ICEX

Ice and Climate Experiment

Report of Science and Applications Working Group

Goddard Space Flight Center
Greenbelt, Maryland

DECEMBER 1979

NASA

National Aeronautics and
Space Administration

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FOREWORD

The Ice and Climate Experiment (ICEX) Science and Applications Working Group was established in February 1979 by the NASA Headquarters' Environmental Observation Division of the Office of Space and Terrestrial Applications. Dr. William Campbell accepted chairmanship of the Working Group, which was asked to consider the ice research needs of the mid-1980s in relationship to the potentially available satellite remote sensing capability. Specifically, the Group was asked to review and make recommendations on:

a. the requirements for satellite sensing of ice parameters for ice processes research, climate studies, resource extraction, and ocean operations;

b. the needs for field projects complimentary to the satellite observations;

c. system implementation options;

d. coordination of the activity with other U.S. and international polar programs.

NASA's Goddard Space Flight Center was assigned the responsibility for conducting the total ICEX definition study, which included the activities of the Working Group, a multi-center instrument definition team, and the preliminary systems design study of the spacecraft and ground systems. The Goddard Study Scientist was Dr. Jay Zwally, the Systems Study Manager was Mr. S. Willis, and the Instrument Study Manager was Mr. F. Flatow. This document presents the results to date of the efforts of the Working Group.

It is appropriate at this time to make special note of the enthusiastic efforts and spirit of cooperation evidenced by the Chairman and members of the Working Group. This has resulted in the establishment of a firm basis for this program in a noteably short time. It is planned that there will be continued strong interactions with the Working Group as the program evolves.

L.H. Meredith
Acting Director of Applications
Goddard Space Flight Center

PREFACE

"I am the eye
through which
the Earth beholds itself."

So exulted Shelley's Apollo as he gazed down out of a Greek sky from his golden winged chariot, viewing whole valleys and mountains, waves and ships on the seas, and the works of man upon the lands. Within a mere century and a half of the writing of this line, men and their instruments traversed the sky far wider than Apollo's and rapidly expanded the breadth and depth of his vision.

Our new vision has given us a better understanding of many geophysical phenomena and forces that shape the environment in which we live. By moving away from Earth, we have gained a new perspective on our planet and our place in it. We begin to see many natural processes as a whole rather than as fragments in space and time.

Although we have seen much more of the realm of ice than did Apollo, we share with him a great ignorance of it. We have only glimpsed its varied nature. Our knowledge of terrestrial ice and its complex interactions with the atmosphere, oceans, and continents is still limited. Since most ice exists where it is dark for nearly half the year and mostly cloudy when it is not, we have been confronted with an "observational barrier". We have no overall view of ice and snow at the time and space scales needed to increase our cause-and-effect understanding.

Now an expanded vision is emerging. The Ice and Climate Experiment (ICEX) is devoted to breaking this observational barrier with recently developed satellite-borne microwave, laser, and other space tools. Imagine how Shelley's Apollo would have thrilled to behold the Earth with eyes such as these. . .So we, today, face exciting new prospects.

W.J. Campbell
Working Group Chairman

ACKNOWLEDGEMENTS

We wish to acknowledge the pioneering work of Dr. William Nordberg in initiating and guiding key remote sensing research. He oversaw the development of the first passive microwave imaging system and directed its use for Arctic aircraft remote sensing in 1969 and for Nimbus-5 satellite observations beginning in 1972. Throughout the last decade of his life, he encouraged polar scientists to explore the use of new microwave techniques, and he strove to assure remote sensing support for international polar experiments that have proved to be of fundamental importance to ICEX.

The ICEX Working Group has been greatly assisted in the preparation of this document by numerous individuals. Of particular importance were the contributions of many NASA scientists and engineers, including the extensive reviews of remote sensing, information processing, and communication capabilities presented at the first Working Group meeting in Harper's Ferry, West Virginia, April, 1979. Coordination, editoral and typing support has been provided by the OAO Corporation; their superb contribution and exceptional efforts are appreciated.

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

1. WHAT IS ICEX?

The Ice and Climate Experiment (ICEX) is a proposed program of coordinated investigations of the ice and snow masses of the Earth (the "cryosphere"). These investigations will be carried out with the help of satellite, aircraft, and surface-based observations that will obtain information hitherto unavailable. Measurements derived from the investigations will be applied to an understanding of the role of the cryosphere in the system that determines the Earth's climate, to a better prediction of the responses of the ice and snow to climatic change, to studies of the basic nature of ice forms and ice dynamics, and to the development of operational techniques for assisting such activities in the polar regions as transportation, exploitation of natural resources, and petroleum exploration and production.

The approach needed to achieve the goals of ICEX must be multidisciplinary and international in scope, and must involve a combination of new observational tools, theoretical studies, and applications of new knowledge. However, the key to ICEX's success--and hence the emphasis in this report--will be the deployment of a high-inclination satellite system with a set of remote-sensing instruments specially tailored to the task of observing the important features of snow, sea ice, and the ice sheets of Greenland and the Antarctic. The near-simultaneous observations of multiple geophysical parameters by complementary sensors is needed for many of the ice processes to be studied. Research on these processes has been data limited, not idea limited.

2. THE PURPOSES OF ICEX

While the ice-bound regions remain largely unexplored and uninhabited, there is a growing realization that mankind must quickly learn to understand and make use of these areas. The impetus to explore is strengthened by the new spaceborne tools now available to assist in the task; this and other reasons for exploration as well as the objectives of ICEX are presented and examined in this document (Chapters 2, 3, and 4).

ICEX objectives can be classified under the customary headings of "science" and "applications." It will be shown, moreover, that the objectives of the scientific investigations will have important implications for the long-term as well as the immediate future.

The scientific objective of ICEX is a clearer understanding of the roles of ice and snow in geophysical processes. Special attention will be given to the interactions between the cryosphere and the rest of the planetary system that determines our climate. This kind of investigation is double edged, since the cryosphere influences the world's climate and at the same time is a most sensitive indicator of climate variations and change. The massive ice sheets of Greenland and the Antarctic will also receive special attention, because they contain such a large fraction of the Earth's fresh water and because the fluctuations observed in the ice sheet volume would serve as precursors of sea level change. (Section 3.3)

The applied purposes of ICEX are responsive to the ever-growing human need to make use of the polar regions and their resources. Those exploring the regions, for example, require improved weather and sea ice forecasts available at remote locations in the Arctic and Antarctic. ICEX will facilitate such forecasts through its unique observational capability and data processing and communication systems designed to analyze these observations and make them available in near-real time. Coupled with existing forecasting services, ICEX will advance polar marine navigation, coastal petroleum exploration and recovery, mining operations, and snow runoff predictions. (Sections 3.4, 3.5).

3. THE CRYOSPHERE: WHAT WE KNOW AND NEED TO KNOW

A better understanding of the processes associated with the various forms of ice is a prerequisite to unravelling the problems of ice in the climate system, of ice as an environmental hazard, and of ice as a renewable resource.

We probably know less about sea ice than any other form of ice. We do know that sea ice grows in thickness and extent during the winter and contracts during the summer melting season, but the scales of the process of growth and decay are very different in the two hemispheres. For example, the area of new pack ice produced each winter in the Southern Ocean is considerably larger than the area of the entire Arctic Ocean. In the same vein, relatively little pack ice survives through the summer around the Antarctic while the central Arctic Ocean pack ice remains throughout the year.

A number of investigations have been carried out to aid our understanding of the dynamics and thermodynamics of sea ice. Conducted predominantly in the Arctic, these investigations have given us some insight into what happens in specific locations well removed from the boundaries of the pack ice. Considerably more information is needed, however, to model the behavior of the pack ice in the marginal ice zone near the shore and at the edge of the pack ice.

We have only begun to obtain information on the motion of the pack ice as a whole; we cannot predict where or when pressure ridges will occur; and we know even less about the processes of atmosphere-ice-ocean interaction at the margin of the pack ice where it bounds on the open ocean. (Sections 2.3 and 4.2)

The proposed approach to solving these and similar problems is to obtain high resolution all-weather imagery of the pack ice distribution, ice motion, open water within the pack, and ice characteristics in terms of age, thickness, roughness, and type of surface. Sea ice motion (from sequential radar imagery) is particularly important for ice dynamics. The area of open water within the pack (from passive microwave imagery) is important for studies of the thermodynamics. Because dynamic and thermodynamic processes are interrelated, nearly simultaneous radar and passive microwave observations are needed. It is also proposed that the existing array of air-droppable buoys be maintained at a number of locations on the ice pack to provide accurate indications of movement and of the causes of these movements. Buoys are needed to measure sea-level pressure, from which winds and the air stresses that push the ice can be deduced. The ICEX satellite systems will locate the buoys and receive their telemetered data. (Sections 4.2 and 6)

Questions exist about aspects of the cryosphere other than sea ice. We must also know more about glaciers, icecaps, and the seasonal snow cover. For example, in order to understand the mass balance of the ice sheets, high quality measurements of ice surface elevation must be available. Only these kinds of measurements can answer such questions as whether the Greenland and West Antarctic ice sheets are shrinking or growing. Little systematic information is available on the water content of snow packs, on the dynamics of ice during freezeup and breakup of the large northern river systems, and on numerous other fundamental processes. The following discussion explains the nature of these fundamental problems and how ICEX can contribute to their solution.

The elements of the ICEX program and the motivation behind them evolved from a decade or more of research and detailed deliberation on the part of the worldwide scientific and operational communities. The resulting reports and specific recommendations describe the steps needed to gain a better understanding of the cryosphere and the capability to operate in the polar regions. The reports listed below are among those exploited in the process of planning ICEX.

1. U.S. Contribution to the Polar Experiment (POLEX), Part I, POLEX -GARP (North); Part II, POLEX - GARP (South). National Academy of Sciences, Washington, D.C. 1974.

2. The Physical Basis of Climate and Climate Modeling. Global Atmospheric Research Programme (GARP) Publ. Series No. 16, World Meteorological Organization and International Council of Scientific Unions (WMO-ICSU), Geneva, Switzerland 1975.

3. Polar Research: A Survey. Committee on Polar Research. National Academy of Sciences, Washington, D.C., 1970.

4. Elements of the Research Strategy for the U.S. Climate Program, U.S. Committee-GARP, National Academy of Sciences, Washington, D.C. 1978.

5. Status of Satellite Observing Possibilities for Studies of Climate Physical Processes. Working Group VI, Intl. Comm. on Space Research of ICSU (COSPAR), 1978.

6. Report of the Informal Meeting of Experts on the Role of Sea Ice in the Climate System. Commission for Atmospheric Sciences (CAS), WMO, Geneva, 1977.

4. RESEARCH ON THE ROLE OF ICE IN THE WEATHER AND CLIMATE SYSTEM

As a large component of the system that determines weather and climate, the everchanging polar regions are considered a strong influence on the dynamic conditions of the atmosphere and world oceans. An understanding of the cryosphere as a regulator of weather and climate will eventually contribute to the following:

a. A better ability to make extended range (seasonal) weather forecasts,

b. A better estimate of the expected climate changes in store for the Earth in the next few decades.

Theories of climate are concerned with determining the many interactions between the parts of the climate system. Called "feedback mechanisms," these interactions can amplify or suppress small perturbations destabilizing or stabilizing our climate. Both climate theory and observations of past atmospheric behavior verify that the polar regions do indeed have a pronounced influence on global weather and climate--and vice versa. The key to obtaining a more quantitative grasp of this important influence lies in a study of the relationships between snow and ice cover (best observed by satellites), on the one hand, and on the other (1) the heat balance of the hemisphere (also observable by satellites) and (2) the large scale circulation patterns of the atmosphere and oceans.

This kind of information is essential for developing improved models of the climate system, models that can serve to simulate the effects that short-term (year-to-year) fluctuations in the cryosphere have upon seasonal weather patterns and, perhaps of even greater significance, to simulate the effects increasing carbon dioxide levels may have upon the course of climate in the decades ahead. (Chapter 2, 3, and 4)

The response of the polar regions to an expected global warming and yearly fluctuations in climate must be anticipated and monitored in order to accomplish the following:

a. Predict the variations in sea ice extent due to both short-term and long-term changes;

b. Predict similar variations in continental snow cover;

c. Monitor the volume of the ice sheets, starting as soon as possible;

d. Determine how rapidly the ice sheets of Greenland and the Antarctic will grow or shrink in the future, with corresponding effects on sea level.

<u>Response of the Polar Regions to Climatic Change</u>

We do know that both the Arctic and the Antarctic experience appreciable interannual variations in temperature and extent of snow and ice. There are a number of theories--mostly untested because of insufficient information--which attempt to relate these variations to changes in ocean circulation, to large-scale and persistent circulation patterns in the atmosphere, to solar disturbances, to the Earth's axis of rotation ("wobble"), and so forth. When considering the possibility of a significant global warming in this century, both modeling experiments and observations of the atmosphere indicate that the warming in the polar regions will probably be three to five times greater than the global average.

The effect of such a warming on the cryosphere is still unclear. The extent of snow cover may decrease with such a warming. At the same time, a warmer atmosphere can hold more water vapor, therefore increasing the snowfall at higher latitudes--but this latter effect is still conjecture. Floating pack ice in the Arctic and Antarctic Oceans would probably decrease, and some modeling studies suggest the pack ice in the Arctic Ocean could disappear entirely--at least in summer. Such an event would create a condition (possibly irreversible) in the Arctic Basin that has not prevailed for the past million years or more. If it does occur, momentous consequences (some good, some bad) are predicted for the entire Northern Hemisphere.

Role of Sea Ice in the Climate System

Sea ice is likely to be the most important ice form to be examined when studying climatic variations and changes. The extent of sea ice has an effect on the solar radiation absorbed in a hemisphere and hence the heat balance. Sea ice extent alters atmosphere-ocean exchanges of heat, moisture, and momentum. Thus, sea ice must be considered in extended-range (seasonal) weather predictions and in climate models simulating longer-term (decadal) changes in climate.

On the seasonal time scale, it is probable that some of the factors that cause climatic anomalies, such as the winters of 1976/77 and 1977/78 in the eastern United States and Europe are related to the regions of maximum cyclogenesis (intensification of storm systems) in the North Pacific and North Atlantic. These areas are also the margins of the wintertime ice packs. While a complete explanation for these climatic anomalies awaits further investigations, the ICEX system will advance the study of these regions by furnishing a description of surface temperature and ice motions.

As mentioned earlier, dynamic and thermodynamic pack ice models developed thus far have suggested that the Arctic ice pack may respond dramatically to a general warming. It is important, therefore, to develop more complete pack ice models to check this tentative result. Several factors must be considered by an investigation of large-scale processes in the ice pack: the fluxes of heat and moisture at the air-surface boundary, the effects of leads and polynyas (open water), the motion of the ice pack under wind stress, the fluxes of heat through the upper layers of the ocean, and changes in surface characteristics with season. Most of these factors can be measured by a combination of satellite systems, aircraft equipped with remote sensors, surface buoys, and a few manned stations (not necessarily operated continuously). (Sections 3.3.1 and 4.2)

Role of Ice Sheets in the Climate System

The great ice sheets of the Antarctic and Greenland contain some 80 percent of all the fresh water on the planet. Should the sheets melt completely, the melt water would raise the Earth's oceans by 65 to 70 m. Thus, even a small change in their volume would have an appreciable effect on sea level.

Each of the ice sheets may behave differently, however. Greenland extends farther from the pole than Antarctica and receives more snowfall--a factor that could even cause the Greenland ice sheet to grow as more water evaporates from an open Arctic Ocean (another conjecture). The West Antarctic ice sheet rests on bedrock below sea level, and it has been suggested that a warming of the ocean waters of the Ross and Weddell Seas or other factors could cause the ice sheet to shrink. The East Antarctic ice sheet is by far the largest and may be the most impervious to change, but even a small amount of growing (from increased snowfall on its top) or shrinking (from melting and ablation at the edges) would have an effect on sea level.

