrogen) or chemicals that are stressful to the resident vegetation. Estimation of nitrogen deposition requires a mapping of source terms (e.g., urban and industrial areas) and their variation over time.

Measurement Requirements: Vegetation characteristics (leaf area index, canopy density, albedo, structural composition, vegetation class), disturbance characteristics (type, timing, severity), wetlands extent, and nitrogen deposition.

2 Issue No. 2: Primary Forcings of the Polar Climate System

2.1 *What are the major fluxes of CO_2 and other trace gases from the polar land surfaces and oceans?*

The exchange of carbon and trace gases from polar ecosystems is regulated by a host of complex processes. On land the exchange of these gases is regulated by the distribution of soil wetness and oxygenation state, vegetation characteristics, disturbance characteristics, carbon substrates in soils, pH, and temperature. Productivity is also regulated by the internal cycling of nutrients and by the delivery of exogenous inorganic nitrogen from atmospheric deposition. Hence the distributions of permafrost, upland and wetland ecosystems, and atmospheric circulation patterns are important features of the Arctic system that must be defined before large-scale assessments can be made. Greenhouse warming and the concomitant changes in the physics of the atmosphere are linked to gas exchange. Carbon balances in the oceans are regulated by the physics of the oceans and nutrient supplies from upwelling and river-borne inputs. A presumed weakening of upwelling associated with a warming Earth could reduce nutrient-dependent CO_2 uptake and oceanic carbon sequestration, but could also reduce the capacity of the ocean to outgas CO_2 from rising deepwater. Reduced extent of sea ice could also lengthen the growing season and expose more of the Arctic Ocean to wind-driven circulation. Changes in ice edge productivity determined by the interplay between altered upwelling and stabilization by increased meltwater constitutes an important process requiring further study. The implications for storage of CO_2 by the high-latitude oceans is a critical global change question.

Measurement Requirements: Sea ice concentration and extent, evapotranspiration, soil moisture, surface temperature, permafrost characteristics, vegetation characteristics, disturbance characteristics, wetland extent, CO_2 and CH_4 fluxes, nitrogen deposition, river discharge, and chemistry.

2.2 *What are the spatial and temporal distributions and variability of aerosols in the polar atmosphere?*

Aerosol radiative effects are important primarily in the spring and summer, when they may influence melt onset and cloud phase changes. Changes in the characteristics of aerosols in the polar atmosphere could change how solar energy is distributed in the system. Since the ice-covered surfaces have very large albedos, most aerosols increase solar absorption in the atmosphere at the expense of the (melting) surface, but once melt begins these same aerosols reflect more sunlight than the surface and inhibit surface heating. Moreover, changes in aerosol composition could affect the seasonal change-over of clouds from ice to liquid phase, which may also alter the surface solar heating.

Measurement Requirements: Aerosol concentration, size distribution, vertical distribution, and composition (index of refraction).

3 Issue No. 3: Responses to Forcing and Associated Feedback Involving the Polar Regions

3.1 *How will the atmospheric contribution to the mass balance of the ice sheets (i.e., precipitation and energy fluxes) change with the effects of global warming?*

Determining ice sheet mass balance requires knowledge of both input (i.e., precipitation) and output (i.e., sublimation, ice flow, melt discharge) fluxes. These in turn will be determined by changes in atmospheric circulation and surface energy characteristics. Global climate change is predicted to show large relative changes in these characteristics across the polar regions. Projected increases in winter precipitation in high latitudes may or may not be balanced against increases in evaporation associated with elevated air temperatures, thus making the corresponding changes in ice mass difficult to predict. Whether the ice sheets are responding primarily to recent forcings or to longer-timescale forcings (i.e., are the ice sheets in balance with the recent climate) remains an open question.

Measurement Requirements: Precipitation and accumulation history, surface heat fluxes, surface temperature, inversion strength, snowpack structure, ice sheet elevation, ice sheet discharge, and runoff.

3.2 *How do the polar oceans respond to and affect global ocean circulation?*

3.2a How sensitive are the polar oceans to changes in freshwater inputs and how does the outflow of sea ice and freshwater affect the global thermohaline circulation?

The Arctic Ocean is a pathway through which the relatively fresh waters of the North Pacific flow toward the saltier North Atlantic. Along the way these waters pick up an additional freshwater component from river runoff and precipitation, and some of this is converted into sea ice. The outflow of these fresh waters into the North Atlantic may strongly affect the formation of North Atlantic deep water which, in part, drives the global oceanic circulation. Evidence suggests that this mechanism undergoes substantial interannual and decadal variability that may have significant effects on worldwide climate. This variability of polar ocean circulation has been observed or modeled in both Arctic and Antarctic regimes. Recent simulations suggest an increasing bias towards warm, wet atmospheric conditions, which could have dramatic but unclear effects on the polar ocean circulation.

Measurement Requirements: Sea ice concentration, thickness, and velocity; precipitation; evaporation; river runoff; sea surface height; and ocean temperature and salinity, and circulation.

3.2b What is the relationship between polar ocean circulation and the large-scale interrannual and decadal modes of atmospheric variability (e.g., El Niño Southern Oscillation, Arctic Oscillation, North Atlantic Oscillation, Antarctic Oscillation)?

At least some of the recent trend toward warmer and wetter atmospheric conditions in the Arctic is associated with the Arctic Oscillation and especially its more regional manifestation, the North Atlantic Oscillation. Fewer trends have been linked to the complementary Antarctic Oscillation, although this has not yet been studied in great detail. Linkages between the Arctic and the El Niño/Southern Oscillation (ENSO) have been suggested but are less clearly established. There is a need to clarify the role of these atmospheric modes in recent Arctic (and possibly Antarctic) changes. In addition, there should be investigations into possible feedback of high-latitude changes to the major modes of atmospheric circulation. This circulation feedback could be key determinants of the atmospheric response to increasing greenhouse gas concentrations.

Measurement Requirements: Surface pressure and temperature, vertical profiles of atmospheric winds, sea ice concentration, ocean temperature, salinity, and circulation.

3.2c How will changes in ice sheets and polynyas affect water mass formation and circulation?

Iceberg calving is a potentially large source of freshwater to the seas surrounding Antarctica, Greenland, and the smaller polar land masses. Climate changes are known to affect the calving rate, and it has been suggested that they may cause decadal-scale salinity anomalies in the polar and sub-polar gyres. Conversely, winter sea ice growth in coastal- and open-water polynyas has been shown to produce quite dense waters that supply a significant volume fraction of certain water mass components. An alteration of climatic conditions could be expected to influence this process.

Measurement Requirements: *Glacier runoff and iceberg calving, sea ice concentration and thickness, sea surface height, and ocean temperature, salinity, and circulation.*

3.3 *How will the albedo-temperature feedback amplify future climate change?*

3.3a How is the albedo-temperature feedback affected by the physical characteristics of melting snow and ice?

Characteristics of melting sea ice are poorly documented in a spatially aggregated sense. The spatial and temporal variability of surface albedo is central to the ice-albedo feedback. While the surface albedo has been mapped for certain portions of the Arctic at certain times, there are no Arctic-wide data sets depicting the means and variability of surface albedo. Melt-pond fraction and summer ice-surface characteristic data sets are needed in order to calibrate and validate model parameterizations. There are no Arctic-wide data sets depicting either the climatology or the variability of melt-pond fraction. Snow depth on sea ice is a key variable in the seasonal transition of surface state. While data sets of mean snow depth have been compiled from Russian ice station measurements (essentially one or two slowly moving points), the spatial and temporal (interannual, interdecadal) variations are not known adequately for model testing.

Measurement Requirements: *Surface albedo, sea ice concentration and thickness, melt-pond fraction, snow depth on sea ice, and surface temperature.*

3.3b How is the albedo-temperature feedback affected by polar clouds and aerosols?

Although the surface albedo in the polar regions is very high, polar clouds can still reduce the amount of surface absorption of sunlight that melts the sea ice. Moreover, the emission of longwave radiation by the atmosphere, acting as the heat sink of the climate system, is significantly altered by the presence of clouds. Both of these modulations are non-linear processes that are sensitive to the correlations between the variations of cloud and the surface and atmosphere properties. Consequently, the net effect of clouds cannot be determined except by detailed observation of the synoptic and seasonal variations of cloud and surface properties.

Measurement Requirements: *Atmospheric temperature and humidity profiles, aerosols, surface temperature and albedo, cloud horizontal and vertical extents and water contents (particle size and phase).*

3.4 *How do seasonal snow and ice cover interact with the modes of interdecadal variability in the Northern Hemisphere and the Southern Hemisphere?*

Dramatic changes have recently been detected in sea ice coverage and thickness. These are, in part, correlated with decadal-scale variability that has been described in the atmospheric circulation as the North Atlantic Oscillation/Arctic Oscillation and Antarctic Oscillation. Thus far it appears that, for the most part, sea ice acts passively in response to these atmospheric changes; however, some feedback in high latitudes is expected. Observations also indicate the presence of long-term trends in sea ice thickness that may not be correlated with these oscillations. Further, some sea ice variability may be more locally forced or, in fact, correlated with tropical ENSO phenomenon. It will take a better understanding of the polar system and its links with the global climate before long-term change in the polar regions can be described and possibly predicted.

Measurement Requirements: *Snow cover and albedo, sea ice concentration and albedo, global surface temperature, precipitation, pressure.*

3.5 *Are changes in sea ice concentration influencing the amount of water vapor in the polar atmosphere?*

An important connection between the ocean surface and overlying atmosphere in the polar regions is defined by the state of sea ice, both in terms of its extent and surface radiation budget. Sea ice can be viewed both as a source of water vapor through sublimation and as regulator of the amount of open Arctic Ocean water exposed to the atmosphere. If changes in sea ice will affect atmospheric humidity, the degree of change will primarily be determined through changes in evaporation (sublimation) and possibly through precipitation associated with a more vigorous hydrologic cycle. Changes in atmospheric humidity may have important impacts on polar cloud cover and the energy balance.

Measurement Requirements: *Surface air temperature, surface evaporative flux (surface air humidity and winds), distribution and transport of water vapor, sea ice concentration, and snow on sea ice.*

3.6 ***How do atmospheric boundary layer processes influence the exchanges of heat and freshwater between the atmosphere and cryosphere?***

A common situation in polar regions is the advection of warm and moist air over a colder surface, usually frozen. This produces unusually stable planetary boundary layers that strongly suppress turbulent transport. However, when leads open in the wintertime sea ice, the underlying surface is warmer than the overlying atmosphere, producing turbulent (convective) heat and moisture transport that may be quite strong locally. Cold air from continents adjacent to the Arctic Ocean can also supply air that is colder than the surface, which can destabilize the planetary boundary layers. This complex switching between extreme situations confounds the determination of heat and freshwater exchanges under polar conditions. The large uncertainty in the heat and freshwater exchanges under polar conditions hinders an understanding of the persistent low-level cloudiness, leading to large uncertainties in the heat budgets of the cryosphere, ocean, and atmosphere.

Measurement Requirements: *Atmospheric temperature and humidity profiles, cloud and vertical layer structure, wind profiles and advective fluxes, surface turbulent fluxes, surface temperature, and salinity.*

3.7 ***What role does the cryosphere play in determining the dependence of the large-scale atmospheric circulation on the global meridional temperature gradient?***

The polar regions are the heat sinks of the climate system, so heat exchange processes occurring there combine with those in the midlatitudes and tropics to determine the large-scale atmospheric circulation and its meridional heat transport. This heat transport is reflected in the equator-to-pole temperature gradient. Most climate models predict a decrease of the equator-to-pole temperature gradient in a warming climate, because of the substantial warming simulated by these models to occur in the Arctic. Specific measurements are needed to ascertain the role of the cryosphere in establishing the meridional temperature gradient. Better understanding of clouds is necessary to determine atmospheric diabatic heating.

Measurement Requirements: *Profiles of atmospheric winds, temperature, humidity, clouds (layer structure and water content), and surface and atmospheric radiative fluxes, and precipitation.*

3.8 ***How will land surface hydrology and energy exchanges be influenced by the climate-induced changes to vegetation structure and distribution across the polar regions?***

Greenhouse warming and the potential intensification of the water cycle may result in enhanced precipitation and evaporation across vegetated regions of the high latitudes. Warming suggests a more dynamic and active layer in permafrost and longer growing seasons to which plant communities will adapt and hence redistribute themselves over new environmental gradients. A changing geography of vegetation will be linked to changes in land surface energy and water exchanges as surface properties such as albedo, roughness length, and rooting depths change. In turn, near-surface atmospheric humidity, radiation, and winds—all critical determinants of latent heat flux—may be altered, creating feedback to the overlying atmosphere. Such changes include treeline advance, which is likely to decrease winter and summer albedo; earlier snowmelt, which is likely to decrease spring-time albedo, and increased shrubiness, which is likely to decrease evapotranspiration in tundra because of lower evaporation from mosses. Alternatively, increased disturbance may alter permafrost characteristics and soil moisture to allow deciduous and boreal forest stands to migrate across the landscape, though numerical experiments indicate an overall net loss of boreal zone forest area. Changes in the outflow of Arctic freshwater could ultimately regulate the thermohaline circulation in the world's oceans through feedback to sea ice and Atlantic deepwater formation. Changes in all elements of the water balance are therefore possible, making the question difficult to address with current data and analysis tools.

Measurement Requirements: Vegetation characteristics, albedo, snow characteristics, precipitation, evapotranspiration, disturbance characteristics, permafrost characteristics, soil moisture, river runoff, rainfall, snowfall, and snow cover.

3.9 *How will terrestrial ecosystems of the high latitudes change in response to CO_2 and trace gas loading of the atmosphere?*

Increased concentrations of radiatively active gases in the atmosphere are expected to significantly alter climate in high latitudes and thereby influence ecosystem function and structure. These responses will affect species composition, wetness and wetland extent, and alteration of freeze-and-thaw dynamics. Disturbance may also promote vegetation transitions by providing substrate for establishment of new species. Given that the rate of recovery after disturbance is unaffected, increases in the extent or severity of the disturbance regime will tend to promote carbon release from high-latitude ecosystems at the regional scale, while regional carbon storage will tend to increase if disturbances become less frequent or less severe. Greenhouse warming is likely to cause later freezing and earlier thaw, which should extend the growing season and has the potential to increase net uptake of CO_2 by the vegetation. Altering the physics and vegetation cover in the Arctic will in turn affect the trajectories of trace gas concentrations in the atmosphere. The total effect on carbon storage depends on responses of soil temperature and soil moisture, which regulate decomposition processes and primary production.

Measurement Requirements: Vegetation characteristics, albedo, snow characteristics, precipitation, evapotranspiration, disturbance characteristics, permafrost characteristics, soil moisture, river runoff, rainfall, snowfall, and snow cover.

4 Issue No. 4: Consequences of Change in the Polar Regions

4.1 *How does permafrost variability affect human infrastructure (roads, buildings) in high latitudes?*

Although the long-term effects of the disappearance of permafrost may reduce construction problems in high latitudes, the thawing of permafrost may damage buildings built on permafrost soils, may damage roads and increase road maintenance costs, and may lead to soil instability, which may increase erosion and landslides, thereby affecting man-made structures. To determine variability, all of the data sets should be in time-series.