Satellites traveling within a few degrees of the poles have the unique capability of measuring the surface topography to better than 1 m absolute accuracy. They can determine changes in ice sheet volume corresonding to 4 cm of sea level or less and can describe the motions of these ice sheets over a period of months to years. Such measurements are essential in order to develop realistic ice sheet models that would simulate the future behavior of dynamic ice sheets and would monitor ice sheet changes as they occur. (Sections 3.3.3 and 4.3)

5. MINIMIZING THE HAZARD OF SNOW AND ICE

The need for more living space and the demand for natural resources (petroleum, minerals, fresh water) imply a continuing demand for increased activity in the polar regions. Exploitation of these resources is faced with numerous threats from hazards posed by sea ice, permafrost, icebergs, and other snow and ice forms. To assist human activities in an essentially hostile natural environment, the following is necessary:

a. To improve short-term weather predictions (including snowfall);

b. To provide improved predictions of sea, lake, and river ice extent and movements for shipping and offshore petroleum drilling activities;

c. To obtain improved climatological statistics concerning seasonal snow cover, river and lake ice extent and thickness, pack ice conditions in the Arctic and Southern Oceans.

In temperate latitudes the daily weather forecast has already become an essential service. Inputs to such forecasts are hemispheric analyses of pressure, temperatures, and winds from the several World Meteorological Centers; regional analyses and forecasts; and satellite imagery. It is in the domain of sea, river, and lake ice that ICEX can provide unique information, since its proposed satellite-borne sensors are especially designed for that purpose. Except in the Soviet Union, where an extensive ice forecasting system along the northern sea route is in operation, ice forecasting is still rudimentary. The ICEX observational system will be able to obtain high resolution imagery of pack ice through clouds and throughout the polar night--an essential tool for ice forecasting. (Sections 3.4 and 4.2.2).

Demands for real-time observations of pack ice and predictions of its movement are increasing as shipping activity in Arctic and Antarctic waters intensifies and as offshore drilling for petroleum in the Arctic begins in earnest. Offshore petroleum-related activities are especially vulnerable to pack ice. Drilling platforms must be able to withstand the enormous pressures of moving ice masses. Exploratory drilling operations, conducted from ships, must have timely warnings of approaching ice. The building of "gravel islands" has already begun, while ice islands and other novel techniques are being considered for such drilling operations. Successful application of these devices requires a knowledge of the nature and magnitude of the threats posed by sea ice.

There are numerous sea ice related problems that must be considered for offshore operations. Representatives of the oil industry in Alaska (the Alaska Oil and Gas Association - AOGA), working in the Beaufort Sea, expressed concern with the following ice features and processes: ice movement during freezeup, winter ice movement, movement during breakup, summer pack ice invasions of the nearshore areas, the character and distribution of first-year and multiyear pressure ridges, grounded ridges, multiyear floes, floeberg and icebergs (ice islands), and the occurrence and intensity of ice gouging of the ocean floor. In addition, problems related to permafrost, waves, and storms must be considered. This list of obstacles is not unique to the Beaufort Sea. Similar problems will confront offshore petroleum development in other polar regions. (Sections 3.4.2 and 4.2.3)

It should be possible, with the capability provided by ICEX, to quantify most of the processes and characteristics mentioned above. For instance, the radar and microwave radiometer on board the ICEX satellite will permit measurements of the distribution of first-year and multiyear ice and the identification of ice islands and multiyear ridges. In fact, it is hoped that eventually ice thickness distribution can be deduced from these observations. (Chapter 5)

6. USING ICE AS A RESOURCE

At present two forms of ice are considered renewable resources--snow and icebergs. Societies in temperate and high latitudes consider snow annoying, dangerous, and at the same time of potential value. Its impact on agriculture, hydroelectric power generation, and recreation can be measured in terms of billions of dollars, as can the cost of snow removal, avalanche protection, and other snow control activities.

Proper utilization of the snow resource requires extensive knowledge of the physics and geophysics of snow plus a method to monitor snow extent, both from spacecraft and from the ground. Some of this prerequisite research can be provided through investigations of the following:

a. Optical properties of snow, including albedo, under different conditions;

b. Water equivalent of snow;

c. Characteristics of snow cover, including snow depth, density, layering, grain size, etc.;

d. Ripening of the snow cover throughout the melting cycle.

Electromagnetic sensing techniques employed through ICEX will aid these studies.

The cost of obtaining potable and irrigation waters in many areas of the world has increased so much that the idea of towing icebergs is now under serious consideration. The identification, tracking, and studies of ablation of icebergs can be conducted most conveniently from spacecraft, as can the navigation of the ships that would tow the icebergs. (Section 3.5.2)

7. DESCRIPTION OF THE SPACECRAFT SENSOR SYSTEM

The key element of the ICEX program will be the spacecraft sensor system, which may be flown on a single dedicated satellite or perhaps on more than one satellite. To observe the polar regions, it will be essential that the system be flown on high inclination orbits that pass within 3^{o} of the pole.

The sensor system contains the following six remote sensing instruments (which will be described briefly in the succeeding text):

Large Antenna Multifrequency Microwave Radiometer (LAMMR)

Wide Swath Imaging Radar (WSIR)

Scatterometer

Ice Elevation Altimeter System (IEAS), Radar

Ice Elevation Altimeter System (IEAS), Laser

Polar Ice Mapping Radiometer (PIMR)

Relay links are included to locate and collect data from buoys and other in situ platforms and to transmit images and other information to various users. A Global Positioning System (GPS) receiver will obtain real time satellite position data.

The LAMMR is a passive multichannel radiometer which will measure the radiative brightness temperature of the surface in seven microwave bands ranging from 1.4 GHz to 91 GHz (22.4 cm to 0.33 cm). The WSIR is an X-band (3 cm) synthetic aperture side-looking radar which produces images of the surface with a pixel size of 100 m over a 360 km wide swath. (25 m pixel size and 90 km wide swath is optional.) A side-looking radar, the scatterometer, has the capacity to measure the scattering cross section of surface irregularities at 14.6 GHz (2.05 cm). The IEAS is an altimeter which can measure ice altitude profiles with two complementary instruments: a microwave radar to provide continuous coverage along the nadir track and a laser ranging system with commandable pointing to provide precision altitude determination, off-axis mapping, fine scale profile resolution, and ranging to reflectors placed on the ice. The PIMR is a passive, 5-channel infrared radiometer (4 near-infrared channels detecting reflected solar radiation and one thermal infrared channel at 11 m) which can map cloud cover, determine cloud parameters, measure surface temperatures, and aid in distinguishing surface ice and snow from clouds.

The system for locating and relaying telemetry from buoys and other in situ platforms will use the ARGOS (or RAMS) principle, in which periodic transmission from the platforms will be received and located by the Doppler shift of the carrier as the satellite passes over the platform.

Versions of these sensor systems, except for the laser altimeter, have already been successfully flown on satellites.

8. INFORMATION PROCESSING AND ANALYSIS FACILITY

The ICEX Data Processing and Analysis Facility (IDPAF) will support scientific analysis of ICEX data in near-real time and also provide data storage and manipulation capability for longer term research programs. Investigators will gain access to the data by means of an interactive analysis terminal systems. These terminals will be similar to the terminals developed for the Atmospheric and Oceanographic Information Processing System (AOIPS) and the Landsat Assessment System (LAS).

In addition to data received from ICEX, the facility will provide direct links to the Climate Data Base and to the Applications Data Service (ADS) for two-way data communication. Raw data, preprocessed data, derived parameters, orbit, and attitude data will reside in the facility data base and will be available instantly to on-line users and to the ADS and Climate Data Base users. Data retransmission from the facility will allow experimental data products to be evaluated for accuracy, timeliness, and application to operational situations. Output data products will also be recorded on film for nonreal-time scientific analysis and other uses. (Section 6.5)

9. SUPPORTING RESEARCH

The success of the ICEX program will depend, to a large extent, on the continuing research required to make best use of the remotely sensed output from the satellite system. There are two main categories of such supporting research: (1) interpretation of snow and ice signatures and (2) physical modeling of the ice system.

Interpretation of Snow and Ice Signatures

During the past decade, advances in remote sensing techniques (microwave, infrared, and visible) have made spacecraft data indispensable to scientific and commercial applications. For example, discrimination of snow and ice regions from land or ocean background and classification of ice types into the categories of fresh/old, thin/thick, first-year/multiyear, and sea ice/ice sheet categories have been addressed by both passive and active microwave remote sensing techniques. In conjunction with the spacecraft (and aircraft) studies, physical modeling efforts have resulted in better understanding of dielectric and scattering properties and brightness temperature of ice.

Nevertheless there is a great need and a great potential for advances in remote sensing of sea ice and snow. For instance, although there are large brightness temperature differences between open water and sea ice (100° K or more) making their differentiation rather easy, the variation between ice types is less well established and understood. Improved physical understanding of the factors contributing to the different signatures and their variations would strengthen the reliability of microwave techniques used to classify sea ice types. It is also difficult to interpret all the striking variations seen in the passive microwave images of polar ice sheets and snowcover on land.

Thus, the most effective use of a system such as ICEX requires additional theoretical and laboratory-scale studies of the variations in the dielectric properties of natural and artificial ice bodies and in their scattering characteristics. This kind of work should improve our understanding of the differences in the contributions of ice surface roughness and internal dielectric variations to active and passive microwave signatures. (Sections 3.3 and 4.2)

Physical Modeling of Ice Systems

As explained earlier, there are two dynamic components of the cryosphere that need to be modeled properly in order to understand and predict their behavior. These are the pack ice of the polar oceans and the great ice sheets on land.

Scientists have been laboring to develop models of these ice systems, and they are generally trained in theoretical research involving fluid mechanics, solid state physics, thermodynamics, and the application of large computers to model development. The work of the scientific community must continue but should be closely allied with that of the engineers and technicians responsible for gathering and interpreting ICEX data from a variety of sources. One group alone cannot succeed in getting to the heart of the problem; others are needed--the modelers to develop the theoretical framework and the observational people to provide the data in a form which can be used to improve and verify the models. (Sections 2, 3.3, 4.2, and 4.3)

10. SUPPORTING RESEARCH AND COORDINATION

The ICEX program should not be funded with the assumption that "someone else" will bear the costs of data analyses and supporting research. It is essential to avoid this pitfall from the outset and to prepare for the large effort needed to take full advantage of ICEX observations.

In particular, the IDPAF should be established well in advance of the satellite launching. It should be associated with a strong in-house research group to ensure high responsiveness to research and development needs. The opportunities for collaboration with other U.S. Government agencies, research organizations in other countries, and industry should be expanded. (Section 7)

Indeed, this responsibility for supporting research and coordination must be considered an integral part of the program itself, and action should be taken as soon as the program is initiated.

CHAPTER 1. INTRODUCTION

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1.1 POLAR REGIONS: CHALLENGE AND OPPORTUNITY

When astronomers first focused their primitive telescopes on Mars, the most striking feature they could discern was "the Red Planet's" polar ice caps. Indeed, a Martian astronomer would have been equally fascinated contemplating the Earth's ice covered poles. Yet we, living on Earth, have until recently shown very little concern with our inaccessible and forbidding polar regions.

This former lack of concern is now giving way to a growing realization of the importance of the Arctic and Antarctic for a variety of reasons. As the population of the Earth doubles every 39 years, and as essential resources decrease in availability, mankind must learn to work with the ice environment and not simply against it.

There is, first of all, practical interest in the natural resources of the polar regions, resources of minerals, petroleum, coal, food from the polar oceans, and ice itself as a source of fresh water. There is also a need to understand the natural variations of snow and ice as well as the possible variations that may be induced by man's activities. Snow and ice are not limited to polar regions, of course, as is often demonstrated by their impact in severe winters. Over longer times, variations of sea ice and ice sheets on land have profoundly and repeatedly altered the face of the Earth.

This report describes a program to probe the mysteries of ice on a scale that would have been inconceivable a generation ago. It involves new sensors flying over the poles that will observe features never before seen in their entirety.

The polar regions are seen as the "heat sink" for the planetary heat engine that drives our atmosphere and oceans and as a critical part of the system that influences our weather and climate. Some of the keys to extended range weather forecasting lie in the distributions of snow and ice, which vary markedly from year to year. Also, the ice and snow of the cryosphere will surely respond in some manner to the warming foreseen in the decades ahead due to the release of carbon dioxide from fossil fuels and its consequent "greenhouse effect." The cryosphere's response might in turn amplify the global warming and produce other effects such as a change of sea level.

ICEX (Ice and Climate Experiment) is an integrated cryospheric program involving ground, buoy, aircraft, and spacecraft data, coupled with theoretical studies, models, and preoperational tests. It demands an extensive integration of many scientific and technological fields. This report briefly reviews the polar regions, the outstanding problems encountered in understanding and exploring them, their role in the weather-and-climate system, and the satellite techniques now available to observe them. All of these considerations are brought together and incorporated in the design of the program called "ICEX." It should be mentioned that although Chapter 4 outlines specific science and applications investigations, the detailed design and implementation of ICEX will involve scientists and engineers beyond the scope of this report.

The results of the ICEX program are expected to improve man's understanding of the cryosphere, to help answer important climatological questions, and to provide insights which may significantly reduce resource extraction costs in the next decades. The data available from ICEX will aid many United States agencies and private industries active in the polar regions as well as approximately twenty foreign countries with programs in the Arctic and Antarctic.

What will be the value of these new data, and are they worth the price? This fundamental question will be answered in detail in the sections that follow. It will be clear that the data will have many uses, both practical and scientific. In particular, the contribution of the frequent observations over large areas to our understanding of basic geophysical processes and to practical activities will be emphasized.

1.2 THE OBSERVATIONAL BARRIER

That part of Earth's surface least known and understood is the realm of polar ice, which we take to include sea ice, ice sheets, snow, glaciers, and permafrost. After several millenia of exploration and discovery by civilized man, the North and South Poles were reached for the first time only in this century. Few chapters in the history of exploration resound with names such as those associated with the Arctic and Antarctic--names connoting courage and daring coupled with keen intelligence and observational abilities--men such as Nansen, Shackleton, Sverdrup, Amundsen, Scott, Rasmussen, and Peary, all of whom performed their great tasks within the last century. The largest single coordinated effort by mankind to increase our knowledge of polar geophysics, the International Geophysical Year (IGY), occurred only 2 decades ago. Hence a vast part of our knowledge of ice is quite recently acquired.

The reason why our knowledge of polar geophysics is so recent and relatively limited can be simply stated: the Arctic and Antarctic are extraordinarily difficult and expensive environments in which to carry out surface investigations. This is the basis of the "observational barrier" surrounding the polar regions. Since the IGY, it has become increasingly clear that many ice processes occur over large space scales and at short time scales. Consequently, synoptic data are necessary to study the dynamic interactions of ice with the ocean and atmosphere systems. Thus, when the meteorological satellite program was started at the end of IGY, there was considerable optimism that "cause-and-effect" studies of many ice processes could finally be attempted with the new information.

But the observational barrier was not to be so easily broken. The early coarse resolution TIROS imagery and later finer resolution Nimbus, NOAA, and Landsat imagery were useful but limited, delineating sea ice extent and morphology for restricted space and time scales, mapping only parts of Antarctica and Greenland, and poorly distinguishing snow from cloud cover. It was apparent that the synoptic scale data needed to study the most important ice processes could not be acquired by satellites on orbits that did not pass near the poles or that carried only visible wavelength sensors. Polar regions are virtually dark for half the year and frequently cloudy when not. Indeed, the areas which are most dynamic are also the most cloudy, such as the boundaries of the sea ice packs. Furthermore, sensing ice with visible and infrared wavelengths gives limited information about the state of the surface viewed and nothing about what is beneath the surface. There is no penetration of the medium to probe the internal structure and physical characteristics of the snow and ice. Other techniques are needed.

1.3 MICROWAVE TECHNIQUES FOR OBSERVING ICE

Just as meteorologists were the first members of the geophysical community of scientists to foresee and exploit the potential uses of visible and infrared satellite observations, ice scientists have been in the forefront of the utilization of passive and active microwave techniques. Since microwave sensors can probe through clouds, darkness, and even below the surface, these sensors are proving as useful for ice scientists as the visible and infrared sensors flown on the TIROS, Nimbus, and NOAA satellite series proved for the meteorologists.

Before the first microwave imager was flown on Nimbus-5 several field experiments on the microwave properties of sea ice had already occurred. An Electrically Scanned Microwave Radiometer (ESMR), for example, was taken to the Arctic on board the NASA "Galileo-I" Convair-990 aircraft prior to being flown on Nimbus-5. This was part of two coordinated expeditions in the Beaufort Sea involving aircraft and surface measurements from drifting ice stations (Campbell, 1973).