Measurement Requirements: Permafrost extent, thermokarst topography, soil temperature profile, land-surface temperature, snow characteristics, soil moisture, vegetation characteristics, disturbance characteristics, wetlands extent.

4.2 *How will changes in coastal sea ice-coverage and sea-level rise affect storm surges, coastal erosion, and inundation of the coastal freshwater supply?*

The coastal zones in and outside the polar regions are highly sensitive to global change, both from the direct human modification of the coastal environment and from changes in sea level. Net changes in sea level have a complex geography, determined by the competing factors of thermal expansion of the global oceans and such local conditions as glacial rebound. Coastal responses to such changes are highly dynamic, as evidenced by the landward migration and net loss of deltas under sea-level rise or reduced river sediment delivery. Coastal systems are adapted to natural variability, but a key question surrounds their resiliency in the face of rapid change—in particular, contemporary sea level rise—which makes them susceptible to increased storm damage. Coastal ecosystems, which provide important support to both commercial and indigenous fisheries species, are therefore placed in jeopardy. Coastal habitation is also at risk from increased storm flooding and damage, especially if the ice-free season lengthens, and the incursion of the sea jeopardizes ground and surface freshwater supplies. On the other hand, if the predicted decrease in meridional temperature gradients were to occur in a warming climate, high latitude storminess may decrease.

Measurement Requirements: Sea level height, sea ice concentration, coastal erosion rates, and coastal topography.

4.3 *What changes will occur in water supplies from snow and snow-fed rivers as the climate changes?*

The seasonal storages of snow are important to energy exchanges with the overlying atmosphere and in many parts of the Arctic constitute the major source of water discharged through river channels to the Arctic Ocean. Although many models of future climate change project an increase of precipitation at high latitudes, several global-warming scenarios indicate a shorter season of snowfall, diminished snowpack, and a movement of snowlines northward. Such changes would have marked impacts on soil moisture recharge and the distribution of streamflow, and hence are important to both terrestrial and aquatic ecosystems.

Measurement Requirements: Precipitation, snow cover, ground water, and river runoff.

4.4 *How will shipping, offshore mineral extraction, commercial fishing, and subsistence fishing and hunting be impacted by changes in coastal sea ice characteristics?*

Changing patterns of sea ice formation, transport, and disappearance have very clear consequences on the ability of society to exploit resources in the polar regions. Longer ice-free periods mean greater opportunity for shipping and mineral extraction. All other factors being equal, a reduction of sea ice can increase coastal primary production by reducing light limitation, with possible increase in fisheries production. Changes in the physics of the high-latitude coastal oceans can, however, create unforeseen changes in ecosystem dynamics and species migrations, with unknown consequences. Changes in the timing and extent of sea ice is also of obvious importance to traditional Arctic fishing and hunting on floating ice.

Measurement Requirements: Sea ice concentration, ice thickness distribution, surface winds, and ocean productivity.

4.5 *How will primary terrestrial productivity, vegetation, and higher organisms be affected by changes in the Arctic's physical environment?*

Patterns of terrestrial primary productivity in the Arctic are keyed closely to the availability of energy and water and hence are sensitive to projected changes associated with global warming. As discussed earlier, changes in growing season and water availability will foster a dynamic redistribution of vegetation and the species dependent on those habitats. Because water and carbon balances differ greatly between contrasting vegetation communities, potentially great differences in net primary production and ecosystem sequestration of carbon might occur. Coastal and oceanic production is regulated by available light, temperature, salinity, and the stability of the photic layer. With potential changes in sea ice distribution, precipitation rates, and potentially higher discharge from melting ice mass, higher air temperatures, and changes in net primary production may also occur. Reductions in sea ice mean a longer period of primary production in newly opened waters, but may result in the disappearance of ice-dependent higher organisms. The influence of ozone depletion and arctic contaminants on primary producers (and hence higher trophic levels) in high-latitude land and ocean systems requires further attention.

Measurement Requirements: Permafrost characteristics, vegetation characteristics, rainfall, snowfall, snow characteristics, disturbance characteristics, wetlands extent, soil moisture, land surface temperature, photosynthetically active radiation, evapotranspiration, vegetation characteristics, sea ice extent and thickness, ultra-violet radiation, and sea surface temperature, salinity, and color.

4.6 *How will changes in growing season and primary production influence agriculture and forestry in high-latitude regions, including disturbed regimes (e.g., fire, insects)?*

The economic side of net primary production is represented by forestry and agriculture in service to society. Boreal forest ecosystems are expected to be highly sensitive to Arctic climate change, and large reductions in area are predicted even as these ecosystems expand into tundra zones. Threats to the boreal forests also arise from potential increases in fire frequency and severity and insect infestations associated with global warming. Because of the severe climate, there are relatively few crops grown in the polar regions. Herding of indigenous animals, fisheries, and hunting are important to native peoples, and these activities may be sensitive to greenhouse warming in the Arctic through changes in net primary productivity.

Measurement Requirements: *Permafrost characteristics, vegetation characteristics, precipitation, snowpack characteristics, disturbance characteristics (e.g., fire frequency, insect population), wetlands extent, soil moisture, land surface temperature, photosynthetically active radiation, and evapotranspiration.*

5 Issue No. 5: Predicting changes in the polar climate system and their global effects

(Note: The required measurements and tools for all the subsidiary questions for the questions in sections 5.1-5.3 are addressed following section 5.3.)

5.1 *To what extent can transient climate variations in the polar regions be understood and predicted?*

Recent cyclic events such as the Arctic Oscillation, Antarctic Oscillation, and North Atlantic Oscillation have been linked to important changes in atmospheric and ocean circulation patterns. These in turn have lead to changes in the delivery of precipitation and hence runoff over the land mass. It will be important to study these quasi-oscillatory climate phenomena to explore whether they are persistent features or more or less transient events associated with the internal dynamics of the climate system. Analysis of contrasting conditions represented in paleo-oceanographic records could lend important insight to this question. Promising recent work in analysis of ENSO signals for making predictions of hurricane number and severity, for example, might be expanded to predict Arctic cyclic phenomena as well.

5.2 *Is there a need for more and/or new observations from the polar regions to support atmosphere and ocean and ice models, including numerical weather prediction models?*

In addition to providing important boundary and initial conditions to diagnostic models of the atmosphere, oceans, and sea ice, routine monitoring of geophysical variables has been used extensively to support operational products, including weather predictions. Surface wind, temperature, humidity and pressure data from rawinsonde observational networks are routinely assimilated with land-based meteorological station data sets into National Center for Environmental Prediction and European Center for Medium-range Weather Forecasting operational forecasts. The assimilation products are imprecise. Comparison of long-term atmospheric convergence fields for moisture versus river runoff, for example, suggests that the rawinsonde network is inadequate over much of the Arctic. The capacity of satellite-based atmospheric sounders to augment the fixed network of rawinsondes, and routine assimilation of the numerous geophysical variables mentioned above, need a systematic assessment.

5.3 ***What improvements to formulations of polar processes (e.g., sea ice, land surface energy exchanges) are necessary for the accurate simulation and prediction of climate and climate change?***

Our ability to forecast changes in the polar climate system and their ultimate connection to the larger global climate system requires a capability to interpret observational data sets and use them to guide the development of process-based models. Much of this discussion has centered around the collection of data sets to help monitor and improve our process-based understanding of the high latitude region. Current model formulations are rapidly increasing their level of sophistication and are being called upon to treat coupled land-atmosphere-ocean exchanges. Fully linked models are becoming available and are being used to analyze past, contemporary, and future conditions. Retrospective analysis, including paleo-analogues to future greenhouse warming conditions, is an important avenue of investigation. Treatment of transient climate conditions is also now recognized as important as we seek to understand changes in the character of climate response to warming (e.g., potentially higher intensity of precipitation events) and to assess its reaction to quasi-periodic events in a prognostic manner. In addition, a clear strategy is needed for gathering and distributing to the research community specific polar data sets to serve as model forcings and validation.

Required Measurements and Tools for Addressing Questions in Section 5

The prediction-oriented questions posed in Section 5 require a broad set of modeling tools. Some of these will be exercised in isolation to better understand particular polar sub-system processes; however, as the science associated with coupled Earth systems models develops, it is likely that these simulations will be linked and applied in an increasingly integrated way.

Four major classes of models will be needed: numerical weather prediction models, sea ice and ocean models, ice sheet models, and land system models for hydrology and terrestrial ecosystem dynamics. These are described below together with their key data needs. These models first require data sets for initialization of their computed fields or specification of boundary conditions. For example, ice/ocean models require salinity distributions as an initial condition. Validation data, including the many variables listed in the foregoing discussion, are also required; such key data sets are repeated below for emphasis. Many of these (for instance, polar cloud properties or surface heat flux data) have virtually no polar coverage for model validation. A good example of the need for such data sets is demonstrated by satellite- and aircraft-based measurements, which are providing new constraints on ice sheet models, including regional ice flow measurements and the age-depth distribution from internal layers (isochrons) traced from well-dated ice core sites. By their very nature, simulations and models provide a large degree of synthesis and thus require input data on a comprehensive list of specific variables, generally the same variables described earlier in this chapter. Listed below are the four major model types and the types of measurements required to support either assimilation and initiation or validation.

(A) Numerical Weather Prediction Models

Assimilation and Initialization: Atmospheric profiles of temperature, humidity, winds, surface temperature, winds, and pressure, precipitation, sea ice concentration.

Validation (additional parameters): Cloud properties, top-of-atmosphere radiation fluxes, surface heat flux components, diabatic heating.

(B) Sea Ice and Ocean Models

Assimilation and Initialization: Surface radiation fluxes; surface air temperature; humidity; winds and pressure; precipitation; ice concentration, thickness, and velocity; ocean temperature; salinity; and currents.

Validation (additional parameters): Ice and ocean interfacial fluxes, surface temperature and albedo.

(C) Ice Sheet Models

Assimilation and Initialization: Ice sheet elevation and thickness, basal conditions accumulation, ice temperature distribution, melt estimates (surface radiation flux components, surface temperature, albedo, surface air temperature, humidity and winds).

Validation (additional parameters): Ice sheet velocity, runoff or discharge, internal layer distribution.

(D) Land System Models for Hydrology and Terrestrial Ecosystem Dynamics

Assimilation and Initialization: Surface elevation and topography, precipitation, surface radiation flux components, surface temperature and albedo, surface air temperature, humidity and winds, vegetation characteristics, river and lake morphology, soil moisture, permafrost extent and temperature profiles, snow cover.

Validation (additional parameters): Surface temperature and albedo, river runoff.

SUMMARY

This chapter began with a broad set of scientific questions that reflect our incomplete understanding of the roles that polar systems play in the Earth system and in global change. For clarity the committee further divided the discussion into a set of more disciplinary issues, specifically around the issues of ice sheets, sea ice, atmospheric dynamics, land surface hydrology, and ecosystems. The committee, of course, fully recognizes the importance of integrative and cross-disciplinary study.

The first major science-driving question and its subsidiary research issues were devoted to the detection of coherent signals of change, either natural or anthropogenic. The committee found that there are significant difficulties in establishing the contemporary spatial and temporal distribution of change and in quantifying such basic biogeophysical variables as precipitation, ice sheet mass, sea ice concentration, land-surface hydrological variables, permafrost, and vegetation distributions. The committee also concluded that our understanding and capability to detect variability and progressive changes to polar systems remains inadequate.

The high-latitude oceans and land mass exert an important influence on the Earth system, and in the second part of this chapter the focus was on how fluxes of CO_2 and trace gases in polar regions affect global atmospheric composition and how aerosols in high latitudes affect atmospheric energy budgets. The third part of the chapter addressed feedback of polar systems in response to global change and thus included a complex array of processes that influence ice sheet atmosphere, sea ice and ocean-atmosphere, land and vegetation atmosphere, land-ocean linkages, and couplings between the polar and non-polar atmosphere. The complexity of these issues means that numerous biogeophysical variables must be observed simultaneously before the questions can adequately be addressed.

The fourth part of this chapter treated the consequences of change in the polar regions, with an emphasis on human systems. Many traditional and industrial activities are located in polar regions and several of these are intimately tied to the state of the natural system and thus are likely to experience the most direct impact. Many of the geophysical variables monitored for Earth System studies also can be used in the assessment of societal impacts.

The final portion of the chapter dealt with the ability to forecast polar change and its effects on the global system. This is fundamentally a modeling and synthesis exercise that will rely on knowledge from observational programs as well as process-based studies of individual components of the polar system. Four classes of models are crucial for progressing in polar system science: ice sheet models, sea and ice ocean models, operational weather prediction models, and terrestrial hydrology and ecosystem dynamics models. The complexities of feedbacks within and among these realms requires a major synthesis effort. The linkage of these models through an integrated initiative would constitute a major step forward in our understanding of the polar regions and their broader role within the Earth system (as was depicted in Chapter 1, Figure 1-1). Reliable and coherent geophysical data sets are critical to the calibration and validation of such models and are therefore essential to continued scientific progress.

Table 3-1 summarizes the measurements required to address the science questions described in this chapter. We have attempted to construct a matrix that relates the specific measurement variables to the specific science questions. In the variable/parameter column, all variables listed in sections 3.1-3.5 (in association with the science questions) are listed. Columns 1-5 relate directly to the science questions 1-5, as discussed in sections 3.1-3.5. The specific numbers in columns 1-5 correspond to specific science questions in section 3. For example, a 9 in column 3 corresponds to question 3.3.9. In column 5, the letters correspond to the parenthetical letters assigned to specific models where they were described in the text. That is, (A) in column 5 corresponds to numerical weather prediction models; (B) indicates sea ice and ocean models; (C) indicates ice sheet

TABLE 3-1 Measurements Required to Address the ESE Science Questions[a]

VARIABLE OR PARAMETER	ESE POLAR SCIENCE QUESTION				
	1 Monitoring	2 External Forcing	3 Feedback	4 Impact	5 Prediction
Top of atmosphere radiation flux	1		7		A
Atmospheric profiles					
-Temperature	1		3,6,7		A
-Humidity	1		3,6,7		A
-Winds	1		2,7		A
Cloud properties					
-Cloud cover	1		3,6,7		A
-Ice/liquid content	1		3,6,7		A
-Particle eff. radius	1		3,6,7		
Aerosol properties					
-Concentration	1	2	3		
-Size distribution	1	2	3		
-Refractive index	1	2	3		
Surface temperature	1,2,4		1,2,3,4,5,6	5	A,B,C,D
Surface albedo	1		3,4		B,C,D
Surface pressure					
Surface heat flux					
-Radiation flux	1,2,4		1,7		B,C,D
-Sfc air temp	2,4		1,6		B,C,D
-Sfc winds	2,4		1,5,6	4	B,C,D
-Sfc air humidity	2,4		1,5,6		B,C,D
Precipitation					
-Rainfall	1,2,3,4		7,8,9	5	A,B,D
-Snowfall	1,2,3,4		1,4,7,8,9	5	A,B,C,D
CO_2 Flux	3	1			
CH_4 Flux	3	1			
Sfc UV radiation				5	
Permafrost					
-Extent	4		8,9	1,5,6	D
-Freeze/thaw dates	4		8,9	1,5,6	
-Temperature profile	4		8,9	1,5,6	D
-Thermokarst topog	4		8,9	1,5,6	
Land snow characteristics					
-Cover			4,8,9	3,5	D
-Depth			8,9	3,5	
-Water Equivalent			8,9	3,5	

continued

TABLE 3-1 Continued

	ESE POLAR SCIENCE QUESTION				
VARIABLE OR PARAMETER	1 Monitoring	2 External Forcing	3 Feedback	4 Impact	5 Prediction
Vegetation characteristics					
-Leaf area index	4	1	8,9	1,5	D
-Canopy density	4	1	8,9	1,5	D
-Albedo	4	1	8,9	1	D
-Structural composition	4	1	8,9	1,5	D
-Land-cover type	4	1	8,9	1	D
Evapotranspiration			8,9	1,5	
Photosynthetically active Radiation (PAR)				5	
Coastal morphology				2	
Surface topography					D
River, lake morphology					D
Wetlands extent	4			1,5	
Sfc elevation, topog					
Soil moisture			9	1,5	4
N deposition & contaminants	4				
Disturbance characteristics (land)					
-Type	4		8,9	1,5	
-Timing	4		8,9	1,5	
-Extent	4		8,9	1,5	
-Severity	4		8,9	1,5	
River runoff	3	1	9	3	
Ice sheet					
-Elevation	2		1		C
-Thickness	2				C
-Velocity	2				C
-Discharge	2		1,2		C
-Runoff	2		1,2		C
Sea ice					
-Concentration	3	1	2,3,4,5	2,4,5	A,B
-Thickness	3		2,3	4,5	B
-Velocity	3				B
-Snow cover			3,5		B
-Melt pond cover			3		
Ocean					
-Temperature, salinity	3		2,6		
-Currents	3		2		
-Surface height				2	
-Color (productivity)	3			4,5	
-CO_2 flux					

continued

TABLE 3-1 Continued

NOTE: eff = effective; sfc = surface; TOA = top of atmosphere.

[a]This table is a matrix that relates the specific measurement variables to the specific science questions. In the variable/parameter column, all variables listed in sections 3.1-3.5 (in association with the science questions) are listed. Columns 1-5 relate directly to the science questions 1-5, as discussed in sections 3.1-3.5. The specific numbers in columns 1-5 correspond to specific science questions in section 3. For example, a 9 in column #3 corresponds to question 3.3.9. In column 5, the letters correspond to the parenthetical letters assigned to specific models where they were described in the text. For example, A in column 5 corresponds to numerical weather prediction models. Examination of the number of times that a specific variable is cited under the various science questions provides a crude measure of the priority of need for measuring that variable.

models; and (D) indicates land system models for hydrology and terrestrial dynamics.

Examination of the number of times that a specific variable is cited under the various science questions provides a crude measure of the priority of need for measuring that variable. For instance, column one addresses the polar variation of ESE science question #1, "How are polar climate and the biosphere changing?" (which is fundamentally a monitoring question). It identifies atmospheric profiles (temperature, humidity, and winds) and a variety of other measurements as being most relevant to this science question. Chapter 4 looks further at the most frequently cited variables and parameters in this table, such as atmospheric profiles (including temperature, humidity, and winds), cloud properties (including cover, ice/liquid content, and particle radius), etc. The committee recognizes that this is a subjective judgement but believes the logic is sound and provides some indication of the kinds of measurements most needed to answer the ESE questions.

4

Assessment

The polar regions are extremely sensitive to global climate change, yet in many regards they are among the most poorly studied systems in the world. While Chapter 3 identified critical observational data sets that could be used to provide better detection and early warning of impending global change, this chapter assesses whether NASA's current polar observational programs and data sets provide the information that is most needed. The assessment, when related to the original scientific questions, will allow judgement of the adequacy of current data-collection efforts and help to formulate advice on ways to improve NASA's overall polar program strategy. The committee's assessment strategy is to briefly review NASA's contributions to development, evaluation, and availability of the data sets for each variable, to identify how NASA could enhance its current contributions, and to identify gaps and what NASA can do to fill the gaps. After the variable-by-variable review, the committee summarizes NASA contributions and identifies key gaps in the current generation of polar geophysical data sets.

This summary provides the basis for recommendations presented in Chapter 5. The variables assessed here include:

atmospheric profiles
cloud properties
aerosol properties
surface temperature
surface heat fluxes
surface albedo
precipitation
permafrost
land surface characteristics
evapotranspiration
soil moisture
terrestrial CO_2 and CH_4 flux
river runoff
ice sheet elevation
ice sheet dynamics
snow cover
sea ice concentration
sea ice thickness
sea ice velocity
ocean surface temperature and salinity
sea surface height
ocean productivity and CO_2 flux
wildlife habitat and migration

ASSESSMENT OF DATA SET AVAILABILITY BY VARIABLE

Atmospheric Profiles

Atmospheric profiles depict the vertical variation of quantities such as air temperature, humidity, and wind. Current conventional meteorological data sets (e.g., collections available at the National Snow and Ice Data Center [NSIDC]) generally do not provide adequate spatial and temporal coverage, especially over ocean and sea ice portions of the polar regions. Even so, some first-order analyses of energy and water transports into the Arctic (e.g., Peixoto and Oort, 1992) and Antarctic (e.g., Bromwich et al., 1998; Giovinetto et al., 1992) have been attempted. Satellite-based temperature and humidity profiles are available from NOAA satellites, but there are substantial uncertainties associated with these products. NASA makes little contribution to this area, except in supplying NOAA data to European centers; the major activities are conducted by NOAA's National Center for Environmental Prediction (NCEP), The Laboratoire Meteorologic Dynamique (LMD), and the European Center for Medium-range Weather Forcasting (ECMWF). NASA has also sponsored a re-analysis of the NOAA data sets in the Arctic, which has improved the operational analysis being done by LMD. NASA should ensure that coverage is extended to the south polar regions. Although the Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit (AIRS/AMSU) may be of some use, NASA's potential contributions are limited unless it sponsors work on advanced, multi-instrument analysis techniques in preparation for Net Primary Production (NPP) and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and its forerunner, the NPOESS Preparatory Project (NPP).

These advanced techniques could also be applied retrospectively to the Advanced Very High-Resolution Radiometer (AVHRR)/High-Resolution Infrared Sounder/Microwave Sounding Unit data sets. Given the challenges associated with surface-based sensors in the extreme and isolated polar regions, flight of a wind-profiling mission could be very useful, but the persistent cloudiness of polar regions could be a constraint.

Cloud Properties

Existing satellite data sets (two global, two Arctic only) provide appropriate coverage, but their accuracy in the difficult polar conditions is still unknown (e.g., Curry et al., 1996; Rossow and Schiffer, 1999). The properties determined are areal cover, cloud top temperature, optical thickness or emissivity, and mean particle size. The Arctic data sets are held at the NSIDC, one global data set is held at Langley Distributed Active Archive Center (DAAC), and one global data set is partially archived at the Goddard DAAC. NASA supports the production of all four of these data sets; however, NASA's contribution would be significantly improved if it supported the studies needed to evaluate the accuracy of these data sets. These studies could be an extension of NASA's First ISCCP Regional Experiment—Arctic Cloud Experiment (FIRE-ACE) Project based on Surface Heat Budget of the Arctic project (SHEBA) and Atmospheric Radiation Measurement (ARM)—Barrow surface radar and lidar data sets and also on more effective use of conventional surface weather observations, which are available from the Oak Ridge DAAC. There is also a need for extended modeling studies of the polar atmospheric boundary layer and its associated cloudiness using recent field data sets.

In the near future, NASA's CloudSat and Picasso missions should add crucial missing information about cloud vertical structure needed for a more accurate assessment of the radiative effects of polar clouds. There will be a need for targeted analyses of CloudSat, IceSat, and Picasso data to characterize the vertical distribution of clouds in polar regions.

Aerosol Properties

There are no extensive aerosol data sets for the polar regions. Existing satellite retrieval methods have not been applied to this region and are unlikely to be successful over snow- and ice-covered surfaces. Little surface-based data are available. New instruments (MISR, MODIS) are unlikely to provide the needed improvement in this difficult situation, although GLAS (the Geoscience Laser Altimeter System to be carried on ICESat, scheduled for launch in mid-2001) has the potential to provide some useful information on the physical properties and distribution of polar aerosols. Because it is unclear how critical this issue is for understanding current polar processes, model experiments incorporating field measurements could provide a basis for the identification of key processes and measurement needs.

Surface Temperature

Existing satellite data sets (two global, two Arctic only) provide appropriate coverage except for the fact that the infrared sensors (e.g., TOVS Path-P) cannot provide surface temperatures when cloud fractions exceed 90%, which leads to a bias and to an incomplete description of energy exchanges at the surface. Although there are four relevant data sets (the two Arctic-only data sets are held at the NSIDC, one global data set is held at the Langley DAAC, and the remaining global data set is partly archived at the Goddard DAAC), little is known of their accuracy. Although NASA has not made a focused contribution to the development of the needed all-sky product, it has supported most of the analyses that have produced this quantity as a by-product; however, this support is waning just when research interest is growing. There are unexploited (microwave) data sets that could improve the information if they were analyzed in combination with infrared measurements; so NASA could make a significant contribution by supporting advanced analyses of combined measurements (this could be a side benefit of careful sea ice product intercomparisons).

Surface Heat Fluxes

Routine meteorological data at the surface (e.g., surface air temperature, winds, and humidity) are available at the NSIDC, but coverage is incomplete, especially over ocean and sea ice and over Antarctica. NASA is not a major contributor, although it could contribute significantly by sponsoring work on advanced multi-instrument analysis techniques in preparation for NPP and NPOESS.

NASA supports two major efforts to determine surface radiative fluxes for the whole globe, including the polar regions. These are state of the art; evaluation under the difficult polar conditions can be done using data from SHEBA and ARM-Barrow. This is a key contribution to polar research that should continue, since such data are needed for characterizing the surface energy budget of all polar surface types. Currently, there is no NASA contribution to the determination of surface turbulent fluxes, except for support for FIRE-ACE, which is ending. Extending studies to modeling of the surface boundary layer and its associated clouds would provide some advancement on this topic: Progress could come from further analysis of the SHEBA and ARM-Barrow data sets, together with modeling studies, but may also require some additional field studies.

The onset of melt on ice sheet surfaces is relatively straightforward to detect. However, measurement of melt rate either directly or through measurement of individual components of the surface energy balance is problematic. Direct measurement of spatial melt extent requires frequent sampling in time; this type of coverage is only available at the coarse resolution of passive microwave sensors and scatterometers. Satellite sensing of surface conditions is further complicated by clouds and difficulties in cloud masking in the visible and near-infrared (IR). Moreover, remotely sensed estimates of melt extent have yet to be quantitatively translated into ablation rates. Measurement uncertainties in several components of the surface energy balance make the combined errors large, thereby limiting the accuracy of estimated changes of surface elevation due to melt, as well as estimation of runoff from snow packs on land. Integrated analysis of available and future satellite measures of albedo and surface temperature, in combination with sensible and latent fluxes, may provide a solution; however, representative in situ studies and instrumentation are required. For ice sheet margins these include the continuation of measurements in Greenland (funded by NASA and the National Science Foundation [NSF]) and in Antarctica (funded by NSF). Re-analyses incorporating these measurements need to be evaluated and most likely improved. The optimum approach to improved estimates of melt rates will likely involve a combination of forecast or re-analysis data sets (at improving resolutions), mesoscale models forced by these observations, automated weather station (AWS) data, and thermal-IR and microwave emission data sets to produce internally consistent pictures of surface processes.

Both accumulation and surface energy balance require an improved characterization of meteorological conditions at the ice surface; storm tracks, drainage winds (also called katabatic winds), and boundary-layer stability all play a role. Current AWS instrumentation in Greenland is adequate for characterizing many of these variables locally; the continuation of this time series is essential to efforts to understand processes and integrate them into climate models. Similar data are available in Antarctica through NSF efforts, although the region is larger and station density is low; future continuity on either ice sheet is not guaranteed. Better integration of the measurements with other research efforts is required.

Surface Albedo

Two existing satellite data sets (one global, one Arctic only) provide appropriate coverage (the Arctic data set is held at the NSIDC and the global data set is held at the Langley DAAC), but these data sets are limited to the visible portion of the spectrum. For sea ice and deep snow, these may be sufficient, since the reflection spectrum is known fairly well, but for shallower snow and vegetation mixtures on land, where the spectrum is not well characterized, these data sets may not be adequate for many applications. Moreover, time resolution may be inadequate for defining melt or thaw onsets (this may be insurmountable because of persistent cloud cover). MODIS data provide complete spectral coverage for the first time, so if clear sky can be successfully identified, analysis of these data will provide the best measure of surface albedo; thus, thorough analysis of the entire time record of MODIS is an important contribution. In particular, there is a need for targeted analysis of MODIS data to obtain better surface albedos for mixtures of snow and vegetation.

Precipitation

Although there are many conventional data sets for precipitation, they do not provide adequate coverage of the polar regions. The one extensive snow cover data set does not contain any information about snow cover on ice. Global precipitation data sets combining satellite and ground-based data are available from other agencies such as the WMO's Global Precipitation Climatology Center and the Global Precipitation Climatology Project. For Arctic applications, the NSIDC maintains historical archives of land-station precipitation from the Former Soviet Union and Canada.

A variety of spatially extensive (in situ and satellite) precipitation (P) data are available as global products that would encompass the polar regions. The WMO-GPCC Global Precipitation Climate Center (GPCC located in Offenbach Germany), serves as official custodian of precipitation data for the World Meteorological Organization (WMO). The Center maintains major compilations of station records, error-checked and merged to yield the most comprehensive station-based P archive (and derived products) for the globe. New fields and time series are developed on an operational (2-month delay) basis, (www.dwd.de/research/gpcc). The standard "monitoring product" starts in 1986, at 1° and 2.5° resolution.

The Global Precipitation Climatology Project (GPCP) is part of the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Program. Currently available GPCP products (Version 1c and 2.x) combine precipitation from microwave (Special Sensor Microwave/Imager, SSM/I) and infrared sensors at 2.5°. Version 2.x products incorporate the TIROS Operational Vertical Sounder (TOVS) and OLR Precipitation Index (OPI) for time periods when SSM/I was not available. The Version 1.c products cover 1987 through the present and Version 2.x covers 1979 to present.

In addition, precipitation data sets are available from individual research teams. For example, monthly climate records and time series (1901-95) of various climatic variables from the Climate Research Unit (CRU) at the University of East Anglia are available for land areas. These include precipitation station data from formal and informal sources, and gridded fields using a variety of interpolation methods.