Every new satellite microwave experiment on Nimbus-5, -6, and -7, Skylab, GEOS-3, and Seasat-1 has been coupled with intensive surface and aircraft ice expeditions. Since 1969, numerous minor and five major international expeditions have included coordinated surface, aircraft, and satellite observational programs for the purpose of testing passive and active microwave techniques for remote sensing of ice. There have been five major expeditions: (1) AIDJEX (Arctic Ice Dynamics Joint Experiment) Spring 1971, 1972, and Spring 1975 through Spring 1976 - Main Experiment; (2) BESEX (Joint U.S./USSR Bering Sea Experiment), Spring 1974; (3) Skylab Snow and Ice Experiment--Winter-Spring 1973 and 1974; (4) SURSAT (Canadian Surveillance Satellite Experiment) Winter-Spring 1978 and 1979; (5) NORSEX (Norwegian Sea Experiment) Autumn 1978 and 1979.

The passive radiometers quickly showed the value of microwave techniques for ice research. Within 2 weeks of the launch of Nimbus-5 in December 1973, the ESMR provided the first synoptic views of the entire polar sea ice cover (Campbell et al., 1974). Examples of ESMR-5 imagery are shown in figure 2-8. The data from this one sensor, which greatly exceeded its design lifetime by operating for more than 4 years, has permitted ice scientists to make several breakthroughs in the remote sensing of sea ice and ice sheets These breakthroughs include the ability to distinguish sea ice from water, multiyear ice from first-year ice, and ratios of the mixtures of these two ice types. Ice concentrations (percentage of ice vs percentage of water per area) can be measured on hemispheric scales (Gloersen et al., 1974). Also, the ability to measure the spatial and temporal variations of snow accumulation rates on the Greenland and Antarctic ice sheets appears feasible (Zwally and Gloersen, 1977). Other applications of ESMR data are discussed later in this report.

Success with the first ESMR was followed by the flying of a similar ESMR on Nimbus-6 and the development of a five-frequency, dual-polarized version called the Scanning Multichannel Microwave Radiometer (SMMR), flown on both the Nimbus-7 and Seasat-1 satellites.

Advances in the active microwave remote sensing of ice have followed those of passive microwave sensing. The first radar altimeter measurements of ice from space were acquired by the GEOS-3 satellite, launched in 1975. Analysis of the observations made over Greenland (Brooks et al., 1978) demonstrated that a microwave space tool could potentially provide the answer to a key question about climate: are the Greenland and Antarctic ice sheets growing or shrinking? No previously existing surveying technique had the capability to measure the ice sheet volumes with sufficient accuracy to determine volume changes. The GEOS-3 data were used to map (figure 1-1) the southern Greenland topography to an accuracy of 1 to 2 orders of magnitude better than earlier measurements. This means that it will be possible to know if the ice sheets are growing or shrinking and by how much, provided that radar/laser altimeter mapping of ice sheet topography can be made for a minimum of 3 to 5 years and repeated every 10 years or so.

Equally important, these altimeter measurements will provide critical data needed for the development and testing of numerical models for ice sheet dynamics. Prior studies suggest that the West Antarctic ice sheet has fluctuated in size in the past and may shrink in the face of the expected global warming in the decades ahead. Such a shrinkage could increase worldwide sea surface levels by many meters. Therefore, it is paramount to develop models that will help us to understand and eventually to predict ice sheet variations.

Another new active microwave sensor recently flown in space for the first time has also yielded exciting ice data. It is the Synthetic Aperture Radar (SAR) on Seasat-1, launched in June 1979. An assessment of some of the first optically processed SAR images (Teleki et al., 1979) shows that we now have the ability to acquire high-resolution, all-weather, day-or-night synoptic-scale observations of sea ice and of ocean surface phenomena. Despite the early demise of this satellite, sufficient ice data were acquired to show (figures 1-2 and 1-3) that the SAR is a unique tool for studying sea ice morphology and dynamics at various space and time scales. Sea ice is the fastest moving solid on the surface of the Earth, with typical speeds of 10 km/day; speeds of 50 km/day have been observed occasionally. Understanding the dynamics of sea ice is of prime importance to climate studies, weather forecasting, and ship operations in ice covered seas.

Several sea ice dynamics models exist, but there are insufficient data with which to develop and test these models properly. A key requirement for understanding sea ice dynamics is to map accurately and frequently the location of sea ice on synoptic scales together with the wind stress field. Sea ice images taken daily for selected periods with a typical spatial resolution of 50 to 100 m are needed. The sequential sea ice mapping data must be coupled with surface wind stress fields. The wind stress fields can be deduced from simultaneous surface pressure observations taken from an array of drifting buoys. A spaceborne radar similar to that flown on Seasat-1 is the only known way to acquire this high-resolution, large-scale imagery at the time rate demanded. Satellites also provide the best platform for locating and receiving the telemetry from drifting buoys.

The past 10 years of intensive surface-aircraft-satellite research on active and passive remote sensing of ice (together with drifting buoys) have led to the advances which now show us a way to break the observational barrier. A new and expanded view of ice and its interactions with the oceans and atmosphere is possible. We have the tools that could enable us to discover in 1 decade as much as we have ever learned about ice.

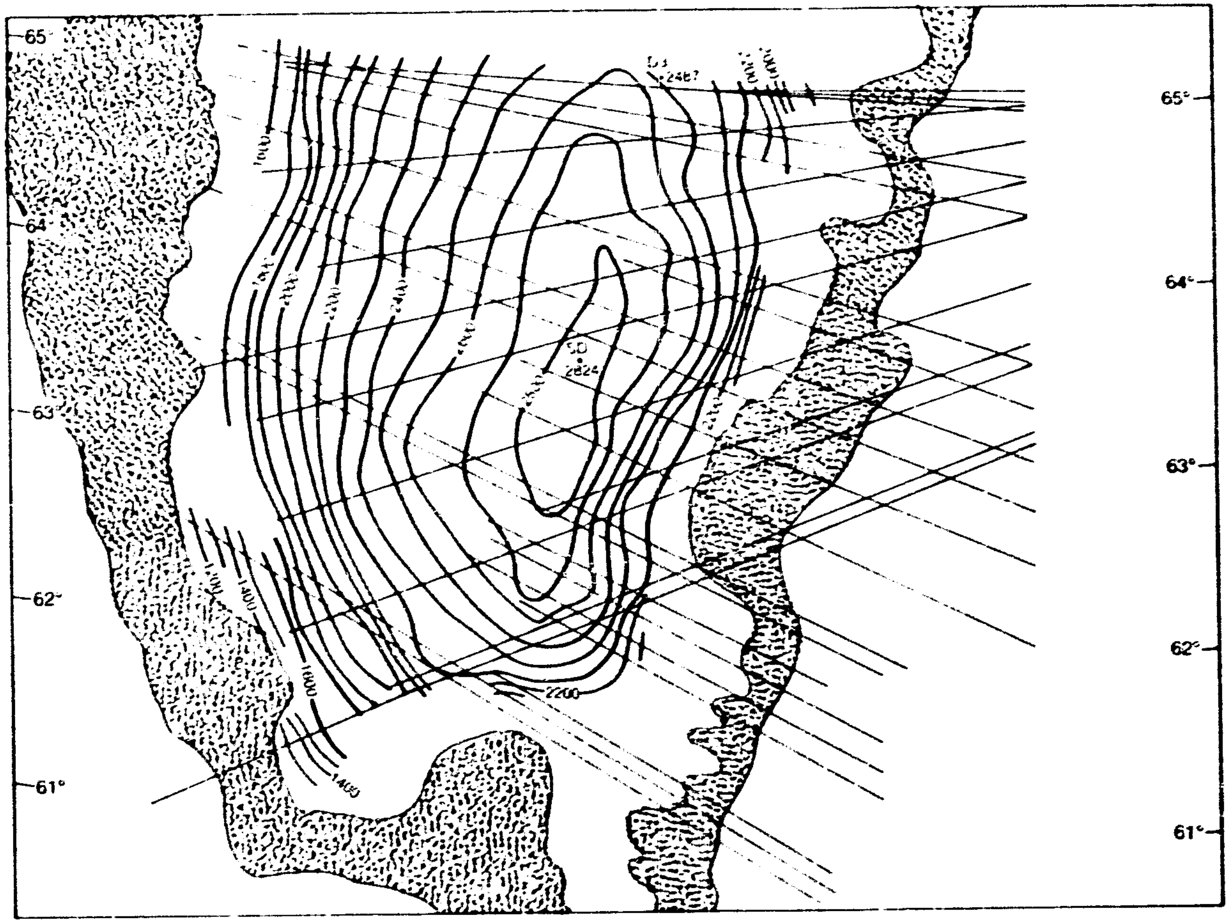

Figure 1-1. Surface Elevation Map of Southern Greenland Ice Sheet Produced from Satellite Radar Altimetry. Elevation referenced to sea level, 100 m contour interval. The elevations determined by this analysis showed errors of earlier topographic surveys as great as 100 m.

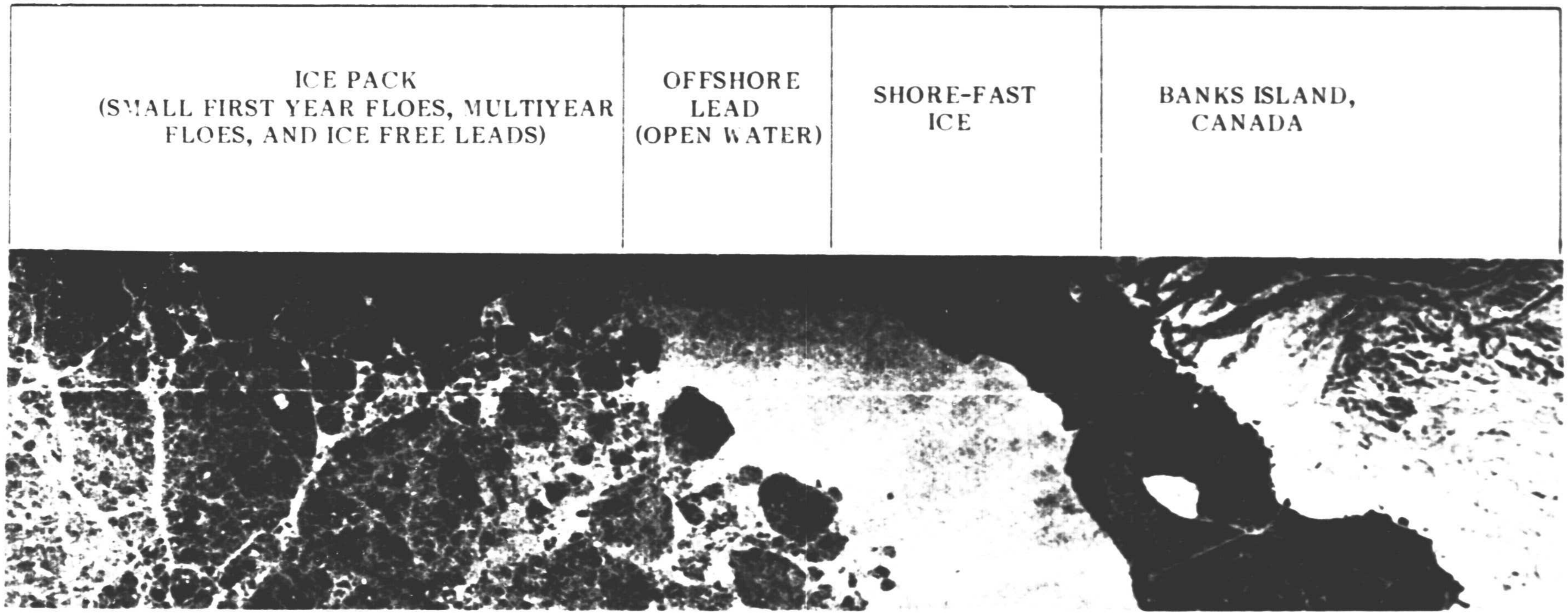

Figure 1-2. Seasat-1 SAR Optically Processed Image of the Ice Pack West of Banks Island, Canada Acquired on 11 July 1978. Total area of this image, produced at JPL, is 33 km by 135 km. The dark area adjacent to the island is shore-fast ice in which pressure ridges can be seen as lighter-toned linear features. The bright uniform zone to the left of the shore-fast ice is a shore lead, the strong radar return signal resulting from a wind-roughened sea. The edge of the ice pack is made up of small first-year and multiyear ice floes separated by numerous ice-free leads. Within the pack are large floes composed of cemented first-year and multiyear floes in which numerous pressure ridges are visible (after Teleki et al., 1979)

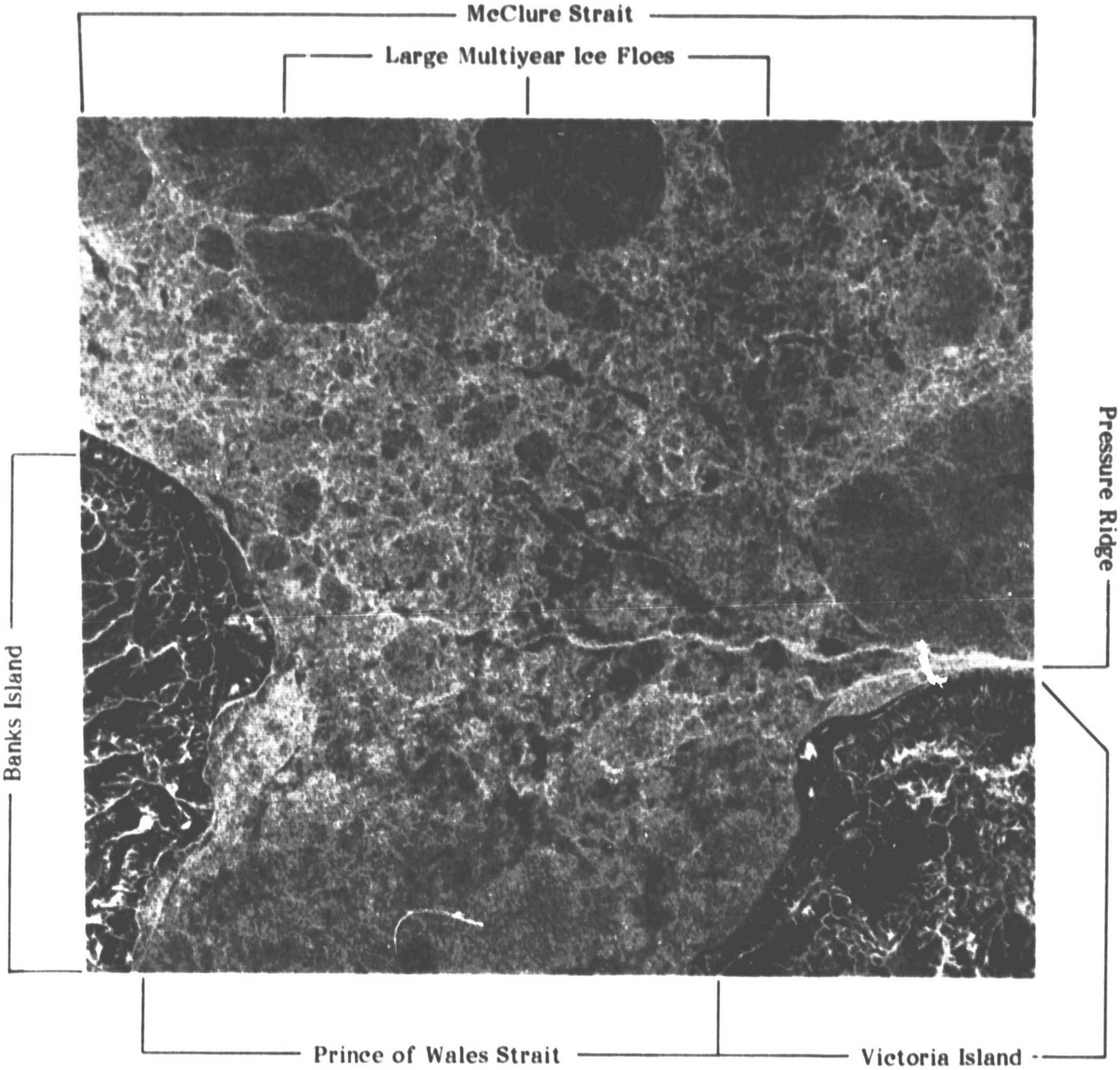

Figure 1-3. Seasat-1 SAR Digital Image of the Ice Pack in the McClure and the Prince of Wales (P. of W.) Straits at the North End of Banks Island, Canada. Both straits are entirely frozen. A variety of different ice features are visible in this $(40\ km)^2$ area including: large, multiyear floes (top of image); smaller multiyear floes cemented together with fractured first-year floes (P. of W. entrance); and a long pressure ridge extending sinuously from the east side of the P. of W. Strait. The pressure ridge is formed by ice shears resulting from the differential ice flow in the two straits. Image digitally produced by MacDonald, Dettweiler and Assoc., Ltd. for the SURSAT Project office.