There are many difficulties in using the available station records to develop spatially varying fields of precipitation. Gauge undercatch is well documented, especially for solid precipitation. The use of station monitoring data sets in a vast remote area that has low station density creates biases in interpolated precipitation amounts. Gaps in station records, re-location of stations, differences in gauge technology and wind correction factors used for snow all add to the difficulties in obtaining a clear picture. Use of un-manned, automated stations is a problem because of equipment failure in the harsh environment. In addition, the closure of stations due to the collapse of monitoring networks, especially in the Russian Arctic, adds to the uncertainty.

The use of coherent, spatially contiguous remote-sensing measurements could therefore make, in principle, a valuable contribution to the monitoring of high latitude precipitation. Despite the potential opportunity, NASA makes only a limited contribution to the direct measurement of precipitation, primarily in support of microwave analyses of snow cover (water content) on land. NASA has supported one recent precipitation-relevant data set, which is due to be released in early 2001; this data set will include horizontal vapor fluxes and moisture convergence or net precipitation (P-E). Net precipitation will not achieve all that is required. Given the importance of hydrological and energy/water balance questions in climate research, an effort to develop a satellite-based determination of precipitation, particularly ice phase, in the polar regions would seem to be of paramount importance and would eliminate a key deficiency of polar observations and data availability for NASA's Earth Science Enterprise science.

While NASA has not taken on a unique role in providing information on polar precipitation, it has supported science and data collection efforts, notably with respect to the special sensor microwave/imager (SSM/I) data products from Defense Meteorological Satellite Program (DMSP) satellites. NSIDC has also been active in identifying and securing ground-based measurements of precipitation and other meteorological variables that can serve as validation for the satellite products. Information from these satellites has been incorporated into the global precipitation data sets noted above. Advanced Microwave Scanning Radiometer E (AMSR-E) data sets for rainfall should become available at the NSIDC from EOS and AQUA (NASA's first and second Earth Observing Systems), and assessments of the polar subsets of these data should be a high priority.

Permafrost

Permafrost-related research is not a prominent feature of NASA's high-latitude science program. The most comprehensive data related to distribution of permafrost is from digitized maps and expert opinion from the International Permafrost Association, but the resolution of the mapping is coarse. Remote-sensing approaches are not capable of directly mapping permafrost extent, but progress in mapping permafrost extent may be possible through approaches that combine remote-sensing technology, modeling of the soil thermal profile, and in situ measurements. In particular, data sets that describe the timing of freeze and thaw with adequate spatial coverage and spatial resolution may overcome some constraints. The NSIDC provides a land-based freezing/thawing/degree-day product based on climatology station records, but it does not provide adequate resolution or coverage of the polar regions, particularly in mountainous terrain. Analyses based on data from NASA scatterometers (NSCAT, SeaWinds) show some promise for monitoring the freeze-thaw status of the land mass, but the algorithms and technology need further evaluation and development as the scatterometers are not formally optimized for land-based cryospheric applications. It may also be possible to detect onset of surface melt from changes in surface microwave emissivity, which would go from relatively high emissivities when the surface is frozen to low values when the surface has standing water. Besides freeze and thaw data sets, other satellite-derived products that can contribute to monitoring or diagnosing permafrost dynamics include land-surface temperature, snow characteristics (cover, depth, water equivalent, thermal properties), vegetation characteristics, disturbance characteristics, and wetlands extent. Also, there are several remote-sensing technologies that could be brought to bear on monitoring thermokarst topography, which would aid in understanding permafrost dynamics.

Land Surface Characteristics

Important variables of land surface characteristics include canopy characteristics (leaf area, canopy density, albedo), structural composition (e.g., proportion of trees, shrubs, and tundra), land-cover type (classification), wetland dynamics, and disturbance characteristics (timing, location, extent, severity). There are numerous NASA and non-NASA sensors that contribute to these data sets. Several European and Japanese sensors, similar to those supported by NASA, can also be used in estimating land cover. NASA's EOS, NASA's contribution to LANDSAT-7, NOAA/NASA SSM/I Pathfinder products (at the NSIDC), and the planned Next Millenium Program ALI sensor are important in this context. Through NASA's Alaska Synthetic Aperture Radar (SAR) Facility, NASA provides an important service to the U.S. and global research community by archiving and distributing European Earth Remote Sensing Satellite (ERS), Canadian Synthetic Aperture Radar Satellite (RADARSAT), and Japanese Earth Remote-Sensing Satellite (JERS) data sets; however, it must be stressed that due to foreign commercial ownership of these data, access to new data acquisitions is highly competitive and as such this service is limited for U.S. investigators, serves a small "NASA approved" user community, and places severe copyright restrictions on the redistribution of this information.

Products to measure land surface characteristics are not adequate for applications in high latitudes. For example, satellite-based technology is not able to monitor temporal changes in land surface characteristics of high-latitude regions, such as gradual changes in canopy characteristics associated with gradual vegetation changes and abrupt changes in land surface characteristics associated with disturbances, particularly fire. Changes in wetland extent are especially important to monitor in high latitudes. Wetland extent can be monitored with analyses of both optical data (multispectral) and microwave data (multitemporal), and a combination of multispectral and multitemporal data has been shown to improve the ability to delineate wetlands. Research in the Boreal Ecosystem-Atmosphere Study region has shown that wetlands were substantially underestimated with analyses based on 30-m TM resolution imagery, and were not identified at all in analyses based on 1-km AVHRR imagery. Thus, the estimation of wetland extent may require high-resolution satellite imagery (e.g., IKONOS) or aircraft imagery (e.g., CASI). With respect to fire disturbance, current satellite technology is capable of determining the timing, location, and extent of disturbance, but it is less clear how well disturbance severity can be determined. The estimation of disturbance severity, which includes effects on vegetation biomass and ground-layer carbon storage, may require analysis of a variety of remote-sensing data sets, including thermal anomalies at the time of fire, data sets on flaming and smoldering ratio, and land surface characteristics after the fire.

Evapotranspiration

The simplest so-called reference surface techniques for measuring evapotranspiration use mean daily temperature as the measured characteristic. Complex, physically-based functions, typically employed in soil-vegetation-atmosphere-transfer schemes and process-based studies, require surface temperature (sometimes called skin temperature), humidity, net radiation, aerodynamic roughness, albedo, leaf area index, and wind speed. Several of these required input variables or parameters measured routinely by satellites. NASA supports the collection of such information either directly through its sensors or indirectly through data support. NASA efforts result in the provision of clear-sky surface temperature, surface albedo, radiation and cloud properties, and clear-sky surface air temperature. Vegetative properties such as land-atmosphere interactions and land cover, discussed earlier, are also essential. These data sets are not unique to the Arctic. Sub-setting and re-projection for Arctic applications is in several cases carried out by the NSIDC. While not space-based observations, variables such as wind, temperature, humidity, and pressure data over polar land areas are obtained from rawinsonde observational networks and are archived at the NSIDC. Important comparisons can be made by utilizing the NCEP and the ECMWF operational and re-analysis activities. Their products provide many of the same surface data sets as listed above, but are derived as blended model and assimilated observational products. Validation over grid-cell areas is needed in order to provide a basis for improved parameterizations of evapotranspiration in future re-analyses.

Soil Moisture

Passive microwave radiometers have been used to detect soil moisture. Systems such as SSM/I and AMSR have the advantage of acquiring this information on a routine basis (few days re-visit time) from space with a resolution on the order of 50 km or larger; however, interference from vegetation limits what can usefully be obtained from these sensors at this time. The Global Soil Wetness Project, as part of the NASA-funded International Satellite Land Surface Climatology Project, uses AVHRR-derived vegetation information and modeling to produce global soil moisture fields. These are not otherwise archived at the NSIDC or the ASF, although they are archived elsewhere within the DAAC system, this fact is not well known. A proposed NASA post-2002 mission to monitor soil moisture at 10-km resolution is under consideration. Higher resolution SAR data have also been shown to provide some information about soil moisture, thereby pointing to a potentially important use of the ERS, JERS, and RADARSAT data sets archived at the ASF.

Terrestrial CO_2 and CH_4 Flux

Data sets required to model terrestrial CO_2 and CH_4 flux include absorption of photosynthetically active radiation, biomass, leaf area index, soil moisture, land surface temperature, precipitation, evapotranspiration, and land surface characteristics. Measurements relevant to these variables are provided by a variety of NASA and non-NASA sensors; however, many of the satellite-derived data sets required for estimating terrestrial CO_2 and CH_4 flux are not yet available to the scientific community. NASA could improve this situation by enhancing the availability of these data sets to the broader community. These data sets can be used to drive models for estimating the timing and location of trace gases exchanged with the atmosphere. Simple algorithms that use remote-sensing inputs have been developed to estimate components of CO_2 exchange at 1-km resolution at regional and global scales (e.g., correlations between sensor signatures and field-measured fluxes, as well as production efficiency models) for mapping the spatial distribution of CO_2 and trace gas exchanges across the landscape. Process-based models driven by input variables derived from remote-sensing technologies represent another possible approach to estimating the temporal and spatial dynamics of CO_2 and CH_4 in high-latitude regions. Although some of the controls over CO_2 and CH_4 fluxes in high-latitude regions are being measured with remote-sensing technologies, these data sets need to be evaluated to determine whether they are adequate for high-latitude applications.

Testing the temporal and spatial dynamics of models at different scales remains a major challenge, and data sets derived from remote-sensing technologies have an important role to play in testing aspects of forward-modeling approaches. NASA makes a valuable contribution in terms of ground-based flask and tower monitoring for carbon fluxes through FLUXNET, as part of a NASA EOS calibration and validation activity. Canopy chemistry, indicating vegetative stress and potential rates of nutrient recycling in ecosystems, can be derived from hyperspectral sensor data. The development of data sets on canopy chemistry, which is responsive to NH_4 and NO_x deposition rates, is important because NH_4 and NO_x deposition rates do not appear to be directly amenable to remote sensing.

River Runoff

River discharge on all but the largest rivers must typically be obtained from ground-based station data available through several non-NASA archives. Major sub-sets of these holdings have been organized into pan-Arctic data collection. One such archive, developed at the University of New Hampshire and funded by the NSF Arctic System Science, resides at the NSIDC. A post-2002 mission using some combination of radar altimetry, interferometric SAR or lidar may be able to detect morphological changes in river channels to infer discharge. Lake morphometry and stage variations, from which volumetric changes can be inferred, are also possible to determine using such sensors. A small archive of "ice-out" data for one river in Alaska is maintained by the NSIDC.

Variations in topography, slope, and aspect are important for defining snow storage and melt, sediment flux, stream channel velocities, potential floodplain inundation, and the presence of sheetflow. A global 1-km data set developed by the USGS (GTOPO30) is already in existence and widely used by the community <http://www.edcdaac/usgs.gov/gtopo3o/gtopo30.html>. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on TERRA (NASA's Earth Observing System first multi-sensor platform) and Geoscience Laser Altimeter System on ICESAT will provide NASA-sponsored data sets for surface topography. ASTER, in particular, will be able to supply very-high-resolution data with 30-m horizontal resolution.

Ice Sheet Elevation

In spite of poor temporal coverage, existing data sets from radar altimetry (SEASAT, GEOSAT, ERS) provide a picture of change in the high interior of ice sheets over the last few decades; this data stream continues but is of no use near the ice margins, where the most rapid variations occur. NASA airborne laser measurements have identified significant changes in the Greenland ice sheet over the last half of the 1990s. This result has provided the first definitive measurement of one ice sheet's contributions to the present rate of sea level rise. ICESAT will provide systematic coverage in Greenland and Antarctica and, with the aid of aircraft results, will allow the first comprehensive assessment of the present contribution of both large ice sheets to sea level rise. Note that extended time series of these measurements are necessary to understand the background variability of the processes that determine surface elevation and provide the opportunity to assess the causes of change; this is required to develop a predictive understanding of ice sheet variations.

Also required are data on accumulation rates and variations, melt rates, and changes in ice flow.

Surface elevation changes may be driven in part by changes in accumulation rate. Understanding the implications of these changes requires knowledge of the background (long-term) accumulation rate and its variability. NASA has funded efforts under the Program for Arctic Regional Climate Assessment Program to provide this information from shallow ice cores in Greenland. There are limited efforts of a similar nature in West Antarctica funded by the NSF. ICESAT interpretation will require data from all sectors of Antarctica. Broad-band airborne sounding radar can reveal the spatial variations of accumulation and NASA has funded a pilot project. The development of an operational version of this radar will greatly enhance our knowledge of spatial variations of accumulation over ice sheets and allow point measurements from ice cores to be placed in a regional context. An ice-penetrating radar that measures both accumulation variations and ice thickness would provide a unique opportunity for completing the ice thickness map of Antarctica. Such maps would provide major contributions to ice sheet mass budget studies and to ice sheet modeling.

Ice Sheet Dynamics

Surface elevation changes may be produced by changes in ice flow, especially in rapidly flowing outlet glaciers and ice streams. Interferometry and feature tracking in visible-band imagery makes measurement of ice flow from space a routine process if suitable data are available. Interferometric measurements can also reveal the position of the grounding line (the boundary between grounded and floating ice), which can shift location in response to changes in ice thickness. Changing rates of ice flow have been identified by a combination of field and satellite studies in both Greenland and Antarctica. Detection of changing flow rates and grounding-line positions is pursued on a glacier-by-glacier basis, depending on availability of data suitable for interferometry. Limited studies to date have shown that variation is common. Comprehensive coverage is necessary. Modified Antarctic Mapping Mission 2 should provide the first nearly comprehensive interferometric coverage of coastal Antarctica. Continuation of suitable SAR acquisition is important, both to cover areas not yet mapped and to follow areas that are changing. NASA should assure access to data for these studies. There would be significant glaciological return from access to data from a sensor optimized for change detection (e.g., one with more frequent revisits and longer wavelength [L band]). Understanding of ICESAT-detected elevation change will require measurement of ice flow variations over longer periods than are represented in the SAR data archive. The present acquisition strategies for LANDSAT-7 and ASTER are providing annual data sets that earlier high-resolution sensors did not provide. These data complement interferometric data, providing greater detail for change detection and helping to ensure continuity of coverage.

Predictability of ice sheet responses requires improvements to available ice sheet models, including defining the domain (through aircraft-based ice-penetrating radar measurements of ice thickness) and improving knowledge of basal conditions and constraining models (using improved measures of ice velocity and the age-depth relationships that come from internal layer distributions and ice-penetrating radar). Present ice flow models incorporate ice streams and outlet glaciers at a rudimentary level; improvements in resolution and incorporation of processes related to outlet glacier flow variation are needed to match newly available measurements of ice flow and variability. Model development is funded in a limited way by NASA and as part of field data interpretation efforts by NSF. Significant efforts are being made by a number of European countries. Efforts are needed to combine models and satellite- and aircraft-derived data to promote the evolution of model designs. In addition to constraining models, ice thickness data are also required to determine discharge rates in combination with ice velocity measurements.

Snow Cover

The spatial distribution of snow cover and its characteristics, including snow water equivalent, are key variables, and attempts have been made to quantify snow cover and snow cover characteristics from space. NASA supports either directly or through science and data archive activities MODIS, AVHRR/GOES, and LANDSAT-7 snow products that can be used to map snow extent. NASA also supports passive microwave data set activities (for SMMR, SSM/I) and will fly its AMSR (on ADEOS-II) and AMSR-E (on AQUA) sensors. Of primary interest in the Arctic is the capability of passive microwaves to characterize snow depth and water equivalent; while this is being applied for snow water equivalent on land, snow data on ice and on ice sheets is not available. Again, NSIDC activities to collect and distribute land-based data sets for precipitation and, in this context, snow cover provide important auxiliary information for satellite snow retrievals.

Sea Ice Concentration

Sea ice concentration and extent fields are perhaps the most frequently used of all polar geophysical data sets. They provide high quality data (daily 25-km resolution) except in the summer, when atmospheric and ice and snow surface moisture creates ambiguous returns. Passive microwave sensors have provided a time series starting in the 1970s that has been used to document climate change (e.g., Cavalieri et al., 1997) and validate numerical models. A confusing variety of these data sets are available to the public at the NSIDC Web site. Some of these have been generated by different algorithms, some pertain to only one sensor, some bridge several sensors, and some cover only certain space and time subsets. Some are provided as near-real-time data in a file separate from identical fields generated with a (presumably) more accurate but slower algorithm. NASA should help clear out this clutter by funding independent studies that clearly document the strengths and weaknesses of differing algorithms and that encourage long time series (i.e., merging of individual sensor data sets). Further work is also recommended on the determination of summer ice concentration.

Sea Ice Thickness

The amount of sea ice in a given region is determined by measuring the ice thickness distribution, which in general includes a category for very thin ice and open water. Our survey revealed much interest in this variable. Sea ice thickness is directly observable by in situ buoys, submarine sonars, or direct ice coring, all of which suffer from gaps in space and/or time. However, several new satellite methods have been introduced that show some promise. The most direct method has been developed by British researchers using ERS altimetric data to estimate thick (greater than ~0.5-1.0 m) ice thickness over a 10-km footprint. Preliminary studies have produced intriguing fields of mean thickness and interannual variance. Another satellite method uses AVHRR surface temperature observations to deduce thin (less than ~0.8 m) ice thickness, although this has been applied only to small space and time regions. Finally, RADARSAT SAR data have been processed through the RADARSAT Geophysical Processing System (RGPS), at ASF and JPL, to produce Lagrangian grids of thin (less than ~2.0 m) ice thickness. Changes in open water area are very accurately observed with this method, which then uses a simple thermodynamic model to calculate ice growth in divergent regions.

Recognition of the possibility of routinely measuring sea ice freeboard (and inferring thickness) using a satellite-based altimeter represents a significant step forward. NASA needs to investigate the utility of ICESAT in this regard, and if it is not suitable, to pursue other techniques and instruments. With regard to other methods, both AVHRR and RGPS "observations" rely heavily on simplifying thermodynamic assumptions, although the resulting errors may in fact be relatively small. These methods (or some combination with or without numerical models) should be strongly encouraged by NASA. Validation and error analysis needs to be emphasized in these still-exploratory studies.

Sea Ice Velocity

Until recently sea ice motion fields were produced solely by tracking a relatively sparse network of drifting buoys. This has changed dramatically, to the point that there now exists a variety of ice motion data sets derived from satellites (SAR, AVHRR, passive microwave sensors, scatterometers) and from combinations of these with buoy data. This information has been used to track interannual-to-decadal changes in the polar regions, although much more could be done. Blending of data types and assimilation into numerical models seem to reduce errors relative to buoys, but more work is necessary to ascertain the best methods. All satellite-based methods suffer from decreased performance in the summer, owing to feature degradation and/or cloud issues. In addition, clouds obscure passive sensor algorithms during much of the year in Antarctic seas. Some algorithms also have problems near the ice edge.

NASA should continue to fund processing of passive microwave sea-ice-motion products (e.g., from the AMSR) since this represents a time series that started in the 1970s. New algorithm development should also be funded if it specifically targets the summer problem.

There is a need for assessments of the relative merits and potential user base of these various data sets. For example, SAR-derived ice motion data sets have lower error and higher spatial resolution relative to passive microwave. However, it is under-used by the observational and modeling communities, probably in part because it is new, but also perhaps because of its large data streams and Lagrangian gridding. NASA should encourage more communication and collaboration between SAR and modeling researchers (e.g., by funding joint workshops). It could prove useful to provide some form of RGPS data on an Eulerian grid such as that used by numerical modelers.

Ocean Surface Temperature and Salinity

In perennially ice-covered seas, sea surface temperature (SST) stays close to the freezing point and is thus not a particularly important variable. This is not the case, however, for areas with seasonal or no ice cover in the polar and sub-polar regions. These regions have significant seasonal and interannual SST variability that may in fact influence water mass properties at higher latitudes (e.g., the Nordic seas origin of recent

Atlantic water layer warming in the Arctic Ocean). Unfortunately, the calibration of global SST fields using AVHRR and other visible/IR satellite sensors is biased toward data-rich conditions (i.e., the tropics). This can lead to significant errors at high latitudes (Emery et al., in press). NASA can improve this situation by supporting measurements of in situ SST (and particularly, surface temperature) at high latitudes. Because one key issue at higher latitudes is changes of SST by storms, a combined IR-microwave method is needed. Instrument calibrations in high latitudes should also be encouraged as part of the global product. This has been proposed for high-latitude Arctic waters as part of the AVHRR polar Pathfinder Project, but has not yet been implemented. This Pathfinder Project has also created a preliminary integrated surface temperature data set that includes ocean, ice, and land, but only for the polar regions. This type of activity should be strongly encouraged, and on a global basis.

Sea surface salinity (SSS) in high latitudes is a crucial parameter, as it controls the ocean stratification and traces the circulation pathways of freshwater. To date it has been observed only by in situ means; however, this is changing as the use of low frequency passive microwave remote sensing to measure SSS has been demonstrated. A European mission known as SMOS (Soil Moisture and Ocean Salinity) will be launched in 2005. Accuracies will be several tenths of a practical salinity unit (psu) for a 200 km footprint. Unfortunately, accuracy decreases with decreasing sea surface temperature and with decreasing SSS, to perhaps 1 psu for typical polar conditions. This spatial resolution is probably inadequate for the polar regions, where land and ice boundaries make large open water regions relatively rare. Until the next generation of sensors, a promising avenue could be the use of aircraft SSS observations such as those performed by scientists at the Naval Research Laboratory (Miller, 2000). These obviously have much better spatial resolution and, if flown in the summer over Arctic coastal regions, could easily detect river water plumes even with 1-psu accuracy. Much of the justification for the SMOS mission centers on the role of the high latitudes in the global freshwater balance; NASA should strive to improve SSS sensors so that the high latitudes are not neglected in future measurement programs.

Sea Surface Height

Sea surface height (SSH) is used to determine the ocean surface geostrophic current. It is obtained from satellite altimeters with an accuracy of a few centimeters. The most precise observations are from the joint NASA-ERS Topex/Poseidon (T/P) satellite, which covers latitudes between 66º S and 66º N. Most work has focused on tropical (e.g., ENSO) and mid-latitude (e.g., Gulf Stream) phenomena, where SSH anomalies can be as large as 100 cm; however, T/P has also been used to study the sub-polar gyres and the Antarctic Circumpolar Current. Altimeters on the ERS-1 and ERS-2 satellites are not quite as accurate, but cover a greater range of latitudes, up to 82º N/S. These data have been applied to some high-latitude problems, although with some difficulty, given the relatively weak SSH gradients found in polar waters; however, much more could be done with very high-latitude SSH data that could contribute to understanding of interannual and interdecadal climate change. At present, NASA has no plans for a polar radar altimeter beyond the latitudinal range of T/P, even as European efforts continue in this field with ERS and CRYOSAT. NASA's participation in future high-latitude radar altimetry programs is a possibility deserving of consideration.

Ocean Productivity and CO_2 Flux

The measurements of ocean productivity and CO_2 flux present different challenges depending on whether the area under consideration is open ocean or is influenced by sea ice. For open oceans, satellite-derived measurements of ocean color provide a means of quantifying phytoplankton chlorophyll. High resolution mapping (~1 km) of ocean color has become possible with Sea-Viewing Wide-Field-of-View Sensor. The continued availability of these measurements must be ensured to monitor ocean color at seasonal, interannual, and decadal time scales. In addition to ocean color, estimating ocean productivity and CO_2 flux of open oceans requires other measurements, including photosynthetically active radiation, clouds, sea ice, sea surface temperature, surface albedo, and surface winds. Because sea ice is a bright target that saturates highly sensitive marine sensors, it is difficult to accurately determine ocean color in the vicinity of sea ice. As the transition area between ice and open water supports more complex food webs than the open ocean, the estimation of productivity and CO_2 fluxes from satellite-based measurements is problematic in these areas. Also, photosynthetically active radiation, clouds, snow, and ice cover are necessary to predict light transmission accurately in these areas. Refinements to snow and ice cover observations are particularly critical as the vertical distribution (< 5 cm) and horizontal distribution (~1 m) of snow and ice thickness would improve estimates of ice algal productivity.

Wildlife Habitat and Migration

Changes in sea ice coverage, sea ice characteristics (e.g., thickness, lead and ridge distributions), permafrost extent and active layer characteristics can have important effects on wildlife (e.g., caribou herds, bowhead whales, seals, walrus, polar bears). Satellite remote sensing may prove useful in monitoring changes in wildlife habitat, migration routes and migration patterns in the Arctic. Such changes will be important to native residents and other Arctic stakeholders. While satellite tracking of wildlife has proven to be feasible and has been implemented on a limited basis, coordinated activity of this kind has yet to be undertaken by the biospheric research community. A related need is the monitoring of subsurface conditions, especially permafrost and active layer characteristics over Arctic terrestrial regions that may serve as wildlife habitats and/or migration routes.

SUMMARY OF MAJOR NASA CONTRIBUTIONS

NASA is contributing to the development, evaluation, and availability of many significant data sets of importance in addressing the science-driving questions. For instance, NASA has done well in supporting demonstration projects and field campaigns that have led to identifying the potential of applying remote-sensing technologies for the development of data sets depicting the spatial and temporal variability of key land-surface quantities: terrestrial CO_2 and CH_4 flux, freeze and thaw dynamics, snow cover, evapotranspiration, soil moisture, and other land surface characteristics. NASA also makes a valuable contribution in terms of ground-based flask and tower monitoring for carbon fluxes through FLUXNET, as part of a NASA EOS calibration and validation activity.

NASA has also supported analyses of satellite data collected by other agencies to determine atmospheric temperature and humidity profiles enhanced for polar conditions; surface temperature and visible albedo; cloud properties including polar-specific products; and surface radiative fluxes. NASA's contributions to the SHEBA/ARM/FIRE field programs have helped produce a valuable suite of in situ measurements for the calibration and validation of satellite-derived products for the Arctic.

A key NASA contribution has been to define and initiate a program of measurement in Greenland that has provided the first useful measure of mass change of an ice sheet. This program has addressed the effects of most variables that influence the measurements, providing context for understanding the implications of measured changes. It is clear from this work that a range of variables must be addressed to understand the implications of measured surface height changes. NASA is also contributing to the understanding of ice sheet surface energy balance, local meteorology, and the patterns of accumulation by supporting a network of AWS stations and several projects measuring accumulation variability and local height change on the Greenland ice sheet. This work uses surface and remotely sensed data.

NASA is contributing to the understanding of ice flow in Antarctica by supporting interferometric studies from RADARSAT and ERS SAR data in the ASF archive, and through limited acquisition of new data. The RADARSAT Antarctic Mapping Project mosaic has provided an excellent base map for change detection. The Modified Antarctic Mapping Mission 2 interferometric map of ice motion, when combined with other NASA-funded interferometric studies and field and remote-sensing work in Antarctica funded by NSF, will give the most comprehensive picture of ice flow to date; it will provide a reference for the detection of changing flow patterns in future interferometric studies.

NASA has also supported the processing and analysis of sea ice data collected by other agencies' satellites (e.g., the Department of Defense's DMSP/SSMI). The documentation and interpretation of variations of satellite-derived sea ice coverage has been a highly visible NASA contribution.

NASA contributes to the high-resolution mapping (~1 km) of ocean color through SEAWIFS. The continued availability of these measurements will permit the monitoring of ocean color at seasonal, interannual, and decadal time scales, thereby stimulating research in high-latitude ocean biogeochemistry. This high-resolution color mapping may also have terrestrial applications for the summer growth period in the Arctic.

BETTER MANAGEMENT OF NASA'S CURRENT GENERATION OF POLAR GEOPHYSICAL DATA SETS

Many of the variables identified in this chapter are already estimated in re-analyses, including atmospheric profiles, cloud properties, surface temperature, surface heat fluxes, surface albedo, precipitation, evapotranspiration and soil moisture. While the reliability of many of these estimates remains to be established, re-analyses and other data assimilation techniques are powerful vehicles for assessing the impacts of data, especially because re-analyses can accept observations whenever and wherever they are made. For example, AVHRR estimates of surface temperature are potentially valuable inputs to constrain the surface energy budget over data-sparse areas in re-analyses. Similarly, SAR and passive microwave observations can enhance land surface descriptions in re-analyses. Atmospheric retrievals of temperature and moisture amount are challenging problems over sea ice, yet reliable retrievals could provide important constraints on the reanalyzed atmospheric circulation in data-sparse areas such as the Arctic Ocean and the interior of Antarctica. A vigorous research program to optimize the uses of polar satellite-derived products in re-analyses will do much to eliminate concerns that polar remote sensing observations suffer from isolation and lack integration into the global context. Such an activity will also enhance the relevance of the measurements to the broader ESE program and hence to societal issues.

In addition to data assimilation activities, there are a number of other ways in which the committee believes that NASA can improve its current contributions. First, NASA could enhance the use of its products by polar users by sponsoring evaluation and intercomparison activities directed specifically at polar sub-sets of its global products. Candidates are products depicting clouds, surface temperature, surface winds, sea ice, and land surface characteristics. These should be assessed from the standpoint of providing consistent quantification of key biogeophysical variables that are bound by mass and energy balance constraints.

The development and application of integrated multi-instrument (infrared, passive microwave, radar) analysis methods would enhance the value of products depicting such variables as surface temperature, surface albedo, wetland extent, and indices of melt occurrence from older satellite data sets and in preparation for NPP and NPOESS missions.

If high-latitude terrestrial products are successfully validated, NASA can greatly facilitate studies of global polar hydrologic interactions by developing global data sets of such land surface variables as vegetation distribution, soil moisture, evapotranspiration, and precipitation.

Many measurements are needed to model high-latitude CO_2 and CH_4 fluxes and to assess the forces that affect these variables. The needed quantities include land surface temperature, precipitation, evapotranspiration, photosynthetically active radiation, soil moisture, biomass, leaf area index, and land surface characteristics. Although some of the variables are already being measured by remote-sensing techniques, these data sets need to be evaluated to determine whether they are adequate for high-latitude applications. Many of the satellite-derived data sets required for estimating terrestrial CO_2 and CH_4 fluxes are still not available in the scientific community. It is recognized that the data stream activity related to the Earth Observing Systems TERRA and AQUA missions has been designed to provide data sets in a timely manner to the scientific community; however, as these missions have a global focus, NASA needs to support evaluations of the adequacy of these products for high-latitude applications.