CHAPTER 2. SCIENTIFIC BACKGROUND

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2.1 INTRODUCTION

The cryosphere is the most changeable physical constituent of the Earth's surface (Untersteiner, 1975). There are six elements comprising the terrestrial cryosphere:

a. seasonal snow on land

b. sea ice

c. permafrost

d. river and lake ice

e. ice sheets

f. glaciers.

Of the elements, snow and sea ice are the most transient ice forms and have the strongest impact on human activities. Millions of dollars are spent to remove snow from cities each year, and its effects upon agriculture, transportation, and construction are obvious. The impacts of sea ice are also costly, as it impedes northern shipping for part of each winter. While the influence of ice sheets and glaciers is less apparent on short time scales, these large land ice masses nevertheless represent both a valuable resource and a potential threat. Representing 80 percent of the fresh water on Earth, the ice sheets covering Antarctica and Greenland would change sea level if they were to grow or shrink. The annual cycle of surface albedo and energy (heat) balance, induced by the expansion and contraction of the seasonal snow and ice covers, strongly affects the global climate system. With their small volume and large surface area these cryospheric elements are extremely sensitive to climatic change. A qualitative measure of the sensitivity of snow and ice masses to climate changes may be seen in their ratio of thickness to diameter. It is $1{:}10^3$ for ice sheets and glaciers, $1{:}10^6$ for sea ice, and $1{:}10^{7-8}$ for seasonal snow. Residence times of particles of frozen water range from days in snow, to 10^4 or 10^5 years in ice sheets. (Estimates of the volumes, surface areas, and mean annual variation of the five elements of the cryosphere are shown in table 2-1.)

The following sections present some scientific background on each of the elements of the cryosphere. Figure 2-1 depicts, in a schematic and qualitative way, the main elements of the cryosphere and the fluxes of mass, heat, and momentum which make up the complex system of air-sea-ice interaction.

2.2 SEASONAL SNOW

At its maximum extent in January, seasonal snow covers an area considerably greater than that of all sea ice and continental ice sheets combined.

Table 2-1. Estimated Inventory of the Terrestrial Cryosphere

SEASONAL SNOW (Max.)			
N-hemisphere		S-hemisphere	
Area	Vol.	Area	Vol.
45	?	Small	?

SEA ICE							
N-hemisphere				S-hemisphere			
Max		Min.		Max.		Min.	
Area	Vol.	Area	Vol.	Area	Vol.	Area	Vol.
15.0	0.05	8.4	0.02	20.0	0.03	2.5	0.005

PREMAFROST			
Continuous		discontinuous (excl. Antarctic)	
Area	Vol.	Area	Vol.
7.6	?	17.3	?

ICE SHEETS			
Antarctic		Greenland	
Area	Vol.	Area	Vol.
13.9	28.0	1.8	2.7

MOUNTAIN GLACIERS	
Area	Volume
0.5	0.24

Units of area are 10^6 km^2 and of volume 10^6 km^3. Similar estimates for river and lake ice are unavailable. (Adapted from Untersteiner, 1975, and other sources).

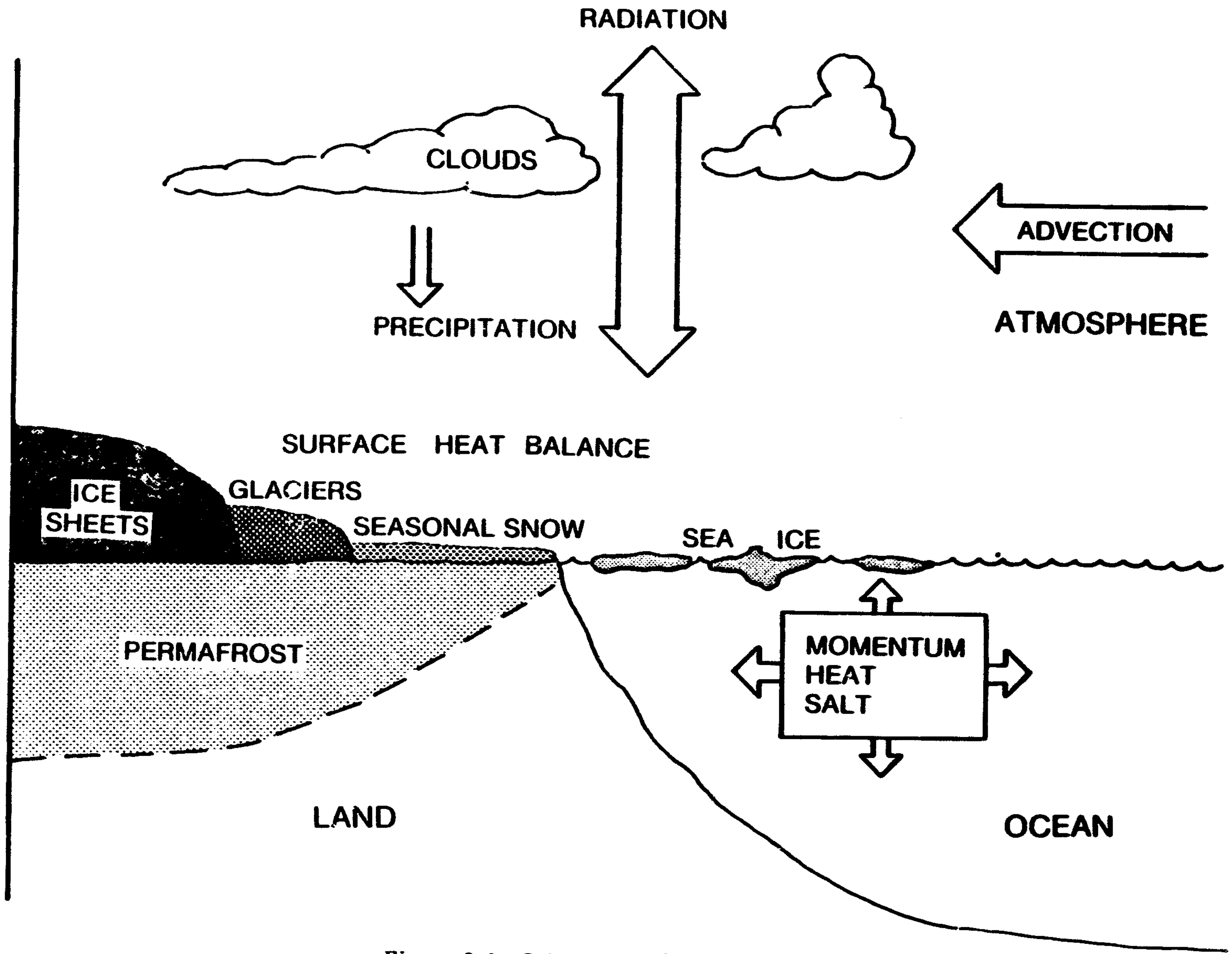


Figure 2-1. Schematic of Cryospheric Processes

The global distribution of snow, shown in figure 2-2, is based on records obtained over several decades. The importance of this snow cover to the heat balance of the Earth, including the possibility of a positive feedback, has been recognized for a long time. However, not until the advent of satellite observations was it possible to obtain the data needed to establish quantitative relationships.

Based on the weekly snow and ice cover maps prepared from ESSA, ITOS, and NOAA satellites, Kukla and Kukla (1974) described a significant but apparently temporary increase of the mean snow cover in the Northern Hemisphere which began in 1971. The authors have speculated that the concomitant decrease in short-wave radiation absorption (figure 2-3) has caused subsequent anomalous weather patterns. Williams (1974) created a dramatic example of the effects of seasonal snow upon atmospheric circulation, by using General Circulation Models to simulate the extreme conditions of the last ice age.

There is mounting evidence that at least some of the major glaciations during the Quaternary era began more or less simultaneously in regions where a small positive anomaly in the area of snow cover may have initiated positive feedback. Increased albedo would have resulted in less absorption of solar radiation-which would have caused a tropospheric cooling. The resultant cold upper vortex would have increased snowfall (e.g., Brooks, 1929; Flohn, 1975; Williams, 1974; Kellogg, 1975). Most of the speculations concerning the possible forces that initiated and terminated glacial periods emphasize large-scale phenomena. Examples of such phenomena could include shifts in the quasi-stationary upper troughs and the attendant changes in cloud and precipitation regimes.

A striking example (figure 2-4) of a short-term (seasonal) correlation between snow cover and a major atmospheric circulation system was recently shown by Hahn and Shukla (1976).

In addition to its role in the heat balance of the Earth's surface, snow is an extremely important (and in some regions of the world the only) source of fresh water. The uses of snow as well as its hazards and impediments, have been discussed by Colbeck et al. (1979).

Progress in understanding the role of snow is predicated on the following factors:

a. Generation of an extended data base for global snow coverage and its seasonal and interannual variability;

b. Process studies aimed at improving subgrid-scale phenomena for global model calculations, with special emphasis on terrain and vegetation effects;

c. Improvement of global circulation models to include realistic simulations for the deposition and melting of snow;.

d. Further development of observing techniques, with special emphasis on satellite-borne remote sensing of the water equivalent of deposited snow.

2.3 SEA ICE

Seasonal and interannual variations of the sea ice cover are somewhat smaller than those of seasonal snow, but the physical processes involved are considerably more complex.

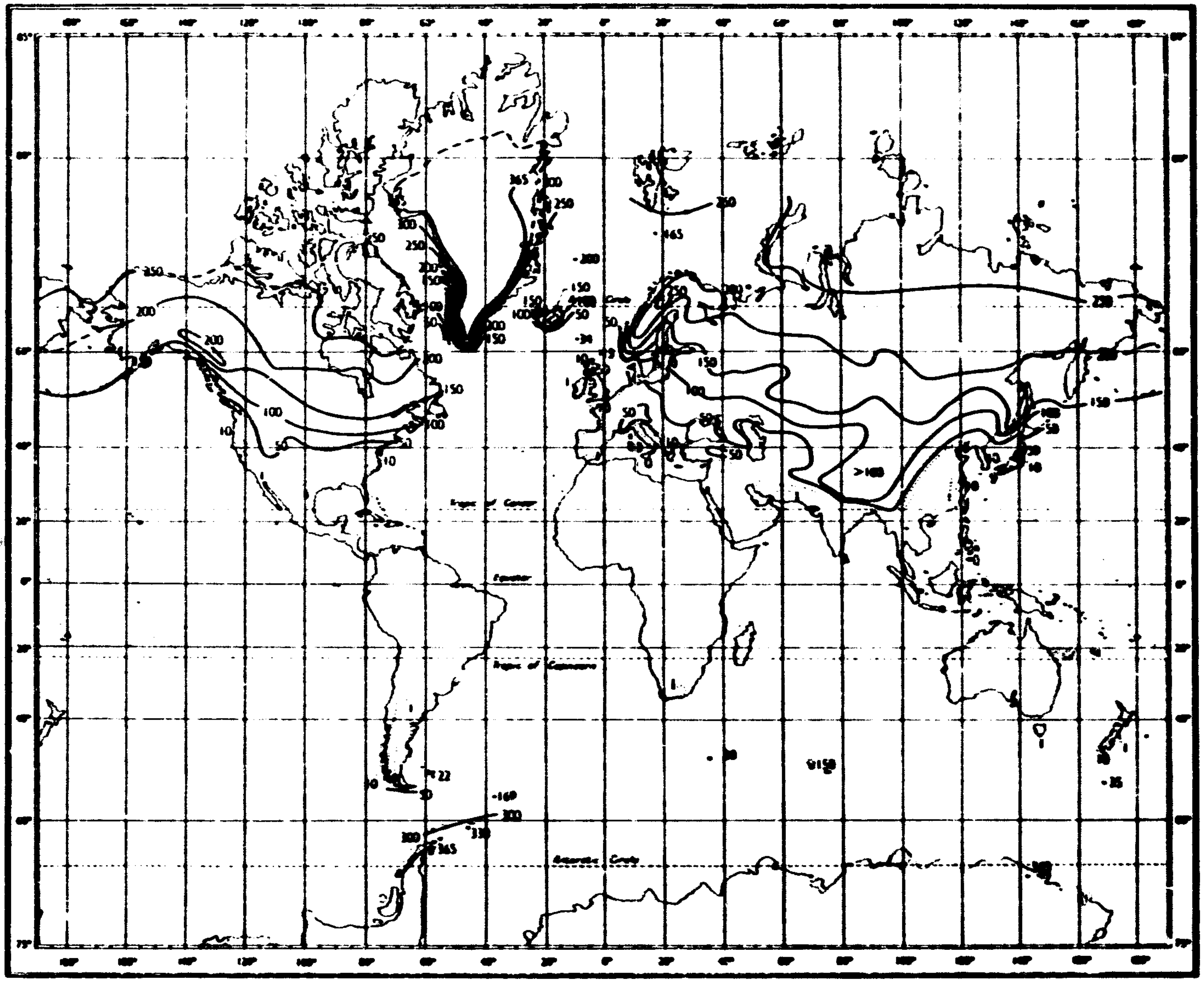


Figure 2-2. Average Yearly Number of Days with Surface Snow (approximate Yearly Average of Days with Low Ground More than Half Covered with Snow at the Morning Observation). (Lamb, 1972)

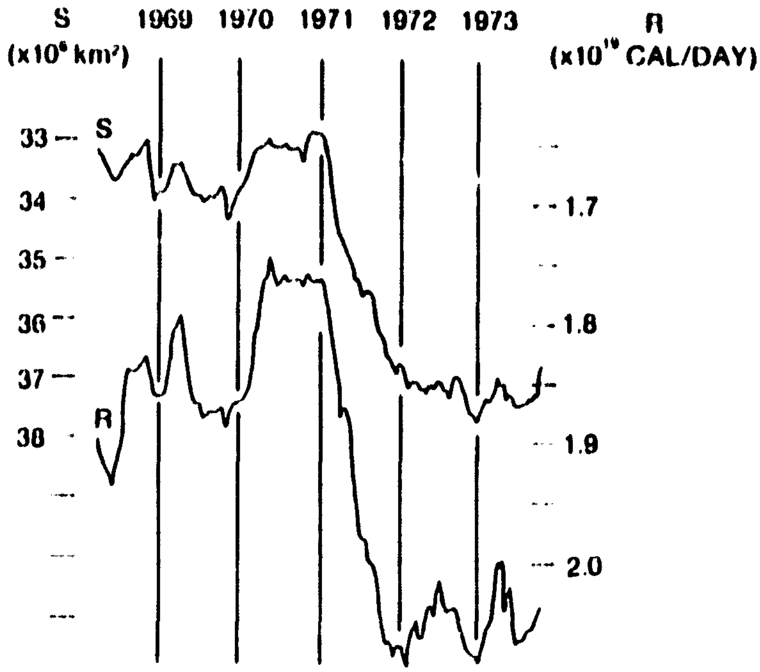


Figure 2-3. Running Annual Means of Snow and Ice Cover (S) and of the Reflection Loss (R). For each year 1 January is marked. Both parameters increased drastically during 1971.

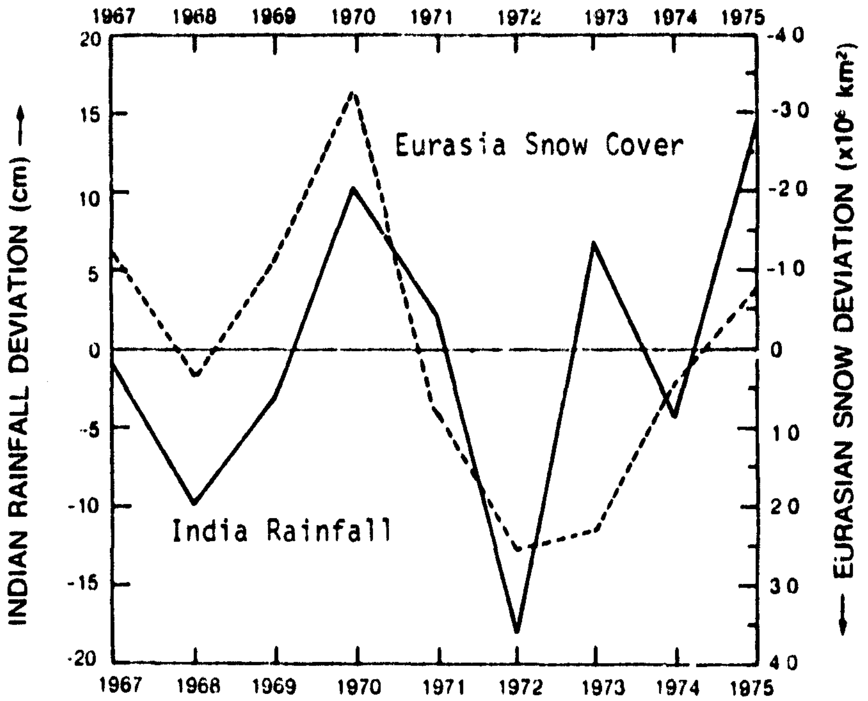


Figure 2-4. Year-to-Year Variation of Winter Snow Cover Deviation over Eurasia South of 52°N, and the Corresponding Variation of Summertime Area Mean Rainfall Departure for India (Hahn and Shukla, 1976).