A particular challenge surrounds the validation of spaceborne estimates of precipitation, when the accurate measurement of precipitation in polar regions using traditional gound-based monitoring remains so problematical. Gage undercatch and interpolation bias are well-known problems in many parts of the globe, but especially in high latitudes. A dedicated effort by NASA to help reconcile the land and space-based estimates would constitute an important enhancement to its current activities in this arena.

The committee was struck by the multitude of sea ice data sets, especially for ice concentration and, to a lesser extent, ice motion. In the case of sea ice concentration, NASA should help to clear up the confusion about similar data sets by funding independent studies to (1) document the strengths and weaknesses of different algorithms and (2) facilitate the construction of longer time series by the merger of individual sensor data sets. Further work is also recommended on the determination of summer ice concentration. Comparative assessments of sea ice motion data sets would also be prudent as soon as the record lengths of the various data sets (e.g., from the AMSR) are sufficient to permit meaningful comparisons.

Surface temperatures over terrestrial and ocean regions are needed for a variety of applications, including turbulent flux determinations, freeze and thaw mapping, and controls on trace gas fluxes. NASA can take steps to enhance surface temperature data sets by supporting programs that measure in situ SST (particularly surface temperature) in high latitudes. Regional calibrations in high latitudes should also be encouraged as part of global temperature products. This has been proposed but not implemented for Arctic waters as part of the AVHRR polar Pathfinder Project. This Pathfinder Project has also created a preliminary integrated surface temperature data set that includes ocean, ice, and land, but only for the polar regions. This type of activity should be strongly encouraged on a global basis.

The terrestrial hydrology, ocean modeling, and ice sheet research communities have all expressed the need for high-latitude precipitation data sets. Polar rainfall and snowfall, which are not measured with adequate spatial and temporal coverage, represent a major missing piece in the climate puzzle. NASA would make a major contribution if it could find a way to remotely sense this quantity in polar regions.

Another major contribution would be the measurement of ocean surface salinity at high latitudes. This quantity links the ocean, air, and land surfaces via the hydrologic cycle. Variations in this quantity are a key indicator of climate variability and ocean circulation. Much of the justification for upcoming international satellite missions to measure ocean salinity concerns high latitude processes. Unfortunately, the measurement precision by satellites in these regions is expected to be inadequate for climate studies. Interim aircraft-based studies might help in sensor and algorithm development.

The five-year changes measured by aircraft laser altimeter in Greenland show extensive thinning at the ice sheet margin; more work on ice flow and melt processes is necessary to understand the origins and implications of this signal. NASA has demonstrated capabilities in

Greenland for measuring ice sheet surface elevation and thickness. This ability, if combined with present efforts at detecting the distribution of shallow layers to understand the spatial variations in accumulation, could produce an unmatched tool for completing the ice thickness map of Antarctica. Tying measurements from an accumulation radar to shallow core sites where background rates and variability have been determined in both Greenland and Antarctica would greatly enhance efforts to determine appropriate forcing for ice sheet models.

Altimetry offers the most promising approach to sea ice thickness mapping for change detection; this approach is the subject of an upcoming European Space Agency mission. The utility of ICESAT data for this application needs to be investigated, along with integrated approaches that use altimetric and ice motion time series, such as AVHRR and RGPS methods in the still exploratory stages. Validation and error analysis for these products should be pursued in an integrated manner as well.

NASA has no plans for a polar radar altimeter to measure ocean surface elevation beyond the latitudinal range of Topex-Poseidon. NASA should consider participation in future high-latitude radar altimetry programs, perhaps in conjunction with the satellite agencies of other nations.

Finally, the Earth Science Enterprise research activities of the polar community will be limited by the lack of appropriate SAR coverage, which may require a U.S. SAR. Many of the recent NASA-funded advances in cryospheric research have come from interferometric analysis of time series of SAR data. The processes that are studied are time-variable and so require relatively frequent repeat observations. Both sea ice and ice sheet research will suffer without access to SAR data acquired at appropriate intervals. The absence of a U.S. SAR satellite and/or MOUs with entities flying SARs is of great concern to the polar ocean and ice sheet communities.

5

Conclusions and Recommendations

The National Research Council charged the Committee on NASA's Polar Geophysical Data Sets to review NASA's strategy for providing derived geophysical data sets to the polar science community. The committee was asked to provide a brief review of the strategy, scope, and quality of existing polar geophysical data sets; suggest ways to make these products and future polar data sets more useful to researchers; and consider whether the products are reaching the appropriate communities. This chapter summarizes the lessons learned in earlier chapters and provides recommendations, where possible, to guide future development of NASA and other polar data sets. The committee's conclusions and recommendations are consensus opinions based on the members' expertise and experience, and derived from committee deliberations, conversations with invited speakers (including our NASA liaison and liaisons from each of the DAACs and their user groups), analysis of the survey responses, and review of available literature.

The committee's conclusions and recommendations fall into three categories:

1. key data gaps and the highest priorities for measurements needed in the context of the polar variations of NASA's Earth Science Enterprise (ESE) science-driving questions;
2. the general NASA strategy for enhancing and providing relevant data sets to the polar science community;

3. issues relating to the effectiveness of the Distributed Active Archive Center (DAACs) and their data distribution activities.

DATA GAPS AND MEASUREMENT NEEDS

Table 3-1 compared the science-driving questions to the types of measurements needed to address the questions and Chapter 4 then assessed available data sets and whether they are adequate to fully support the ESE. Chapter 4 then concluded with a discussion of specific measurements that would enhance NASA's present and future contributions to ESE science. In this section, the committee presents its view of the highest priorities for measurement in the cryosphere[1] and data set assessment based on (1) previously identified gaps between data needs and availability; (2) the potential scientific payoffs if these gaps are filled; and (3) the feasibility and likelihood of significant progress over the next several years. The measurements identified here are generally the ones that appear repeatedly in Table 3-1, but are currently lacking or deficient in ways that present significant obstacles to progress on the fundamental ESE science issues. These 10 high-priority measurements are:

- polar precipitation,
- surface albedo,
- freshwater discharge from terrestrial regions,
- all-sky surface temperature,
- surface turbulent fluxes,
- permafrost,
- ocean surface salinity,
- ice sheet mass flux,
- land surface characteristics, and
- sea ice thickness.

In some cases, products that appear to be lacking (e.g., surface radiation fluxes) are under development with current sensors, so these are not included in this list. For all variables, the need is for data sets sufficient to determine the spatial and temporal variations. For those variables deemed suitable for monitoring, temporal continuity across instruments must be a key consideration.

[1]The committee's deliberations and this list of 10 high priority measurements focuses directly on the cryosphere (i.e., surface characteristics) and the fluxes that determine cryospheric characteristics.

- **Polar Precipitation—**NASA should attach high priority to testing and flying appropriate sensors to measure precipitation, especially in its frozen form, in the polar regions. High-latitude precipitation data sets are needed by many segments of the research community; polar snowfall and rainfall represent a major gap in the polar geophysical database. Key needs include space-time distributions of precipitation rates for moisture budget determinations. Existing sensors (e.g., millimeter-wavelength radiometers) cannot measure precipitation over ice and snow surfaces. For uses in surface budget and hydrologic applications, fields should include the precipitation rate and the water equivalent of snow. Over ice sheets, airborne ice-penetrating radar can measure accumulation layers for information about longer timescales. It will be a challenge to identify unbiased precipitation data sets and reconcile land- and space-based measurements. Land-based station gauges suffer from well-known problems of under-measurement, particularly for solid precipitation under windy conditions. Interpolation in data-sparse regions, such as the high latitudes, also creates biases related to topography and coastal proximity.

- **Surface Albedo—**Fields of surface albedo must capture the progression of melt and freeze-up over spatial and temporal scales adequate for surface energy budget evaluations and for forcing and validation of models. Meeting this objective also requires surface temperature measurements with similar time and spatial resolution. Effects of sub-grid heterogeneities must be included in grid-cell averages. Recently launched instruments that measure in the visible spectrum show promise for determining (clear sky) surface spectral albedo at appropriate resolution. Focused and careful evaluation of these products over snow and ice surfaces is required.

- **Freshwater Discharge from Terrestrial Regions—**Needed quantities include lateral fluxes of freshwater to polar oceans from ice sheets and glaciers (including runoff and ice discharge) as well as surface and sub-surface runoff from non-glaciated land areas. The deterioration of surface monitoring networks adds to the urgency of exploring new satellite techniques (although it may be more economical to support the surface monitoring networks). Telemetry of gauge measurements should be feasible. Accurate discharge measurements are also required to estimate transport of land-derived materials into coastal and ocean ecosystems.

- **Surface Temperature—**The wide variety of applications of surface temperature data makes all-sky measurements a high priority. Routine measurements under cloudy skies are needed to eliminate the clear-sky bias in existing satellite-based surface temperature data sets. NASA can take steps to enhance surface temperature data sets by supporting programs that measure in situ temperatures in high latitudes. NASA should work to develop multisensor analysis approaches that combine microwave, infrared, and radar measurements, as this approach could provide improved surface temperature products in preparation for the NPP and NPOESS missions. Calibrations accurate at the extreme conditions found in high latitudes should also be encouraged as part of efforts to generate products dealing with global temperature.

- **Surface Turbulent Fluxes—**Sensible and latent heat fluxes are needed over all polar surfaces. Impediments to progress are the lack of all-sky fields of surface temperature, surface moisture availability, and surface winds over land and ice. Satellite-derived near-surface air temperatures and relative humidities (from NPOESS) are most likely 10 years away. While waiting for more direct measurements, NASA can support analyses using existing multisensor data sets to obtain estimates of all-sky temperatures and albedo (i.e., surface radiative fluxes) and use re-analyses to infer winds and other variables as possible.

- **Permafrost—**Needed variables are the extent of permafrost, depth of permafrost, vertical temperature profiles and timing of thaw and freeze-up of active layer. Current technologies show some promise, and efforts could be made to exploit existing sensors (e.g., scatterometers). These sensors have been designed for other purposes, however, and their configurations will need to be optimized for permafrost. Some permafrost variables will likely require multiple-sensor products. For example, an analysis combining radar backscatter, passive microwave, and infrared measurements could significantly enhance present capabilities in permafrost mapping. NASA should support experimental multisensor analyses.

- **Ocean Surface Salinity—**For polar regions, key requirements include high-to-moderate (10 km or finer) resolution for coastal and ice edge environments and good performance in near-freezing temperatures. Existing and proposed sensors have inadequate resolution and accuracy for polar regions; further technical development is necessary.

- **Ice Sheet Mass Flux (Accumulation, Ablation, and Ice Discharge)—**The key needs related to ice sheet mass flux are for continued measurement and interpretation to understand the variability introduced by ice accumulation and ablation, both temporally and spatially. The NASA PARCA Program has clearly shown the utility of laser altimeter measurements for detecting changes in large ice sheets; ICESAT will make these measurements over both ice sheets and smaller ice caps on an operational basis. The interpretation of these measurements requires an understanding of the variability introduced by accumulation and ablation, both temporally and spatially. Airborne broadband radar measurement of internal layers tied to ice cores can provide a view of the spatial patterns of recent accumulation, while measurement or estimation of ablation rates near the ice sheet margin will require a new multifaceted approach. Interferometric studies of outlet glaciers have shown evidence of rapid change in both Greenland and Antarctica; improved Synthetic Aperture Radar (SAR) data acquisition and access, as well as airborne radar measurement of ice thickness in these drainages is required to determine changes in ice sheet mass.

- **Land Surface Characteristics—**Particular needs to increase understanding of land surfaces include information for the monitoring of changes in wetland extent and for quantitative determinations of the severity of disturbance. Required measurements are leaf area index, water storage, canopy density, structural composition of vegetation, disturbance characteristics at resolution sufficient to capture seasonal timing of disturbance events and the interannual and decadal variation in disturbance frequency. Such data sets have been produced for other regions of the globe; particular effort is needed to produce and evaluate them for polar land areas. Effort should be made to develop pan-Arctic products spanning the past 20 years. Research is under way using existing sensors; calibration and validation is needed.

- **Sea Ice Thickness—**Routine measurements of sea ice thickness require development of remote-sensing techniques beyond those required for mapping ice age and type. New altimeter techniques show some promise and should be encouraged, especially in view of the large recent changes in sea ice mass implied by small samples of in situ data in both hemispheres. Products must be compatible with those obtainable from aircraft, submarines, and the network of moored sonars.

NASA'S GENERAL STRATEGY ON POLAR DATA SETS

The committee strongly believes that measurements should not be made in isolation and that there is a need for across-sensor and across-variable evaluations to be an integral part of remote-sensing activities. In addition, the committee found a pervasive need for evaluations and documentation of the accuracy of existing data sets (e.g., cloud, snow, and sea ice products). These themes are common to several of the following recommendations.

• In several respects polar data sets have been isolated from global data sets in the overall NASA data set framework. Examples are the global satellite-derived atmospheric temperature data sets and global sea surface temperature data sets versus the TOVS vertical profiles and the POLES surface air temperatures. **The committee recommends that NASA make efforts to integrate polar data sets and global data sets in the architecture of the NASA data distribution system.**

• The committee was struck by the multiplicity of data sets available for some polar variables. Cloud products, sea ice coverage, and sea ice motion are examples. **The committee recommends that NASA support systematic comparisons of different versions of the same product, including calibration and validation activities, the establishment of error bars, and the merger or consolidation of data sets depicting the same variables.** This activity should include the determination of needs for (1) ground-based validation sites in addition to those planned for EOS; and (2) additional field campaigns directed at validation of remote sensing products.

• In general, satellite sensors and products have not been optimized for polar regions. Examples include those used for precipitation estimation, determination of cloud properties, and sea surface salinity. **The committee recommends that NASA give higher priority to sensor optimization for polar applications.**

• For some of the variables listed in the preceding section, alternative measurement approaches may be more appropriate than reliance on satellite products. Alternative and complementary approaches could include aircraft (manned and unmanned), automated underwater vehicles, and other ground-based measurements. **The committee recommends that NASA explore such alternatives from a cost-benefit perspective in the planning and design of its polar programs.**

• There is a need for enhanced interaction and feedback between modelers and data providers. This interaction can occur to some extent through data assimilation activities. There is often, however, a disconnect between modelers' needs for forcing and validation data sets and the products derived from remote sensing. **The committee recommends that NASA strengthen the connection between modeling and its remote-sensing strategy for the polar regions.**

• **The committee recommends that NASA support research to determine optimum uses of polar remote sensing measurements in**

re-analyses so these measurements are better integrated into a global context, thereby enhancing their value to ESE and reducing their insularity. For the broadest impact, this activity should entrain, in the earliest stages, the two leading global re-analysis centers, NOAA/NCEP and ECMWF.

• Consistency within and among data sets is a necessary prerequisite for detecting, with a known degree of certainty, the effects of climate change on high-latitude systems. Such an effort would also enhance the interaction of modelers and data providers and constitute an important framework activity for developing and testing new sensor designs. **The committee recommends that NASA give high priority to fostering the development of spatially and temporally coherent, internally consistent polar geophysical data sets.**

• Finally, the continued use of satellite-derived data sets in intercomparison and synthesis activities, such as those described above, argues for the long-term archiving of satellite data sets within the NASA data distribution system. **The committee considers the DAACs to be the natural vehicles for long-term archival, and we recommend that long-term archival be a DAAC function.**

EFFECTIVENESS OF THE DISTRIBUTED ACTIVE ARCHIVE CENTERS

As a result of its deliberations—including consideration of the 1998 National Research Council report, *Review of NASA's Distributed Active Archive Centers*, conversations with DAAC managers and representatives of associated user groups, and a survey of the science community—the committee learned much about the effectiveness of the polar-oriented DAACs. Unlike the recommendations in the two preceding sections, the following recommendations pertain specifically to the polar DAACs.

• **Redundancies—The committee recommends that NASA support quantitative evaluations of possibly redundant data sets to help provide a rational basis for decisions about discontinuing certain data sets.** The results of coordinated evaluations should be used by the DAACs to minimize redundancies in their holdings and to streamline their distribution responsibilities.

• **Outreach—**The survey responses showed a surprising lack of unawareness of the availability of holdings of the DAACs. **The committee recommends that the DAACs increase the efforts to disseminate and**

publicize their holdings, particularly among investigators who are not involved in large NASA programs, as well as provide overview documentation of the broad spectrum of data sets available at a site.

- **Links—With regard to the distribution of data products by the DAACs, the committee recommends that the DAACs install more extensive web links to other global products that contain polar data, with brief descriptions of the holdings in the sites.** These "pointers" should include available information about data sources, quality, and limitations, specific to the polar regions. This information can be provided through literature references or through DAAC-initiated assessments.

- **Improvements in Tools—The committee recommends that data set providers document their individual holdings more effectively, and also provide overview documentation of the broad spectrum of data sets available at their site.** The addition of browse products to data sets would help users unfamiliar with the data to judge the utility of the data set for their uses. To help overcome obstacles faced when trying to combine data sets from different sensors, data set providers should increase availability of user-friendly software tools to help with tasks such as converting from one format to another and among standard grid formats. Attention should also be given to the issue of changing technology so that archived data will remain readable with future technologies.

- **Feedback—The committee recommends that data set providers offer additional opportunity for community feedback via the creation of web bulletin boards where users may comment on their experience using data at that site.** This will encourage a more coherent user community, thereby facilitating the solution of problems by users without direct intervention by the data site provider.

- **P-I Web sites—The committee recommends creation of an archive of principal investigator-generated websites containing relevant data sets or information about these data sets.** This type of archive will complement the data distribution activities of the DAACs and will enhance their utility as information resources for the polar community.

- **Alaska SAR Facility—**While ASF received expressions of both praise and frustration from our survey respondents, the use of ASF products has been limited by data product availability, by costs, by ease of access, and by access and distribution restrictions. There has been some recent improvement in access to SAR products. Nevertheless, we share the concern of the 1998 DAAC review and reiterate the need to facilitate access to and utilization of ASF products. **In particular, the committee recommends that ASF become more proactive in the assembly of pan-Arctic data sets.**

References

Arctic Research Consortium of the United States. 1997. People and the Arctic: A Prospective for Research on the Human Dimensions of the Arctic System (HARC Prospectus). Fairbanks, Alaska: Arctic Research Consortium of the United States.

Barry, R. G., ed. 1998. Proceedings of a Meeting of Experts on Cryosphere and Climate, February 3-5, 1997. WCRP-102, WMO/TD-No. 867. World Climate Research Programme, Cambridge, U.K.

Bromwich, D.H., R.I. Cullather, and M.L. van Woert. 1998. Antarctic precipitation and its contribution to the global sea-level budget. *Annals of Glaciology* 27:220-226.

Cavalieri, D.J., P. Gloersen, C.L. Parkinson, J.C. Comiso, and H.J. Zwally. 1997. Observed hemispheric asymmetry in global sea ice changes. *Science* 278:1104-1106.

Curry, J.A., W.B. Rossow, D. Randall, and J.L. Schramm. 1996: Overview of Arctic cloud and radiation characteristics. *Journal of Climatology* 9:1731-64.

Emery, W.J., D.J. Baldwin, P. Schlussel, and R.W. Reynolds. 2001. Accuracy of in situ sea surface temperatures used to calibrate infrared satellite measurements. *Journal of Geophysical Research.*

Frolking, S., K.C. McDonald, J.S. Kimball, J.B. Way, R. Zimmermann, and S.W. Running. 1999. Using the space-borne NASA scatterometer (NSCAT) to determine the frozen and thawed seasons of a boreal landscape. *Journal of Geophysical Research* 104(D22):27895-907.

Giovinetto, M.B., D.H. Bromwich, and G. Wendler. 1992. Atmospheric net transport of water vapor and latent heat across 70ºS. *Journal of Geophysical Research* 97(D1):917-930.

Houghton, J.T., and L.G.M. Filho, B.A. Callandar, N. Harris, A. Kattenberg, and K. Maskell (eds.). 1996. Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, U.K.

Houghton, J.T., L.G. M. Filho, B.A. Callandar, N. Harris, A. Kattenberg, and K. Maskell (eds.) 1996. Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change, Scientific-Technical Analysis. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, U.K.

Kwok, R. 2000. Recent changes in Arctic Ocean sea ice motion associated with the North Atlantic Oscillation. *Geophysical Research Letters* 27:775-78.

Lindsay, R.W., Y. Yu, H.L. Stern, D.A. Rothrock, and R. Kwok. 2000. RADARSAT geophysical processor system products: Evaluation and validation. Available online at <http://psc.washington.edu/RGPS/validation>. Accessed December 18, 2000.

Miller, J.L. 2000. Airborne remote sensing of salinity, Backscatter, summer, pp. 24-27.

NASA (National Aeronautics and Space Administration). 1988. Earth System Science, A Program for Global Change. Report of the Earth System Sciences Committee. National Aeronautics and Space Administration, Washington, D.C.

NASA. 1998. Catalog of Data Sets and Services Available from the EOS Distributed Active Archive Centers (DAACs). Washington, D.C.: National Aeronautics and Space Administration.

NASA. 2000. What is the Earth System Enterprise? Available online at <http:www.earth.nasa.gov/whatis/index.html>. Accessed December 18, 2000.

NRC (National Research Council). 1998. *Review of NASA's Distributed Active Archive Centers.* National Academy Press, Washington, D.C.

Peixoto, J.P., and A.H. Oort. 1992. *Physics of Climate*. American Institute of Physics, New York.

Prigent, C., W.B. Rossow, and E. Matthews. 1997. Microwave land surface emissivities estimated from SSM/I observations. *Journal of Geophysical Research* 102:21867-890.

Rignot E., and J.B. Way. 1994. Monitoring freeze-thaw cycles along north-south Alaskan transects using ERS-1 SAR. *Remote Sensing Environment* 49:131-37.

Rossow, W.B., and R.A. Schiffer. 1999. Advances in understanding clouds from ISCCP. *Bulletin American Meteorological Society* 80:2261-87.

Rossow, W.B., and Y-C. Zhang. 1995. Calculation of surface and top-of-atmosphere radiative fluxes from physical quantities based on ISCCP data sets. Part II: Validation and first results. *Journal of Geophysical Research* 100:1167-97.

Running, S.W., J.B. Way, K. McDonald, J.S. Kimball, A.R. Keyser, S. Frolking, and R. Zimmermann. 1999. Recent advances in the use of satellite radar data to monitor freeze/thaw transitions in boreal regions. *EOS* 80(19):213-21.

Secretariat of the American Geophysical Union. 1999. The Arctic Paleosciences in the Context of the Global Change Research–PARCS, Paleoenvironmental Arctic Sciences, Earth System History. American Geophysical Union, Washington, D.C.

White, M.A., and K.J. Heywood. 1995. Seasonal and interannual changes in the North Atlantic subpolar gyre from Geosat and TOPEX/POSEIDON altimetry. *Journal of Geophysical Research* 100:24931-941.

World Climate Research Programme. 1991. Scientific Concept of the Arctic Climate System Study (ACSYS). WMO/TD-No. 486. World Climate Research Programme, Cambridge, U.K.

WCRP (World Climate Research Programme). 1994. Arctic Climate System Study (ACSYS): Initial Implementation Plan. WCRP-85, WMO/TD-No. 627. World Climate Research Programme, Cambridge, U.K.

WCRP (World Climate Research Programme). 2000. Climate and Cryosphere Initiative (CliC).

APPENDIX A

Acronyms and Initialisms

ACSYS	Arctic Climate System Study
ADEOS-II	Japan's Advanced Earth Observing Satellite II
AHAP	Alaska High-Altitude Aerial Photography
AIRS/AMSU	Atmospheric Infrared Sounder/Andvanced Microwave Sounding Unit
AMM-2	Antarctic Mapping Mission 2 – Radarsat mapping devoted to interferometry
AMSR-E	Advanced Microwave Scanning Radiometer E
AQUA	NASA's second Earth Observing System Platform (TERRA is the first)
ARCSS	Arctic System Science
ARM	Atmospheric Radiation Measurement (DOE Archive)
ASF	Alaska SAR Facility
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATSR	Along-Track Scanning Radiometer on ERS-1
AVHRR	Advanced Very High-Resolution Radiometer
AVNIR	Advance Visible and Near-Infrared Radiometer
AWS	Automated Weather Station
BALTEX	Baltic Sea Experiment (A GEWEX continental scale experiment)
BEDMAP	project collecting all ice thickness data of Antarctica
BOREAS	Boreal Ecosystem-Atmosphere Study

BSRN	Baseline Surface Radiation Network
CIRES	Cooperative Institute for Research in Environmental Sciences
CLIC	Climate and Cryosphere program
CRYOSAT	European mission to measure sea ice using interferometry starting in 2002
DAAC	Distributed Active Archive Center
DISP	Defense Intelligence Satellite Program
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
ECMWF	European Center for Medium-range Weather Forecasts
ENSO	El Nino Southern Oscillation
ENVISAT	European multi-sensor satellite, follow on to the ERS satellites
EOS	Earth Observing System
EOSDIS	Earth Observing System Data and Information System
ERBE	Earth Radiation Budget Experiment
EROS	Earth Resources Observations Systems
ERS	European Earth Remote Sensing Satellite
ESA	European Space Agency
ESE	Earth Science Enterprise (NASA)
FIRE-ACE	First ISCCP Regional Experiment – Arctic Cloud Experiment
FLUXNET	Global CO_2 Flux Network
FY	Fiscal Year
GEOSAT	US Navy satellite that measures sea surface height with radar altimeter
GEWEX	Global Energy and Water Cycle Experiment
GISP2	Greenland Ice Sheet Project 2
GLAS	Geoscience Laser Altimeter System
GlI	Global Imager
GOES	Geostationary Operational Environmental Satellite
GPCP	Global Precipitation Climatology Project
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GTOPO30	Global 30 Arc-Second Elevation Data Set
GVAP	Global Water Vapor Project
HARC	Human Dimensions of the Arctic System

HIRS	High-Resolution Infrared Sounder
ICESAT	NASA Ice, Cloud, and land Elevation Satellite
IKONOS	A 1-2 m resolution commercial satellite
ILAS	Improved Limb Atmospheric Spectrometer
IMG	Interferometric Monitor for Greenhouse Gases
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land Surface Climatology Project
JERS	Japanese Earth Remote-Sensing Satellite
JPL	Jet Propulsion Laboratory
LAII	Land-Atmosphere-Ice-Interactions
LANDSAT	A series of US satellites carrying visible, near-IR, and thermal IR imagers
LMD	Laboratoire de Meteorologie Dynamique
MAGS	Mackenzie GEWEX Study
MISR	Multi-angle Imaging Spectroradiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MOU	Memorandum of Understanding
MSU	Microwave Sounding Unit
MTPE	Mission to Planet Earth (renamed Earth Science Enterprise)
NAO/AO	North Atlantic Oscillation/Arctic Oscillation
NASA	National Aeronautic and Space Administration
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar Orbiting Environmental Satellite System
NPP	NPOESS Preparatory Project
NSCAT	NASA Scatterometer
NSIDC	National Snow and Ice Data Center
NSF	National Science Foundation
OAII	Ocean-Atmosphere-Ice-Interactions
OCTS	Ocean Color and Temperature Scanner
PALE	Paleoclimates of Arctic Lakes and Estuaries
PAR	Photosynthetically Active Radiation
PARCA	RadarSat Antarctic Mapping Project, Snow and Hydrology Group, Program for Arctic Climate Input Assessment

PARCS	Paleoenvironments of the Arctic System
PBL	Planetary Boundary Layer
PO.DAAC	Physical Oceanography DAAC (JPL)
POLDER	Polarization and Directionality of Earth's Reflectances
POLES	Polar Exchange at the Sea Surface
PI	Principal Investigator
PROBA	Project for On-Board Autonomy
PSU	Practical Salinity Units
QSCAT	NASA's Quick Scatterometer
RADARSAT	Canadian Synthetic Aperture Radar Satellite
RAMP	RADARSAT Antarctic Mapping Project
RGPS	RadarSat Geophysical Processing System
SAR	Synthetic Aperture Radar
SASS	Subsonic Assessment
ScaRab	Scanner for Radiation Budget
SEASAT	Sea Satellite
SEAWIFS	Sea-Viewing Wide-Field-of-View Sensor
SHEBA	Surface Heat Budget of the Arctic project
SIMS	Synthesis, Integration, and Modeling Project of NSF-ARCSS
SMMR	Scanning Multichannel Microwave Radiometer
SMOs	Soil Moisture and Ocean Salinity
SPOT	Satellite por l'Observation Terre (French earth observation satellites)
SRB	Surface Radiation Budget
SSH	Sea Surface Height
SSM/I	Special Sensor Microwave/Imager
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
T/P	NASA-ERS Topex/Poseidon Satellite
TERRA	NASA's Earth Observing System first multi-sensor platform
TIROS	Television Infrared Observing Satellite
TOA	Top of Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOVS	TIROS-N Operational Vertical Sounder
WCRP	World Climate Research Program
WDC	World Data Center
WMO	World Meteorological Organization

Appendix B

Data Sets Survey

RESPONSES TO THE COMMITTEE'S SURVEY

To gather input from the polar science community, the committee developed a questionnaire[1] on the strengths and weaknesses in the current data system (the questionnaire follows at the end of this appendix). Scientists were asked to characterize their research in terms of scientific and regional foci. This was followed by a list of polar geophysical data sets from NASA and non-NASA sources that respondents could mark if they used them in their research. The final four questions dealt with satisfaction issues.