The most important material constituents of sea ice are pure ice, inclusions of liquid sea salt solution and (at temperatures below -9°C) solid salt crystals. The brine inclusions are generally in phase equilibrium with the surrounding ice and have a profound effect on bulk material properties of sea ice. These properties are specific heat, thermal conductivity, strength, elasticity, and all radiative properties.

The bulk salinity of sea ice ranges generally from 20 to 30 parts per mil in young, rapidly frozen ice to 2 to 6 parts per mil in perennial, slowly grown ice. A considerable amount of data on the material properties of sea ice and their dependence on salinity and temperature has been accumulated over the past few decades. However, there remains the need for a unifying theory relating growth rate, thermal history, and the evolution of salinity in time which has not been formulated (Untersteiner, 1968). The present lack of such a theory limits the accuracy of determining sea ice types from microwave data.

The motion of sea ice is affected by both wind stress which acts upon the ice surface, and ocean currents which act upon the ice from below. A modest beginning toward acquiring suitable air stress fields from atmospheric surface pressure observations is being made under POLEX (Polar Experiment, World Meteorological Organization, 1978). An array of air-dropped buoys, equipped with barometers and tracked by the satellite-borne ARGOS system, has been in operation since February 1979 (figure 2-5).

Sea ice floats on oceans of variable currents and variable fluxes of heat and momentum. In addition, the dynamics of sea ice itself are influenced by heat and mass exchanges with the atmosphere and the ocean as well as the internal mechanics of the ice. Considerable progress has recently been made toward modeling the dynamics in the interior of ice-covered oceans (AIDJEX - ICSI Symposium, in press). On the other hand, efforts at simulating processes at the ice margins (and especially the seasonal cycle of the sea ice cover in the Arctic and Antarctic) are only in the initial stages (Parkinson and Washington, 1979).

An example of the current ability to model the behavior of sea ice under the influence of external and internal stresses is shown in figure 2-6 (Coon et al., in press). Another demonstration of the current status of this work was given by Hibler (in press), who showed that the ice dynamics can significantly affect the equilibrium thickness and air-sea heat exchange in seasonal simulations of sea ice. The results also suggest that, the ability to model the dynamic behavior of sea ice exceeds the means of "driving" the models with atmospheric and oceanic stress fields and the ability to verify the results with sea ice data.

The effort to model the behavior of sea ice is far more than a scientific exercise, since adequate sea ice models are needed for operational predictions of sea ice motion and extent and for predicting the longer-term response of polar ice to the expected warming trend of global climate. One dynamic sea ice model has already been run to simulate what might happen in the Arctic Ocean if a warming did occur early in the next century. The results of that model indicate an ice-free Arctic Ocean in summer (Parkinson and Kellogg, 1979)—a condition that apparently has not existed at any time in the past million years or more. This is an important example of the likely cryospheric response to a climatic change, and it illustrates the potential impact on the polar regions.

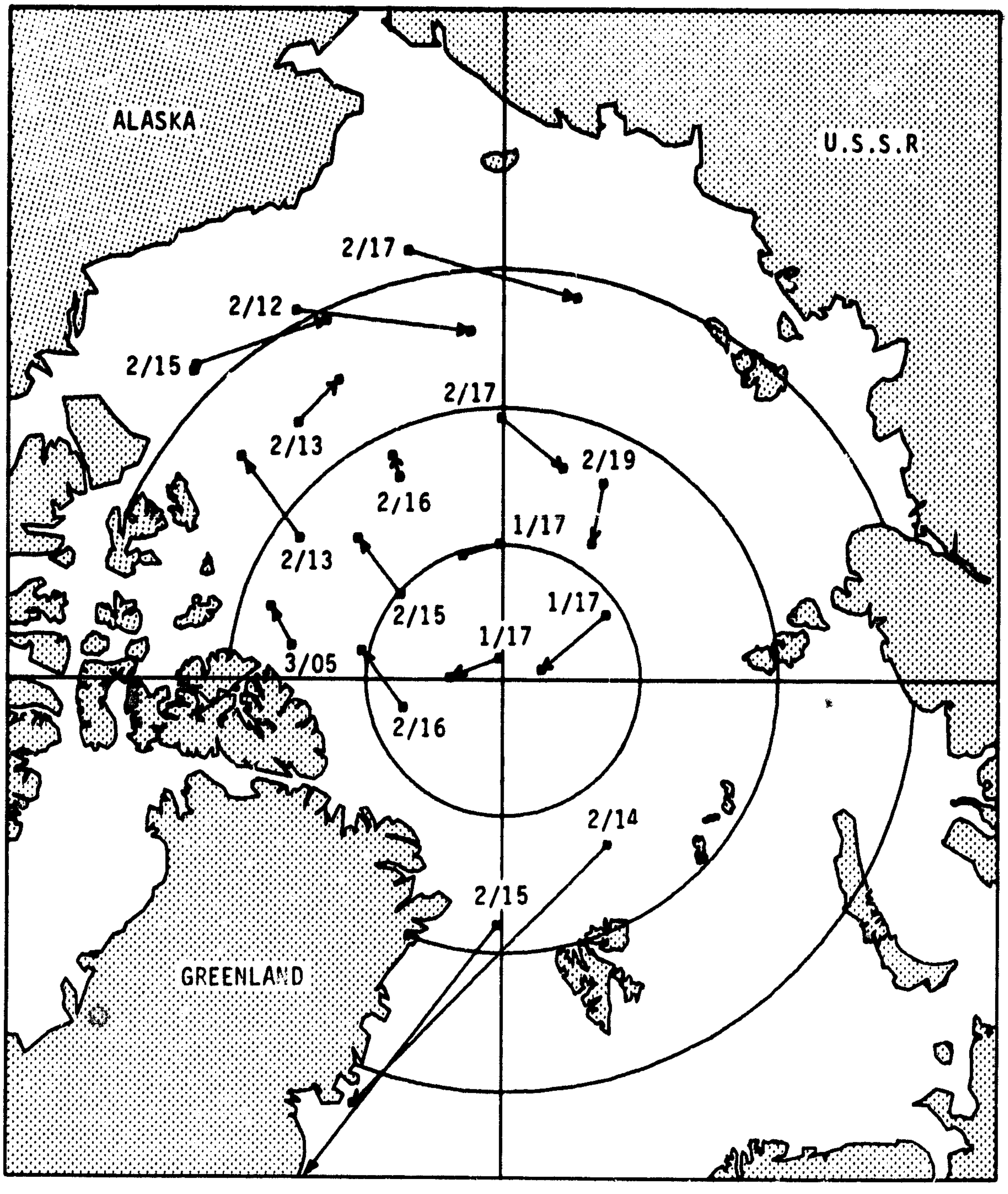


Figure 2-5. Drift of Arctic Data Buoy Network Air-Dropped in January and February 1979 on the Dates Indicated. The arrows represent net ice displacement between those dates and 1 October 1979 (Thorndike, pers. comm.).

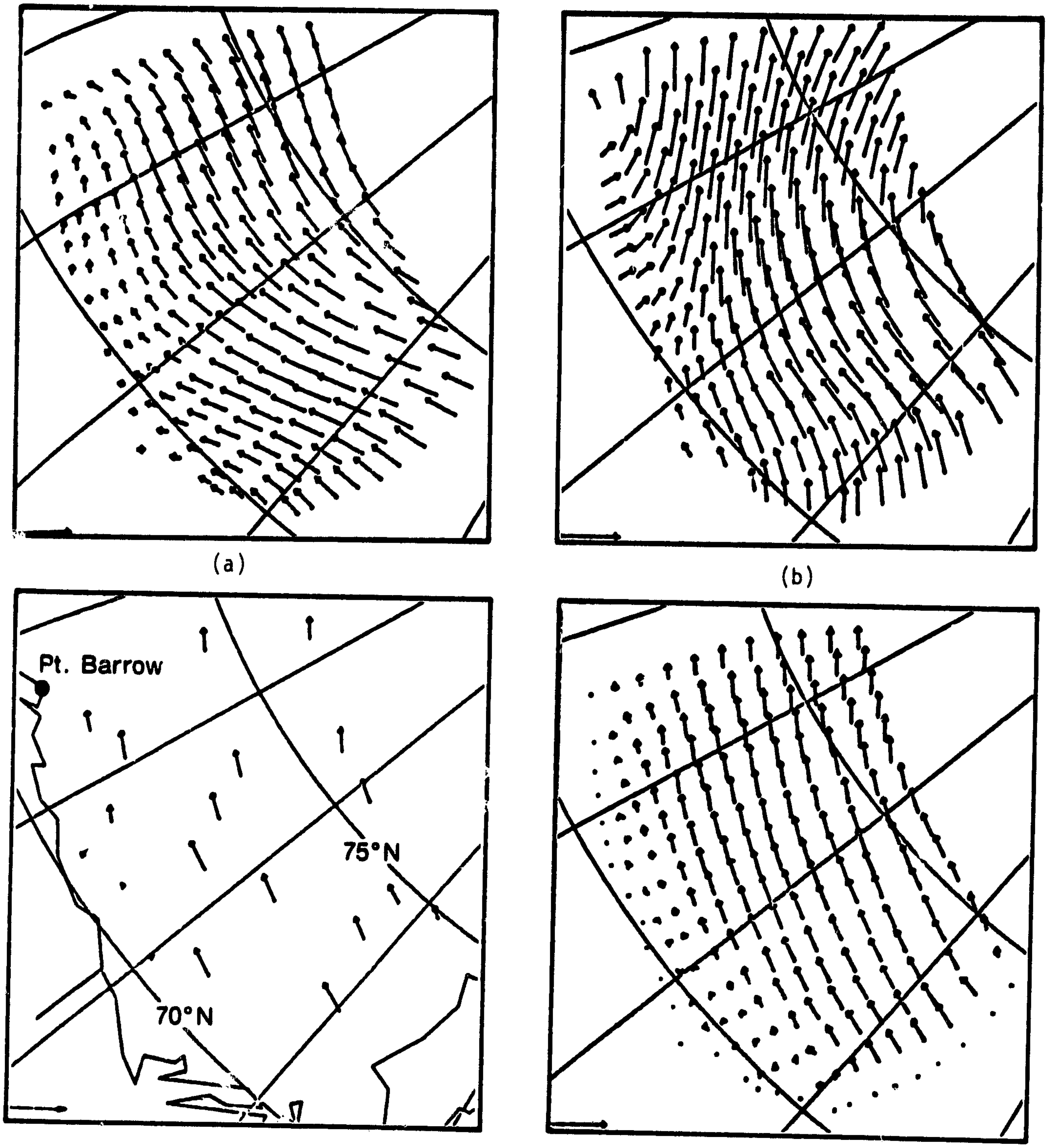


Figure 2-6. Daily Average Data for 31 January 1976 for the Beaufort Sea. (a) Air stress with scale vector 4 dym cm-1. (b) Free drift velocity with scale vector 25 cm sec^{-1}. (c) Data buoy and manned camp velocity with scale vector 25 cm sec^{-1}. (d) Model velocity with scale vector 25 cm sec^{-1}. Calculations were carried out with the AIDJEX model (Coon et al., in press).

Nothing is known quantitatively about the variability of ice motion in the interior of the Arctic Basin. Therefore, it was recommended (NAS, 1978) that a buoy network of the kind shown in figure 2-5 be maintained for an indefinite period. Because methods of remotely determining surface pressure with sufficient accuracy (± 0.5 mb) are not expected to be available in the near future, a surface buoy network in both the Arctic and at least in part of the Antarctic sea ice should be considered an integral and essential part of ICEX.

The most difficult problem in sea ice research is the modeling of the behavior of the outer (unconfined) sea ice boundary (NAS, 1974). Here, both conceptual (modeling) formulation and data are lacking. The schematic diagram shown in figure 2-7 indicates the processes involved.

A connection between the location of the sea ice margin and storm tracks in the North Atlantic has long been suspected and empirically studied by Brennecke (1924), Strubing (1967), and others. Model calculations by modern means (Herman and Johnson, 1979) are still at a stage where feedbacks between the ice and the atmosphere cannot be included except in a stochastic manner (Lemke 1977, 1979).

The "marginal" or "seasonal" sea ice zone is the subject of two special workshops--ICSI/AIDJEX Symposium, 1977 and the SSIZ Workshop, 1979 (Seasonal Sea Ice Zone). The proceedings of these workshops are in preparation. Examples of the "seasonal" sea ice zone are shown in figure 2-8. These pictures, generated from ESMR data, show the maximum and minimum extent of sea ice for the year 1974 in the Arctic and Antarctic.

2.4 PERMAFROST

Permafrost, or perennially frozen ground, underlies about 20 percent of the Earth's land surface. It is assumed that most of the ground beneath the Greenland and Antarctic ice sheets is at temperatures well below freezing. The greatest recorded permafrost depths are 1400 m in Siberia (Markha River) and 600 m in North America (Prudhoe Bay). Figure 2-9 shows the present distribution of permafrost in the Northern Hemisphere.

Perhaps the most important aspect of permafrost is the fact that it inhibits groundwater recharge and movement, restricting plant growth and enhancing runoff. Permafrost results from a delicate equilibrium between surface heat balance and geothermal heat flux and is affected by the water content and thermal properties of the ground. Like glaciers, permafrost responds to, and integrates, climatic change in a complex fashion that is difficult to unravel. In theory, a vertical profile of ground temperature should faithfully reflect the accumulated (although damped) trends of surface temperature over long spans of time. In practice, the evolution of vegetation, soil structure and composition, and interaction with the hydrosphere tend to obscure this temperature record. Where these effects are weak, for instance in the cold and arid region of the Alaskan north coast, bore hole temperatures can be interpreted with precision. According to Lachenbruch and Marshall (1969), temperature gradients to a depth of 100 m beneath Barrow, Cape Thompson, and Cape Simpson indicate a warming of 4°C since the middle of the 19th century and a cooling of 1°C after about 1950. Relatively rapid changes occur in the regions of thin, discontinuous permafrost (e.g., Thie, 1974).

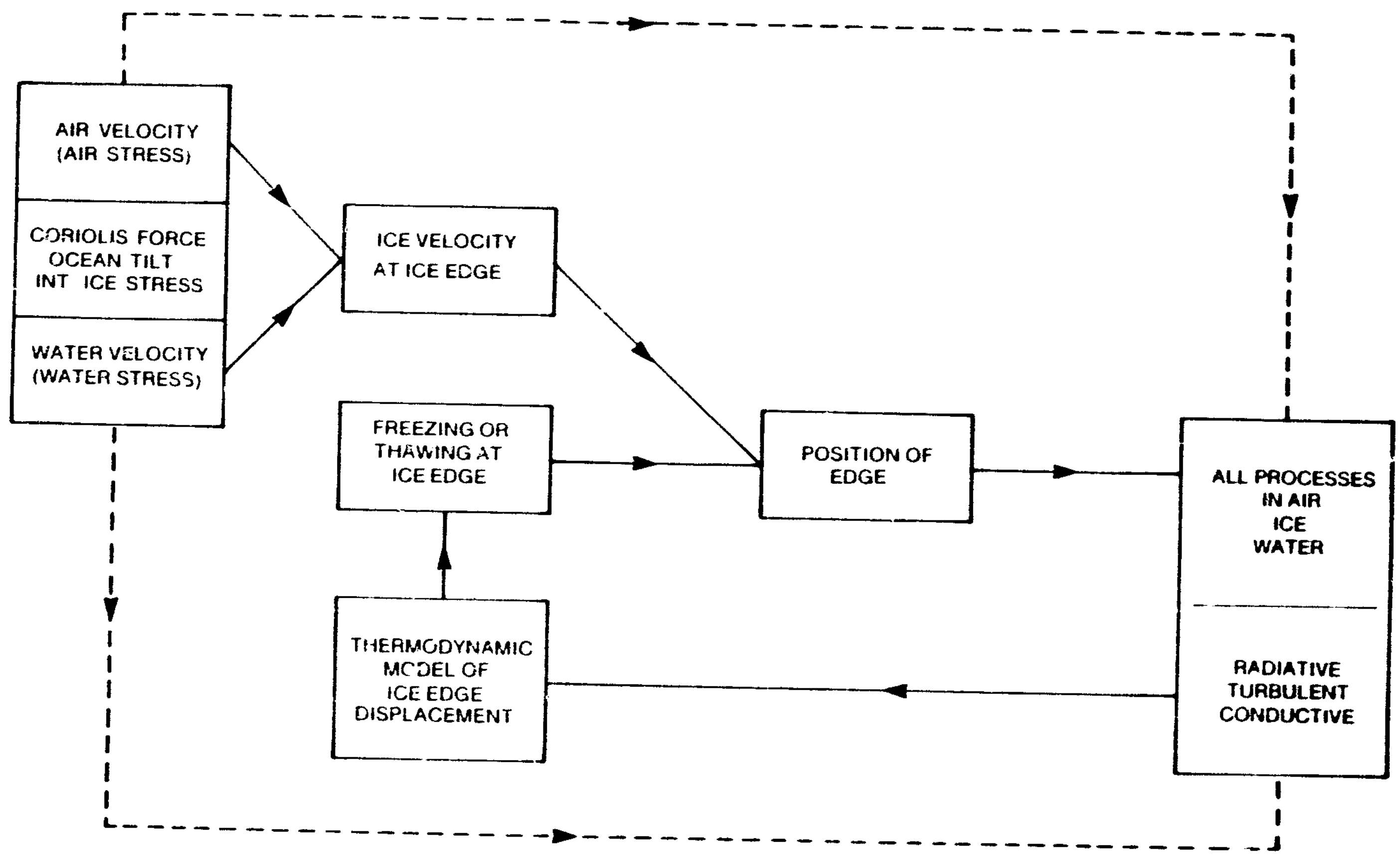


Figure 2-7. Schematic Representation of Processes Controlling the Position of an Unconfined Sea Ice Boundary

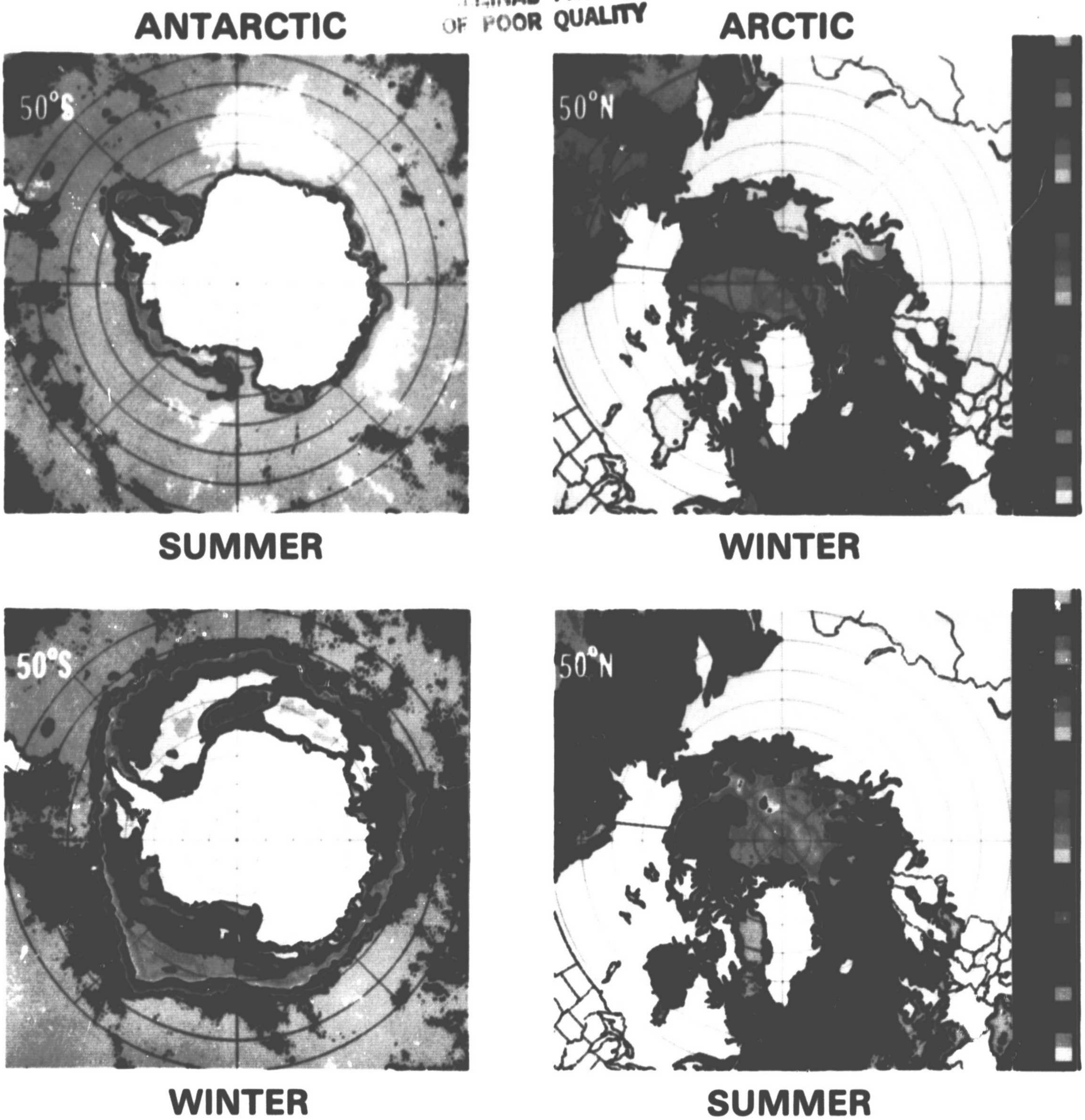


Figure 2-8. ESMR Pictures - Passive Microwave Image of Polar Regions from Nimbus-5 Satellite Showing Maximum and Minimum Seasonal Extent of Sea Ice (150°K Brightness Temperature, Light Blue, Defines the Sea Ice Boundary at 15% Ice Cover)

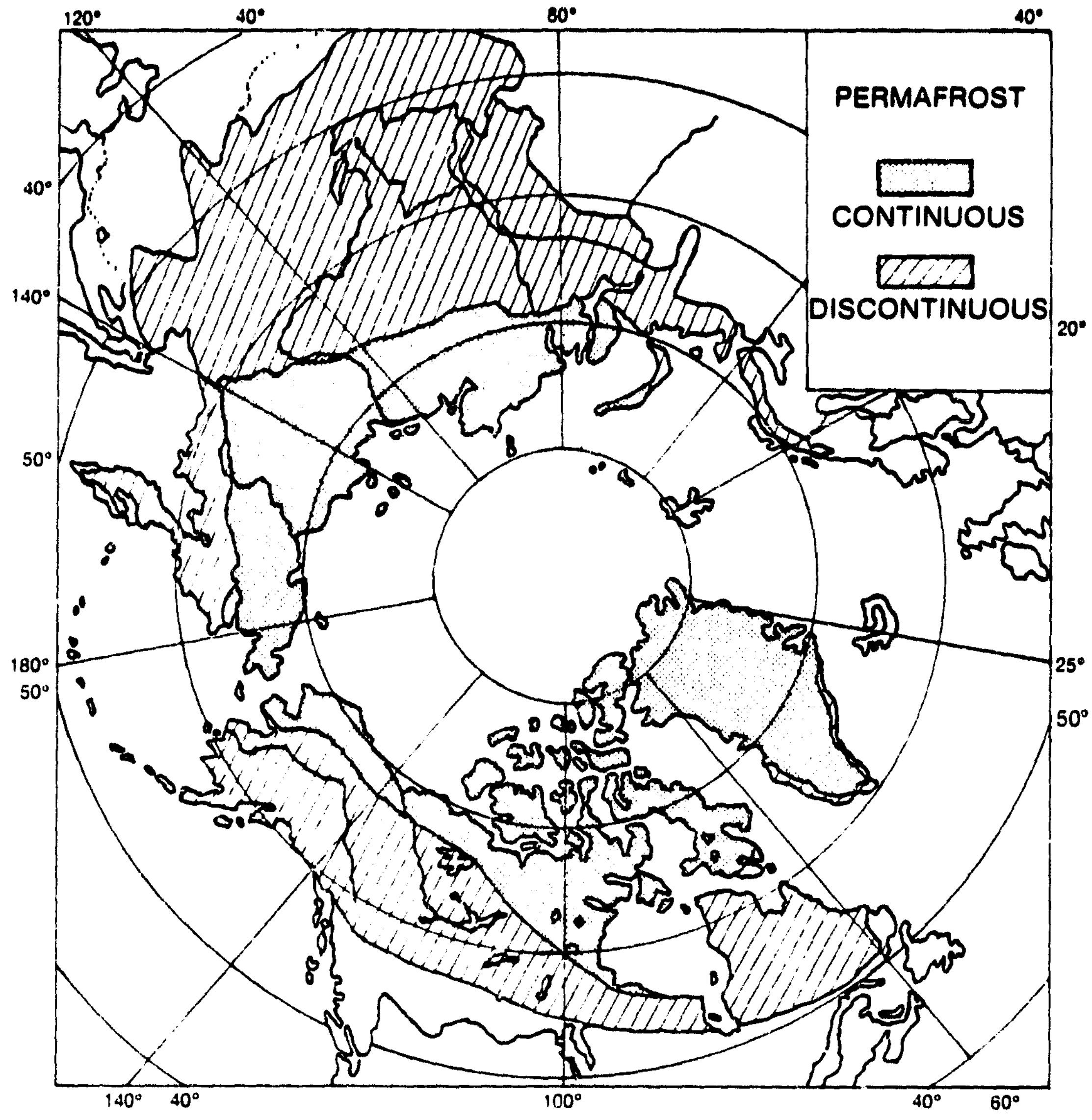


Figure 2-9. Permafrost of the Northern Hemisphere (from Pewe, 1969)

The present day distribution of continuous and discontinuous permafrost bears no semblance to the present day distribution of any other physiographic, geologic, botanic, or climatic characteristic. There are numerous indications that part of the existing permafrost is of Pleistocene origin, as evidenced, for instance, by preserved tissue from Pleistocene animals, by temperatures decreasing with depth, and by maximum permafrost thickness in areas not glaciated during the Pleistocene. Conversely, it stands to reason that some of the contemporary permafrost in formerly glaciated regions should be of post-glacial origin (Washburn, 1973).

Permafrost is not only constantly and subtly responding to climatic variations, it is also highly susceptible to alteration by human activities (witness the environmental problems encountered in planning the Trans-Alaska Pipeline) (Lachenbruch, 1970). An important recent discovery is that of subsea offshore permafrost along the North Alaskan coast, where hydrocarbon extraction is expected to occur in the near future. Clearly, the existence and changes of permafrost per se are of great economic importance.

A useful summary of priorities for basic research on permafrost was published by the National Academy of Sciences (NAS, 1974). Summaries of priorities for basic research on permafrost were published by the National Academy of Science (NAS, 1975, 1976), and the latest progress is reported in the proceedings of the third International Permafrost Conference held in Edmonton in 1978.

2.5 ICE SHEETS

It seems safe to assume that over the last 10^5 years the role of the Antarctic and Greenland ice sheets in global climate has not been drastically different from what it is today. The present day climates of Greenland (e.g., Putnins, 1970) and Antarctica (e.g., Schwerdtfeger, 1970) are well documented. The ice sheets of both these regions have high average elevations, and the present models of the atmosphere make somewhat simplistic assumptions to incorporate the effect of the ice sheets on the general circulation of the atmosphere.

Perhaps the most important contribution to the study of climate variation made by research on continental ice sheets has been the paleo-climatic information extracted from deep ice cores (e.g., Dansgaard et al., 1971, 1973). The interpretation of these ice core data is, in most locations, predicated on a realistic model of the thermodynamics and dynamics of the ice sheet (topography, flow, temperature).

A phenomenon of potentially great significance for world climate is the possibility, first proposed by Wilson (1964), that the Antarctic ice sheet (especially that of West Antarctica) is capable of surging. (Ice surging is discussed in greater detail in paragraph 2.6.) Detailed speculations on the consequences of such an event for world climate were recently presented by Flohn (1975). A surge of Antarctic ice would cause worldwide eustatic sea level changes of many meters (Hollin, 1965; Hughes, 1970; Mercer, 1978). No direct evidence of a surge on the Antarctic continent itself has yet been found, but there is reason to believe that the West Antarctic ice sheet, grounded as it is on bedrock below sea level, might break up under a marked climatic warming. If it did, a rise of over 5 m in sea level is possible.

According to Bodvarsson (1955), ice sheets may be inherently unstable over long spans of time. Suppose the Greenland ice sheet is in equilibrium today and in a given profile the equilibrium line (accumulation = ablation) lies at a fixed height. A perturbation which makes the ice sheet expand laterally, while the height of the equilibrium line remains unchanged, will increase the accumulation area. This will enhance the further growth of the ice sheet and amplify the initial perturbation. A mathematical analysis showing the unstable and stable modes of this process was developed by Weertman (1961). Our contemporary ice sheets (except for a portion of southern Greenland) are bounded by the ocean and are unlikely candidates to exibit this type of unstable behavior. However, both the Laurentian and the Eurasian Pleistocene ice sheets terminated on land and may well have been affected by this instability.

The modeling of ice sheets has fascinated theorists for the past two decades. Ice sheet modeling requires these considerations:

a. A knowledge of the topography of the surface and the bedrock, in order to determine the configuration of the major ice streams;

b. Surface temperature data;

c. Data on accumulation, ablation, and net elevation changes;

d. A flow law for ice relating stress and strain rate;

e. Geothermal heat flux;

f. Information about the state of the ice (frozen or melting) at the bedrock interface;

g. Rate of iceberg discharge (volume).

A review of the extensive literature on this subject was given by Budd (1969), Budd and McInnes (1977), and Radok (1978) and is discussed in Chapter 4.

2.6 MOUNTAIN GLACIERS

Man has only in recent times overcome his fear of mountains and mountain glaciers. It was Louis Agassiz in 1863 who initiated the scientific study of glaciers in Switzerland. Since then, glaciers in the major mountain ranges around the world have become increasingly important to man, not only as objects of scientific curiosity but also for many practical applications. Among these are utilization of meltwater runoff for hydroelectric power generation and irrigation as well as recreation in a variety of different forms. Nevertheless, glaciers still pose a threat to man. Periodic discharge of glacier-dammed lakes causes annual loss of life and property. Iceberg calving from the tidewater glaciers in Greenland, Alaska, and elsewhere imperil shipping. Surging glaciers, such as the Black Rapids Glacier in Alaska, have on occasion sliced highways and threatened houses and other structures. Also, the glacier-clad active volcanoes of Alaska can produce mud and debris slides when volcanic activity increases. The exposure of the population to the hazards of glaciers is increasing as more people are forced, by the growing density of world population, to locate within short distances of mountain glaciers.

Glaciers have been of interest in the study of climatic change and have been included in the earliest investigations. Some of the first indirect evidence for climatic change came from the study of certain geomorphic features and the realization that they must have been caused by glacial variations in the past. Since the late 19th century, there have been literally hundreds of attempts to relate observed climatic trends and variations with the termini of glaciers in the Alps and other mountain ranges. At present, the total area of all mountain glaciers on Earth is so small that it is safe to assume that mountain glaciers have no appreciable feedback effect on global climate. This is probably true even on the time scale of the entire Quaternary Age: the great ice sheets of that era did not descend from glaciated mountains, but formed on the flat terrain of northern North America and Eurasia.