The committee received 109 responses from a variety of university, governmental, and private industry institutions. Foreign respondents numbered 22. The number of scientists who identified their research focus as exclusively Arctic was 48, exclusively Antarctic 20, and global 41. The latter category generally denoted those with both Arctic and Antarctic interests (there were few responses from those who study more temperate regions).

Although the survey provided six categories of research focus, a large number of respondents chose "other." Many of these would have marked

[1]Although the survey provided useful information, it should not be considered a statistically rigorous study. Its availability was widely announced, but participants were self-selected. The information was used in a general way to help the committee form its conclusions and recommendations.

more than one research category, if that option had been allowed. Others were in categories that were not listed (e.g., hydrology). The committee's response was to create several new research focus categories that better reflect the disciplines of most respondents who marked "other." Multiple choices were also allowed. The resulting breakdown of research foci in Table B-1.

"Sea ice or ocean" researchers were the most frequent respondents, more than double the next category. "Ice sheets or sea level" researchers were the second most frequent respondents. These category names are somewhat misleading, however, since very few oceanographers responded to this survey. This begs the question, "Where do high latitude oceanographers seek support?" The answer is in a variety of global and other programs. This may serve to enhance cross-latitude oceanography at NASA, but it also limits cross-disciplinary research in the polar community. An example of this situation is the lack of coherent surface-temperature data sets that include open water and other surfaces (i.e., ice, snow, land).

Table B-2 shows the breakdown of "types of research data sets used" by the survey respondents, broken down by whether they use only NASA data sets or some combination of data supplied by NASA and others. These two lists are fairly similar, perhaps showing that NASA is generally

TABLE B-1 Areas of Primary Research Focus as Indicated by Survey Respondents

Research Focus	Number of Respondents
Sea ice/ocean	41
Ice sheets/sea level	20
Terrestrial—physics, hydrology, and land-atmosphere linkages	13
Terrestrial—biology and biogeochemistry	9
Terrestrial—physical and biology	4
Other	6
Atmospheric circulation, planetary boundary layers, climate, and upper air studies	3
Clouds/radiation	3
Sea ice/oceans, atmospheric circulation etc.	3
Sea ice/oceans and terrestrial—biology	2
Glaciers	2
Snow cover	2
Sea ice/oceans and terrestrial—physics	1
TOTAL	109

TABLE B-2 Types of Data Most Commonly Used by Survey Respondents

NASA and Non-NASA		NASA Only	
Types of Data	Number of Respondents	Types of Data	Number of Respondents
Atmospheric	185	Sea Ice	81
Sea Ice	131	Atmospheric	51
Radiance and Backscatter	82	Radiance and Backscatter	37
Imagery (Visible and IR)	78	Imagery (Visible and IR)	24
Ice Sheet	63	Vegetation	15
Snow Cover	56	Ocean	16
Ocean	48	Ice Sheet	14
Vegetation	38	Snow Cover	13
Glaciers	21	Glacier	11
Hydrology	18	Hydrology	7

responding equitably to data needs by discipline, although there are some specific gaps and deficiencies to be discussed elsewhere in this report. Also note that the frequency of research foci (Table B-1) is not in general the same as the frequency of data sets used (Table B-2). For example, one of the most frequently used type of data is atmospheric, although relatively few respondents identified themselves as meteorologists. This shows how some types of data sets can easily cross disciplines. It may also identify the potential underuse of data, for example, by global-scale atmospheric scientist).

Turning to the final four questions, the respondents were generally positive about the current data system. The ASF and especially the NSIDC were complimented on the quality of their service. NSIDC was singled out for its simple, easy-to-use Web site, and for its willingness to provide data by Internet before a final CD was published.

About 25 percent of the respondents had negative comments. These fell into two broad categories: inadequate publication of available data sets and difficulty of access or use of data sets. Those who were simply unaware of existing data sets were more frequently (but not exclusively) new to the field or from more isolated institutional environments; however, even experienced researchers had problems. Some of these problems could be relieved by more extensive linking of data set Web sites. Several responses were from heavy users of the NSDIC and the ASF who did not know that these were DAACs. Perhaps the heavy reliance on acronyms and other NASA jargon can discourage and thus limit usage of data sets.

In the survey responses, it appeared that a broad spectrum of users (including DAAC employees) experienced data access problems. Even experienced researchers noted some difficulty with the formatting of data. Insufficient documentation of individual data sets was also noted as a problem by some survey respondents, in regards to time and space resolution, data format, and sensor information. Similar concern was expressed about insufficient overview guidance for DAAC holdings, which is standard information that typically should appear on or near the main home page. Recommendations for NASA data set providers to help improve the utility of existing data sets are included in Chapter 5. Opportunities for improvement lie in the areas of links to other related data sites, outreach to more aggressively publicize activities and holdings, improvements in access through better documentation, and opportunities for community feedback and information exchange, such as via Web bulletin boards.

QUESTIONNAIRE

Under the auspices of The National Academies' Polar Research Board and at the request of NASA, a committee is reviewing the strategy, scope, and quality of existing polar geophysical data-sets and suggesting ways to improve future products. The committee's charge and a list of its members can be seen here. As part of this effort, the committee is seeking input from scientists who use these types of data-sets, whether those produced by NASA or others with similar purposes. The committee will keep your comments confidential, so we appreciate your frankness in describing the strengths and weaknesses of current data-sets and dissemination strategies.

Name:

Affiliation:

Brief description of your research (1-2 Sentences):

1. Which of the following scales best describes your research:

- ❏ Arctic
- ❏ Antarctic
- ❏ Global

2. Which of the following areas best describes the focus of your research:

- ❏ Sea Ice/Oceans
- ❏ Ice Sheets/Sea Level
- ❏ Clouds/Radiation
- ❏ Terrestrial—Biology and Biogeochemistry Related
- ❏ Terrestrial—Physics and Land-Atmosphere Linkages
- ❏ Other—please specify:

3. What NASA geophysical data-sets and products relevant to polar regions do you use in your research and for what purposes? What other geophysical data-sets (e.g., global, international, or other U.S. sources) do you use and for what purposes? Please mark the following checklist and note the specific products you use in the text boxes provided.

Sea Ice

Concentration
- ❑ NASA
- ❑ Other

What specific product?

Ice Type
- ❑ NASA
- ❑ Other

What specific product?

Ice Motion
- ❑ NASA
- ❑ Other

What specific product?

Other
- ❑ NASA
- ❑ Other

What specific product?

Snow Cover

Areal Average
- ❑ NASA
- ❑ Other

What specific product?

Water Equivalent
- ❑ NASA
- ❑ Other

What specific product?

Albedo
- ❑ NASA
- ❑ Other

What specific product?

Other
- ❑ NASA
- ❑ Other

What specific product?

Ice Sheet

Elevation (Altimeter data)
- ❏ NASA
- ❏ Other

What specific product?

Surface Meteorology
- ❏ NASA
- ❏ Other

What specific product?

Ice Core Data
- ❏ NASA
- ❏ Other

What specific product?

Other
- ❏ NASA
- ❏ Other

What specific product?

Glacier Data

- ❏ NASA
- ❏ Other

What specific product?

Atmospheric Data

Cloudiness
- ❏ NASA
- ❏ Other

What specific product?

Radiative Fluxes
- ❏ NASA
- ❏ Other

What specific product?

Surface Temperature
- ❏ NASA
- ❏ Other

What specific product?

Precipitation
- ❑ NASA
- ❑ Other

What specific product?

Temperature Profiles
- ❑ NASA
- ❑ Other

What specific product?

Moisture Profiles
- ❑ NASA
- ❑ Other

What specific product?

Other
- ❑ NASA
- ❑ Other

What specific product?

Ocean Data

SST
- ❑ NASA
- ❑ Other

What specific product?

Color
- ❑ NASA
- ❑ Other

What specific product?

Other
- ❑ NASA
- ❑ Other

What specific product?

Hydrology

Streamflow/Runoff
- ❑ NASA
- ❑ Other

What specific product?

Soil Moisture
- ❏ NASA
- ❏ Other

What specific product?

Vegetation Data

Vegetation Classification
- ❏ NASA
- ❏ Other

What specific product?

Indicies of Biomass
- ❏ NASA
- ❏ Other

What specific product?

Indicies of Absorbed Radiation
- ❏ NASA
- ❏ Other

What specific product?

Albedo
- ❏ NASA
- ❏ Other

What specific product?

Other
- ❏ NASA
- ❏ Other

What specific product?

Miscellaneous (other uses)

Microwave Radiances
- ❏ NASA
- ❏ Other

What specific product?

Radar Backscatter (SAR or Altimetry)
- ❏ NASA
- ❏ Other

What specific product?

Visible Satellite Imagery
- ❏ NASA
- ❏ Other

What specific product?

IR Satellite Imagery
- ❏ NASA
- ❏ Other

What specific product?

4. If you are not using NASA data-sets or don't find these useful, please explain why:

5. If you do use NASA data-sets, how do you judge the quality of the data and the ease of access for obtaining the data? Please note any specific problems you've encountered or suggestions for improvements.

6. Is there a data-set you wish was available? If so, please describe briefly and why it would be useful to your work.

7. Do you now or have you in the past used a Distributed Active Archive Center (DAAC) to obtain data? If yes, please note whether request for and receipt of data was satisfactory or if you have suggestions for improvements. If not, why not?

APPENDIX C

Biosketches of the Committee's Members

John E. Walsh is Professor of Meteorology, Department of Atmospheric Sciences, University of Illinois, Urbana. He received his Ph.D. in 1974 from the Massachusetts Institute of Technology. He has done research on the interannual variability of sea ice and snow cover in the Northern Hemisphere, seeking to better understand the roles of ice and snow in short-term climatic variability, particularly in the high latitudes. Related work has examined the patterns of year-to-year variability of weather elements over the United States, including statistical and dynamical studies of these patterns. He is currently Associated Editor of the Journal of Climate, has served as a member of the NOAA Council on Long-Term Climate Monitoring, and has been a contributing author for IPCC Scientific Assessment, 1995 and 1999. He served as a member of the NRC's Panel to Review NASA's Distributed Active Archive Centers (NRC, 1998), working with the group charged to review the National Snow and Ice Data Center.

Judith Curry is Professor at the University of Colorado with appointments in the Department of Aerospace Engineering Sciences and the Program in Atmospheric and Oceanic Sciences. She participates in the World Meteorological Organization's World Climate Research Program, is a member of the Science Steering Group of the Arctic Climate System (ACSYS) Program, and chairs the GEWEX Cloud System Studies Working Group on Polar Clouds. She co-chaired SHEBA's Science Working Group and was a member of the Arctic System Science (ARCSS) Steering

Committee. Her research interests include polar meteorology and climatology, atmospheric physics and remote sensing, and air/sea interactions. In addition to her expertise in clouds and radiation, she also brings considerable experience on sea ice issues. She received her Ph.D. in Geophysical Sciences from the University of Chicago in 1982.

Mark Fahnestock is Assistant Research Scientist at the University of Maryland's Earth System Science Interdisciplinary Center. His research efforts have several themes focused on improving understanding of the current and past behavior of the large ice sheets. Investigations include the use of Synthetic Aperture Radar to measure ice motion (through interferometry) and surface properties of the large ice sheets; the use of passive microwave data to produce a picture of the last 20 years of ice sheet surface conditions; and field measurements to control ice motion studies and measure surface conditions. The goals of this work are to understand the current contributions of the ice sheets to the climate system (such as sea level rise), and to reach a point at which understanding of ice flow is evolved enough to make predictions about the likely response of the ice sheets to climate change. He received his Ph.D. from the California Institute of Technology's Department of Geology and Planetary Science.

Mahlon C. Kennicutt II is Director at the Geochemical and Environmental Research Group in the College of Geosciences at Texas A&M University and member of the graduate college faculty at the College of Geosciences & Maritime Studies. His research interests are in marine chemistry, organic geochemistry, the chemistry of contaminants in the environment, the design and implementation of environmental monitoring programs, the fate and affect of xenobiotic chemicals in the environment, and the development of integrated indicators of ecosystem health. Dr. Kennicutt has significant Antarctic experience, and has participated in 35 ocean research cruises over the past 20 years. He assited in organizing and writing the workshop report, "Monitoring of Environmental Impacts from Science and Operations in Antarctica," July 1996. Dr. Kennicutt is one of the two U.S. delegates to the Scientific Committee on Antarctic Research (SCAR). He serves on the SCAR Group of Specialists on Environmental Affairs and Conservation and SCAR Group of Specialists on Subglacial Lakes, where he has been key in developing the international science plan for exploration of subglacial lakes.

A. David McGuire is Associate Professor (Biology and Wildlife) and Assistant Unit Leader (Landscape Ecology) at the Alaska Cooperative Fish and Wildlife Research Unit, Institute of Arctic Biology, University of Alaska, Fairbanks. He received his Ph.D. in Biology from the University of Alaska, Fairbanks in 1989. He has conducted extensive field research in Alaska including studies of ecosystem function and structure throughout the state, breeding biology and trophic relationships of seabirds in western and south-central coastal Alaska, and breeding biology of passerine birds in interior Alaska. His expertise is in modeling ecosystem dynamics that have implications for atmospheric dynamics in high latitudes, and he has experience with the use of various remote sensing products in modeling carbon dynamics and land-surface change in arctic and boreal regions.

William B. Rossow is with NASA's Goddard Institute for Space Studies and has extensive experience in satellite remote sensing research, primarily as head of the Global Processing Center for the International Satellite Cloud Climatology Project for the World Climate Research Program. His work focuses on the study of the properties and behavior of clouds, how changes in clouds alter the planetary and surface radiation budgets, and studies of the dynamics of cloud processes that produce feedbacks on Earth's climate. In this role he has processed large geophysical datasets obtained from satellites and conventional sources and conducted research diagnosing energy and water exchanges using global, decadal data with large number of variables. He holds a Ph.D. in astronomy from Cornell University (1976) and has been at GISS since 1978.

Michael Steele is a Senior Oceanographer at the Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle. He received his Ph.D. in Geophysical Fluid Dynamics from Princeton University in 1987. His research focuses on Arctic Ocean physical oceanography and sea ice studies, from both modeling and observational perspectives. He has investigated the origins and variability of arctic water masses using data collected by a variety of techniques. His modeling work has often involved the investigation of arctic-wide budgets for heat, salt, and momentum. He has recently synthesized several oceanographic data sets into a global climatology that contains a good representation of the Arctic Ocean. Dr. Steele is active in education outreach programs at the undergraduate and grade school levels.

Charles J. Vorosmarty is a research associate professor in the Department of Earth Sciences and Institute for the Study of Earth, Oceans, and Space at the University of New Hampshire. His research focuses on development of ecosystem models that help understand the interactions between the water cycle and nutrient biogeochemistry. He has been active in the field for over fifteen years, and he has participated in numerous multi-institutional, interdisciplinary research efforts at a variety of spatial and temporal scales. Dr. Vorosmarty is currently heading a small research group at the Complex Systems Research Center within the larger Institute for the Study of Earth, Oceans, and Space. A major and recent group effort has centered on the development of GIS and scientific visualization tools that help to link complex data sets and models of land surface and riverine processes. He received his Ph.D. from the University of New Hampshire in 1991.