In the 1930's and 40's Harald Sverdrup (1936), Hans Ahlmann (1946), and others began to study the physical processes controlling the heat and mass balance of glaciers. In the early 1960's, John Nye (1960, 1963, 1965) pioneered the theory of the dynamics of glacier flow and its relationship to mass balance. Today, evidence has been accumulated to indicate that as many as 5 percent of all mountain glaciers are capable of "surging" at periods ranging from 10 to 100 years. While the mechanism of surging is not clearly understood, it is virtually certain to depend on the mechanism of sliding on the glacier bed, and it may react to subtle changes in the integrated glacier mass and heat balance (Kamb, 1970).

2.7 RIVER AND LAKE ICE

River and lake ice is formed when the air temperature falls below $0^{\circ}C$ for a sufficient period of time to cool the surface waters to the freezing point. This phenomenon occurs much farther south than sea ice because the freezing point of fresh water is about $2^{\circ}C$ higher than that of seawater, and because lakes and rivers have a smaller reservoir of sensible heat that must be removed before freezing is possible.

Lake ice is, in many ways, similar to sea ice because it is largely produced by simple one-dimensional freezing. The end result is a layer of pure ice commonly containing, as its principal "impurity," layers of elongated gas bubbles. The maximum thickness of lake ice is variable, depending on the winter climate at a given location and on the characteristics of the lake. Ice as thick as 2.5 m can occur on lakes in the Arctic. Because it contains no brine, lake ice is quite strong and even ice covers of modest thickness are capable of supporting large loads. Therefore, lake ice is commonly used as a bearing surface by industries such as logging; trains have even been operated across lakes during the winter.

The ice cover of most small lakes becomes fast soon after initial freeze-over and stays that way until breakup. However, on large lakes, winds and currents may cause ice to drift in a manner similar to pack ice on the sea. The varying patterns of ice upon large lake systems such as the Great Lakes create obstacles for the considerable ship traffic in these waters. Operational ice forecasting can assist shipping activities.

Although similar to lake ice, the ice covers on rivers exhibit many unique features. For instance, strong currents cause the formation of individual ice spicules (so-called frazil ice) that can be swept along to form massive accumulations of fine-grained, randomly oriented ice crystals. Frazil ice can also stick to and grow on objects on the bottom of rivers-resulting in anchor ice. Perhaps the most interesting aspect of river ice covers are ice jams, large accumulations and pile-ups of ice that can form at bends and restrictions of rivers. At times, ice jams can effectively block river channels causing severe local flooding; it can damage bridges and other structures by ice impact and close rivers to barge and ship traffic. When ice jams curtail shipping on rivers such as the Mississippi and the Ohio, the economic losses are several million dollars per day.

CHAPTER 3. SCIENCE AND APPLICATION RESEARCH PROBLEMS

CHAPTER 3. SCIENCE AND APPLICATIONS RESEARCH PROBLEMS

3.1 INTRODUCTION

Ice is studied in different scientific disciplines and on different space and time scales. Those scales vary from individual ice crystals to the planet's large ice sheets, and from nucleation processes that require split-second timing accuracy to the ice-age processes of large ice masses. As shown in Chapter 2, ice is of crucial importance to the study of climate and climatic change; it is of equal importance to applied science in such activities as offshore exploration and extraction of mineral resources (particularly oil and gas). Sea ice is a major problem to offshore activities, while on land, ice-associated hazards include permafrost, river and lake ice, avalanches, and drifting snow.

Snow and ice, nonetheless, constitute a valuable resource for hydroelectric power generation, irrigation, food production, and recreation. As pointed out in the previous chapter, ice and snow affect not only the lives of those living in the polar or subpolar regions, but the life of every human being. How they do so is the subject of this chapter.

3.2 REMOTE OBSERVATIONS OF ICE FORMS AND PROCESSES

The use of suitably designed spaceborne sensors would advance significantly research on, for instance, the processes and resulting patterns of pressure ridging in the ice pack of the Arctic and Antarctic Oceans. The combined use of laser and radar altimeters and imaging radar systems would produce synoptic maps of ridging patterns, facilitating interpretations of the formation and mechanisms of ridging. Questions about the amount of open water and ice of different thicknesses within the polar ice pack and the way these areas change with time are relevant to both the dynamic and thermodynamic processes in the polar regions. The combinations of imaging radar, laser altimeter, and microwave scanning radiometer data would resolve these questions.

One of the most difficult aspects of sea ice to examine is the nature of the ice-air-ocean interactions at the margins of the ice pack, (i.e., where it bounds on the open ocean). A large antenna multifrequency microwave radiometer on a space platform would locate the ice edge, even through clouds, with sufficient definition to study the large wave-like patterns apparently associated with the passage of storms. An imaging radar would provide information on ocean waves, on changes in pressure ridges, and on the relative movements of identifiable ice features. A microwave radiometer would also allow the examination of thermodynamic problems such as the formation of large "bays" of open water during the ablation or melting period. The "bays" are presumably the result of thermal "erosion" of the ice by warm currents. Examining these problems using surface-based operations is effectively impossible because of the large areas that must be sampled almost simultaneously. Suitable remotely sensed satellite data can be used to extrapolate, to wide areas, individual ground observations performed by ship or aircraft-based teams.

Various aspects of large ice caps and glaciers must also be examined. In order to understand the mass balance of these ice masses, for example, high quality measurements of both ice surface elevation and ice surface elevation changes must be available. It is surprising in this time of precision surveys to discover that little is known about the surface topography of the world's great ice sheets. Precise satellite altimetry measurement would rapidly fill this gap by providing high resolution surface topography. This topography would serve as the primary input to numerical glacier flow models used to examine a wide variety of problems related to ice sheet dynamics. Questions, such as whether or not the West Antarctic ice sheet is about to experience an accelerated flow, could be addressed with additional confidence. The quality of precision altimeter-derived topography would permit the observation of the migration of individual kinematic waves. Seasonal changes in the surface roughness of Greenland and Antarctica could be mapped for the first time. Other ice sheet "features" that could be mapped include the presence of free water in the surface layers of snow (by the use of the passive microwave radiometer), and perhaps the surface stratigraphy and near-surface temperature.

The sequential mapping of regions where free water is expected in the seasonal snow cover would help to specify regions where the snow pack is, or is about to become, isothermal at the melting point. Such information would be of assistance to a variety of applied problems such as avalanche forecasting and runoff prediction. At present, the water equivalent of the seasonal snow pack (the parameter that would be of the greatest use to the study of snow hydrology) still cannot be determined via satellite observation techniques, although progress is being made on potential remote sensing techniques.

To date, the dynamics of ice covers during freezeup and breakup in large northern river systems have only been addressed in a limited, qualitative way. Spaceborne observational systems designed for ice studies will help in understanding the processes responsible for such problems as ice cover initiation during freeze-up and ice jam formation during breakup. Such observations are also necessary in order to develop quantitative descriptions and models of these occurrences.

The list of basic research problems presented here is hardly exhaustive. It represents only a few typical investigations to which the ICEX program can contribute. Other fundamental problems will become apparent from the more extensive discussion of the applied science aspects in the following sections.

3.3 ICE AND ITS ROLE IN THE CLIMATE SYSTEM

Estimated areas and associated volumes of the various components of the cryosphere have been conveniently summarized in table 2-1 by Untersteiner (1975). The aspects of the cryosphere that are of concern to studies of climate variability and change vary with the time scale involved and the relevant problems of society.

Abnormal meteorological conditions (climatic anomalies), lasting from a few months to a year or two, can be presumed to interact primarily with changes in snow cover and sea ice and are relevant to food production and energy consumption. Climatic variations, lasting from a few years to a few decades or so, produce systematic changes in the extent of snow, sea ice and mountain glaciers. These changes are relevant to hydroelectric energy production and planning, and operation of water storages. Finally on longer time scales, climatic changes, in addition to affecting snow and sea ice, may influence the polar ice sheets and consequently sea level. Such influences have important implications when considering manmade effects on climate. Furthermore, the layers of such ice sheets contain useful records of past climatic changes. Thus, while all ice forms have some bearing on climate, the principal focus shifts significantly with ice types and time scales of interest.

3.3.1 SNOW IN THE CLIMATE SYSTEM

Until the advent of satellites, snow ranked among the more difficult meteorological elements to observe on a regional and global scale. This situation is now changing with the introduction of versatile remote sensing methods from spacecraft and aircraft, especially those using the naturally emitted radiation in the microwave band of the spectrum and the gamma ray emission from radioactive minerals in the soil. Multiple spectral vegetation imagery obtained from the Landsat satellite registers relatively recent climatic changes in the climatological snow line of regions occupied by the North American ice sheet up until about 6,000 years ago (Barry et al., 1975). Satellite measurements of the thickness and structure as well as the thermodynamic condition of the snow appear within reach and will, in due course, aid the interpretation of the effects of snow on climate and vice versa.

The presence of snow cover on land obviously increases the surface reflectivity (albedo), which in turn changes the amount of solar radiation absorbed and the heat balance of the entire hemisphere. Indeed, climatologists have identified snow as part of an important feedback mechanism: more snow results in the absorption of less solar radiation which cools the region thereby producing more snow cover--the net effect may be to amplify a small anomaly (Kellogg, 1975). Thus, year-to-year changes of snow cover on a continental scale have an important effect on the hemispheric heat balance (Kukla and Kukla, 1974) and knowledge of this phenomenon offers a potential for improving extended-range forecasts of the weather. However, the development of such forecast techniques will depend, in large part, on improved observations of snow cover from satellites over a period of many years.

The new remote-sensing capabilities have facilitated a number of experiments, initiating the regular monitoring of a range of parameters derived from the extent of the snow cover on land and of sea ice. So far, the parameters mainly relate to albedo (refer to figure 3-1) and include both direct information such as the total snow-covered area, and derived quantities such as the absorbed radiation.

The contribution of polar snow to the global albedo is not the only climatic effect of snow. Of equal or greater significance may be the insulating properties of snow which trap ground warmth below the colder snow, consequently reducing the terrestrial heat loss. Another important climatic factor may be the change from net cooling to heating caused by aerosols which modify the effectiveness of snow albedo (Kellogg et al., 1975). The latent energy absorbed in the ripening and melting of snow and the association between snow cover and cloudiness are other factors. All of these aspects have only just come within reach of larger scale studies, and will show, in due course, which aspects of snow constitute climatic causes and which are effects. Regular monitoring of the large-scale annual snowpack will aid a multitude of practical concerns, as discussed in other sections.

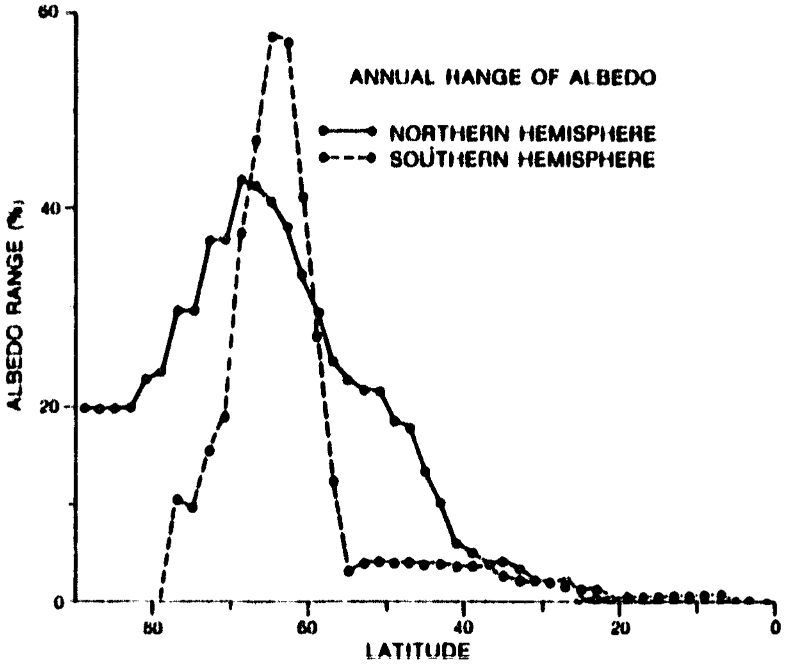


Figure 3-1. Annual Range of Zonal Monthly Surface Albedo Estimated by 2° Latitudinal Belts

3.3.2 SEA ICE IN THE CLIMATE SYSTEM

Like terrestrial snow, sea ice strongly modifies the albedo of the Earth's surface. In fact, it is an even more significant factor modifying the transfer of heat from the local surface to atmosphere. Solid ground below snow cannot accept or give up any substantial quantity of heat, owing to its poor heat conductance relative to water, for example. In contrast, the ocean surface, especially in winter, provides large amounts of heat and moisture to the air whenever the ice opens into leads or polynyas. The magnitude of the heat transfer from leads in the sea ice can far exceed that of conduction through a closed ice cover and is largely controlled by the ice dynamics.

An understanding of these complex processes is currently emerging from field studies such as AIDJEX. The concepts are being incorporated into the surface layer parameterization of atmospheric and oceanic models. Untersteiner (1975) has summarized this work for the Stockholm Conference (GARP 1975); progress since then will be covered by the Proceedings of the 1977 ICSI/AIDJEX Symposium on Sea Ice Process and Models (University of Washington Press, in press). In addition, a good deal of empirical information has accrued on parallel changes in sea ice and climatic parameters. In the Arctic, a millennium of observations of Iceland (Bergthorsson, 1969) has shown a fairly tight relationship between temperatures and the extent of the northern sea ice. The much shorter series of observations of Laurie Island in the South Atlantic now covers almost 75 years and indicates a similarly close relationship (Prohaska, 1951). For the even shorter period of hemisphere-wide satellite observation of sea ice, Budd (1975) has shown how related anomalies in temperatures and sea ice extent tend to move around the Antarctic continent, affecting sections of about 90 degrees of longitude.

An apparent effect of the sea ice edge on the track of atmospheric depressions or vice versa (Schwerdtferger and Kachelhoffer, 1973) remains to be explained in terms of detailed dynamics and thermodynamics. In broad terms, fluctuations in sea ice melting should be more effective than sea surface temperature anomalies in creating air temperature anomalies. Moreover, the sea ice influence may spread much further afield through the physical processes resulting from the ice formation and decay all along the coast.

As an example of widespread sea ice influence, consider the Antarctic sea ice life cycle. In late summer, the Antarctic sea ice has largely disappeared and left a layer of relatively fresh melt water extending in places as deep as 200 m (Gordon, 1967). This cold, fresh surface layer gradually absorbs quantities of O_2 and CO_2 before the new sea ice forms in Fall and isolates the water from the atmosphere. The exception occurs in leads and in coastal polynyas created by katabatic winds from the ice sheet. A crucial process then ensues, lasting through the winter and through the ice decay in the following summer: the water below the ice becomes more saline, first due to rejection of salt from the growing sea ice, and then due to brine drainage as the ice decays. The resulting increase in density leads to a continual overturning which forms the cold saline and O_2/CO_2 rich Antarctic bottom water. The bottom water flows northward and emerges ultimately in the northern oceans, notably in the Atlantic.

These process of bottom water formation and transport may play a part in the long-term fluctuation of ocean temperatures and, hence, climate. Monitoring of this sequence has been recommended by the Stockholm Conference (GARP, 1975).

3.3.3 GLACIERS AND ICE SHEETS IN THE CLIMATE SYSTEM

The advance and retreat of mountain glaciers have been among mankind's first indications of the variability of climate. The advances and retreats of glacier tongues follow climatic anomalies with a substantial lag, however, and represent the net balance of diverse climatic effects. The monitoring of mountain glaciers therefore provides a natural integration of regional climatic fluctuations which may be difficult to dissect (Radok, 1978).

The large ice sheets of Antarctica and Greenland are not only indicators of climatic anomalies, but they are sufficiently massive to interact with climate and influence its course. Wilson (1964), for example, has claimed that surges of the Antarctic ice sheet could fill the southern ocean with ice and initiate a global glaciation by raising the Earth's albedo. It has also been suggested that such surges could be induced by a general warming of the polar region and would produce a distinct rise in sea level (Hughes, 1973; Mercer, 1978). This and other similar hypotheses cannot be tested conclusively, however, until more detail is learned about the past climatic record and about the ice sheets themselves (Radok, 1978).

In order to understand what is now happening to the large ice sheets of Antarctica and Greenland—how they have responded to or perhaps caused major climatic changes in the past and how to predict what the ice sheets will be doing in the future--we must first know their surface and basal configurations and whether the total amount of ice at present is increasing, decreasing, or remaining constant. This is a complex problem because, in all probability, different parts of the ice sheets are behaving in different ways. In Antarctica, in particular, there is reason to believe that some drainage systems within the ice sheet are decreasing in mass while others are increasing. It is not enough, therefore, to know the overall balance of the ice sheet; the separate behaviors of individual drainage basins must also be known.

The important terms in the mass balance equation of the ice sheets are the rate of mass input from snowfall on the surface of the ice sheet and the rate of ice loss at the margins. Knowledge of these rates, however, is not the only element needed to understand present changes. Rates of raising or lowering of the ice sheet surface and horizontal velocity gradients (strain rates) are also needed. In other words, six quantities--surface elevation, surface elevation change, surface mass input, velocity, strain rate, and ice thickness--must be determined.

The most fundamental ice sheet measurements attainable from spacecraft are those used to produce an accurate map of the surface elevations of the ice sheet and its changes. Knowledge of the ice sheet configuration to an accuracy of approximately 1 m will make it possible to distinguish the various drainage basins and to determine the direction and magnitude of the surface slope within those drainage basins. The surface slope parameters, in turn, control the direction and speed of ice flow, including the ice streams and outlet glaciers which carry most of the ice outflow. Aircraft and satellite remote-sensing techniques, together with surface platforms, can also help in determining the remaining parameters.

In view of the general warming expected in the next few decades and the effects this will eventually have on the ice sheets, it is clearly of the utmost importance to begin monitoring their behavior immediately. Our present knowledge of ice sheets is so incomplete that we cannot predict whether they will surge or break up (as suggested above), will shrink due to faster melting of their edges, or will grow due to more snowfall on their surfaces. However, the ability to monitor ice sheet surface topography to an overall accuracy of 1 m would allow the detection of a change of ice volume that would correspond to 3 to 4 cm of sea level change. An early warning could be issued to the world concerning the trend in ice sheets and sea level.

3.4 ICE AS AN ENVIRONMENTAL HAZARD

The polar regions are rich in mineral resources. In the Arctic petroleum is produced on land in the United States, Canada and the Soviet Union, and exploration is proceeding offshore. The investment by the petroleum industry in Arctic offshore exploration is enormous. In Canada about $1 billion has already been spent by the Arctic Petroleum Operators' Association (APOA). Of this amount over $150 million went to studies concerned with the characteristics, dynamics, and mechanics of sea ice. The investment by the petroleum industry in Alaska is considerably larger, exceeding 9 billion dollars for the Trans-Alaska Pipeline alone. Such investment costs will presumably increase rapidly following offshore lease sales in the Beaufort Sea, Chukchi Sea, Norton Sound, and Bering Sea; all areas covered by seasonal sea ice. Safely operating offshore drill rigs in the ice covered waters of the Arctic is at best a costly business. If the nature of the ice hazards can be well defined, then more efficient offshore designs can be achieved with the possible savings of several millions of dollars per structure as compared to structures that must be overdesigned because of inadequate environmental information.

Coal deposits are known to exist in both polar regions. Of the estimated and identified sub-bituminous coal resources remaining in the ground in the United States, 25 percent is in Alaska (Averitt, 1973). Coal is mined in the Spitsbergen Islands, the Soviet Union, and Alaska. Large coal deposits are also located in the Antarctic. Metallic mineral resources are extensive north of latitude 60°N and in Antarctica.

The possibility of exploring potential mineral resources in the Antarctic is rapidly becoming a subject of considerable international interest. The Antarctic Treaty, which is due to expire in 1991, limits all territorial claims but leaves the question of resource exploration and exploitation open.

The polar regions are also the source of abundant renewable resources, including fish and marine mammals. Arctic fish catches exceed five million metric tons annually (CIA, 1978). In the Antarctic, krill fishing may become a major new commercial activity.

Much of the money and time spent on polar resources is devoted to the study of the snow and ice that impede all phases of industrial activity--from initial detection of a resource, to extraction, to transportation.

In addition to the problems of sea ice already discussed, there are also permafrost hazards, both onshore and offshore, to buildings, roads, pipelines, etc.; mountain glacier surges which pose dangers to roads and pipelines (e.g., the Black Rapids Glacier in Alaska); and iceberg calving which threatens shipping. Drifting snow and avalanches block roads and railway tracks. River and lake ice formation and breakup and the spring snow melt may cause ice jams and flooding. Snow and ice are in fact a constant threat to many areas of the Northern Hemisphere. The effects of these hazards and countermeasures to control them on land probably cost the United States billions of dollars annually.

Specific implications of ice and snow hazards are discussed in the following sections, with emphasis upon petroleum development. Alternative solutions, which have been utilized or are presently under design, are also discussed. In many cases, particularly for sites in deeper waters, additional information is needed before designs can be optimized.

3.4.1 ICE HAZARDS TO POLAR PETROLEUM ACTIVITIES

As worldwide petroleum resources dwindle, and the number of conveniently explorable geologic structures diminishes, the search for oil and gas turns to frontier areas such as the polar regions.

Large oil and gas resources exist in the Arctic. The demonstrated reserves of the Alaskan Prudhoe Bay oil field are 10^{10} (10 billion) barrels, or 25 percent of the known United States reserves. According to Miller et al. (1975), the total remaining resources for the Alaskan North Slope are estimated to be between 6 and 19 x 10^9 barrels of oil onshore, 3-31 x 10^9 barrels offshore, 16-57 x 10^{12} ft^3 of gas onshore, and between 8 and 80 x 10^{12} cubic feet of gas offshore. In the Canadian

Arctic, the proven recoverable hydrocarbon reserves are 3.77×10^7 barrels of oil and 3.85×10^7 barrels of natural gas liquids, and the estimated resources are 15.9×10^9 barrels of oil and 154.6×10^{12} ft^3 of gas (DEMR, 1976).

Some of the ongoing and projected offshore petroleum activities of the Arctic are shown in figure 3-2. There is also onshore exploratory drilling in NPRA (National Petroleum Reserve Alaska) at Prudhoe Bay, in the Mackenzie Delta, and in the Canadian high Arctic.

The distribution, morphology, type, and movement of sea ice affect the timing and length of the offshore oil drilling season and the transportation of drilling supplies and petroleum from the production area. Typical sea ice features and zonations are shown in figure 3-3. Whenever sea ice is present, it is a major hazard to offshore operations if structures are not adequately designed to resist forces induced by ice movement (Weeks et al., 1977).

Below the surface, scouring of the sea floor by ice keels also presents hazards to drilling operations (Reimnitz and Barnes, 1974; Lewis, 1977; Hnatiuk and Brown, 1977). The depth of individual ice scours ranges from a few centimeters to over 6 m, and scours occur across the entire continental shelf of the Beaufort and Chukchi Seas. Pipelines, subsea completion systems, and well-head equipment must be placed well beneath keel depths.

Additional problems on land are frequently caused by "ice push" or "ice shove," in which islands and mainland coastlines are overridden by sea ice over considerable distances (Kovacs and Sodlin, 1975).

Sea ice related problems facing offshore operators are numerous, as shown by table 3-1 below (extracted from a document AOGA, 1978).

Table 3-1. Sea Ice Environmental Concerns (AOGA, 1978)

	Number of Obstacles to Offshore Operations		
Degree of Concern / Type of Ice Zone	Bottom Fast Ice Zone (2 m Zone Water Depth)	Floating Fast Ice Zone	Pack Ice and Grounded Ridges
Some Concern	23	28	4
Considerable Concern	4	25	8
Major Concern	--	2	18

Table 3-1 represents a composite of an intricate matrix which pitted the phases of potential offshore industrial activities against the obstacles created by ice conditions. The matrix was created by listing the detailed steps involved in major

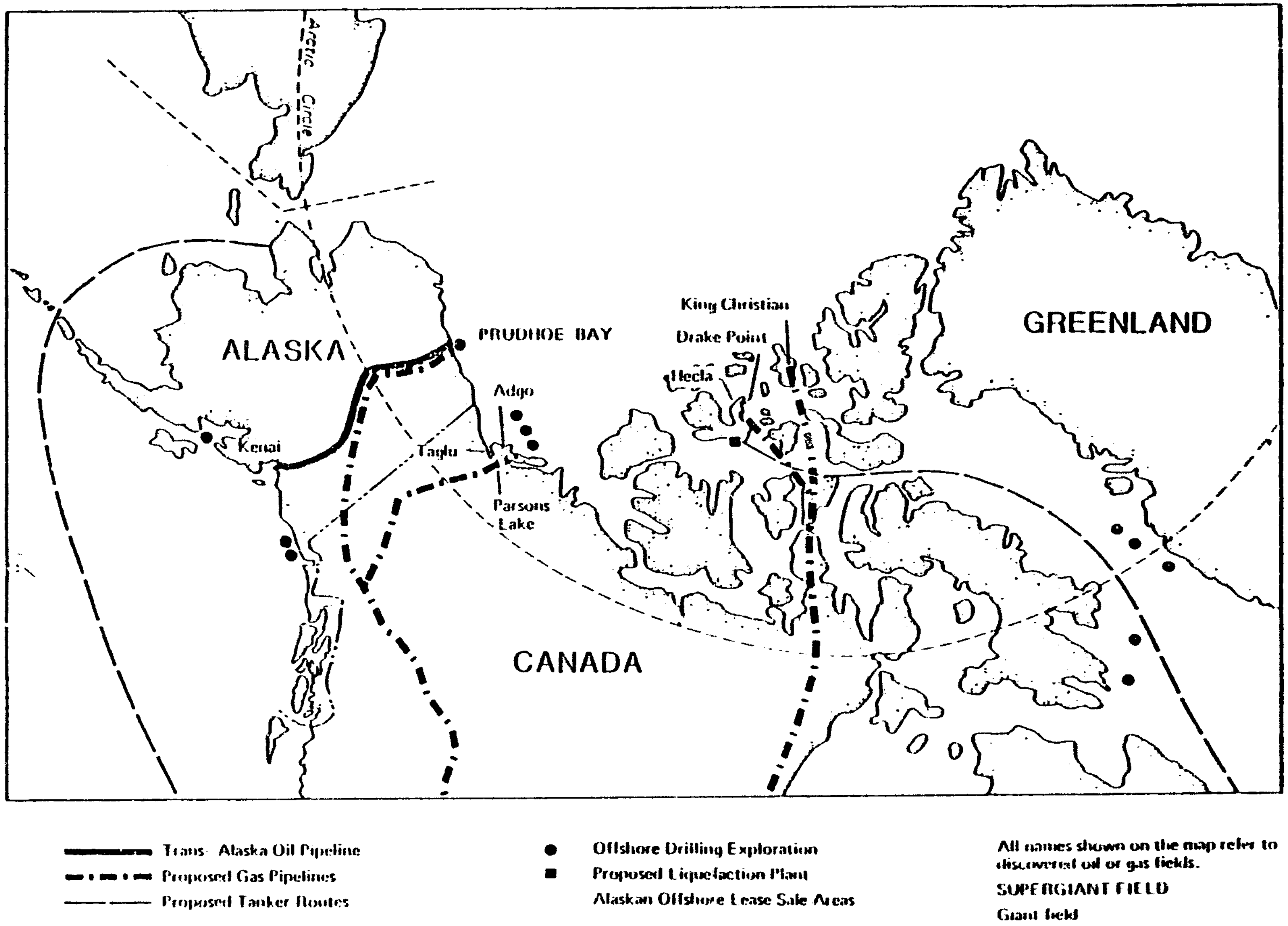


Figure 3-2. Oil and Gas Activities in the Arctic

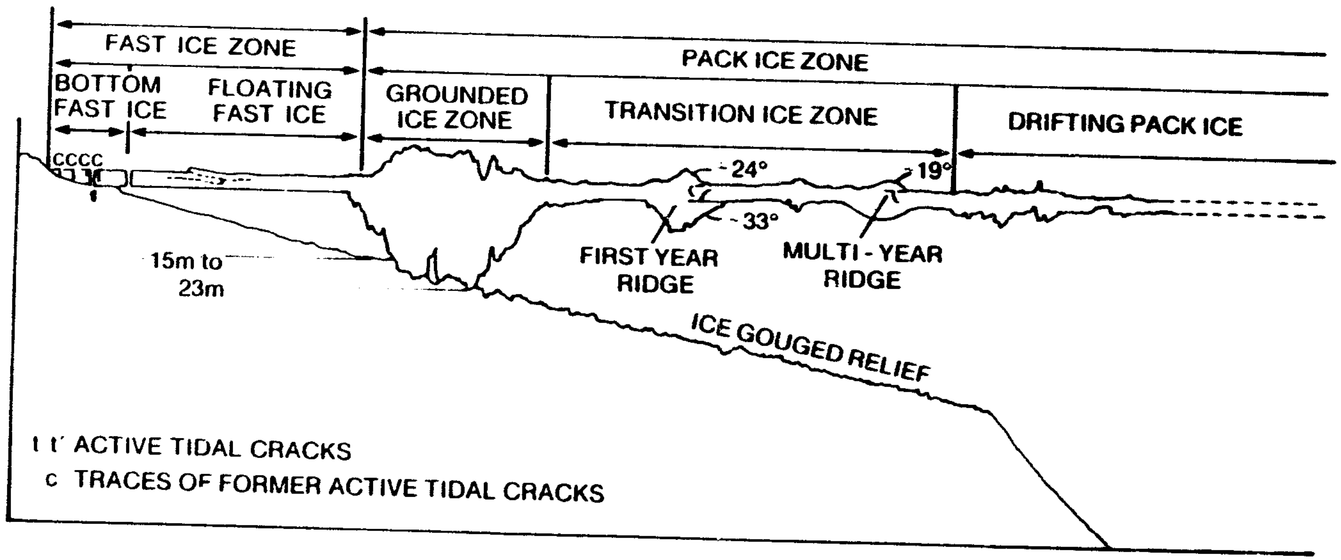


Figure 3-3. Late Winter Ice Zonation of the Beaufort Sea Coast (after Kovacs, pers. comm.)

Beaufort Sea activities (drilling, transportation, etc.) and then interviewing groups involved in these activities. Those interviewed listed the steps for which sea ice presented problems, and then ranked the severity of those problems. The interviews showed which ice processes affect particular activities. For example, summer pack ice invasions are a major threat to floating exploratory drilling platforms and multiyear ice floes are hazardous to fixed core structures. The study also revealed the present ability to deal with those events.

The major sea ice features and processes in which AOGA had an interest were as follows: ice movement during freezeup, winter ice movements, and movements during breakup (all such movements could include ice override), summer pack ice invasions, first-year ridges, multiyear floes and ridges, grounded ridges, floebergs, ice islands (icebergs), and ice gouging of the ocean floor. This list of problems, known to occur in the Beaufort Sea, is not unique to that area; similar problems will confront offshore petroleum development in other polar regions.

The detection of pollutants, including spilled oil, under and in ice also presents a very difficult problem, particularly if the spill occurs under sea ice. The sea ice cover may retain spilled oil for prolonged periods of time (Campbell and Martin, 1973). The oil is usually trapped in the uneven undersurface of the ice, and new ice will form below the oil layer (OCSEAP, 1978). The oil migrates upward during the melting season, increases the amount of solar radiation trapped, and melts the ice 2 to 3 weeks earlier than under natural conditions.

Remote sensing of albedo changes can be an important tool to monitor this kind of pollution. Information on the movement and deformation rate of the ice is also required in order to predict the trajectory, fate, and final destination point of the oil. Countermeasures to clean up the pollution depend on this information, which must be obtained in real time and under all weather conditions. The type of cleanup equipment and procedures to be used also depends on the characteristics of the ice. ICEX would clearly contribute valuable information in dealing with these problems.

Novel technological concepts are beginning to be used to confront the hazards of ice, which limit exploration of the polar regions for energy resources. These concepts are illustrated in figure 3-4. Figure 3-5 shows ice floes in the vicinity of an oil drilling ship in the Davis Strait.

Before the fine tuning of such designs for specific locations is possible, more information must be known about the ice characteristics and dynamics associated with each potential oil field. A large number of regional ice studies are required to detect the characteristics of individual areas. According to Canadian estimates, satellite monitoring of sea ice would benefit offshore drilling development from $2 million to $5 million annually (McQuillan, 1975).

Onshore, permafrost affects the construction of pipelines to the extent that the Trans-Alaska Pipeline, for example, initially estimated to cost about $800 million, finally cost over $9 billion because of, in part, the unexpected effort needed to preserve the permafrost. Rapid, detailed, and economical determination of permafrost distribution and of properties of frozen ground is required for many other engineering purposes such as transporting construction materials. The development of new or improved equipment and technology for studying permafrost, including remote sensing, is recommended by the National Academy of

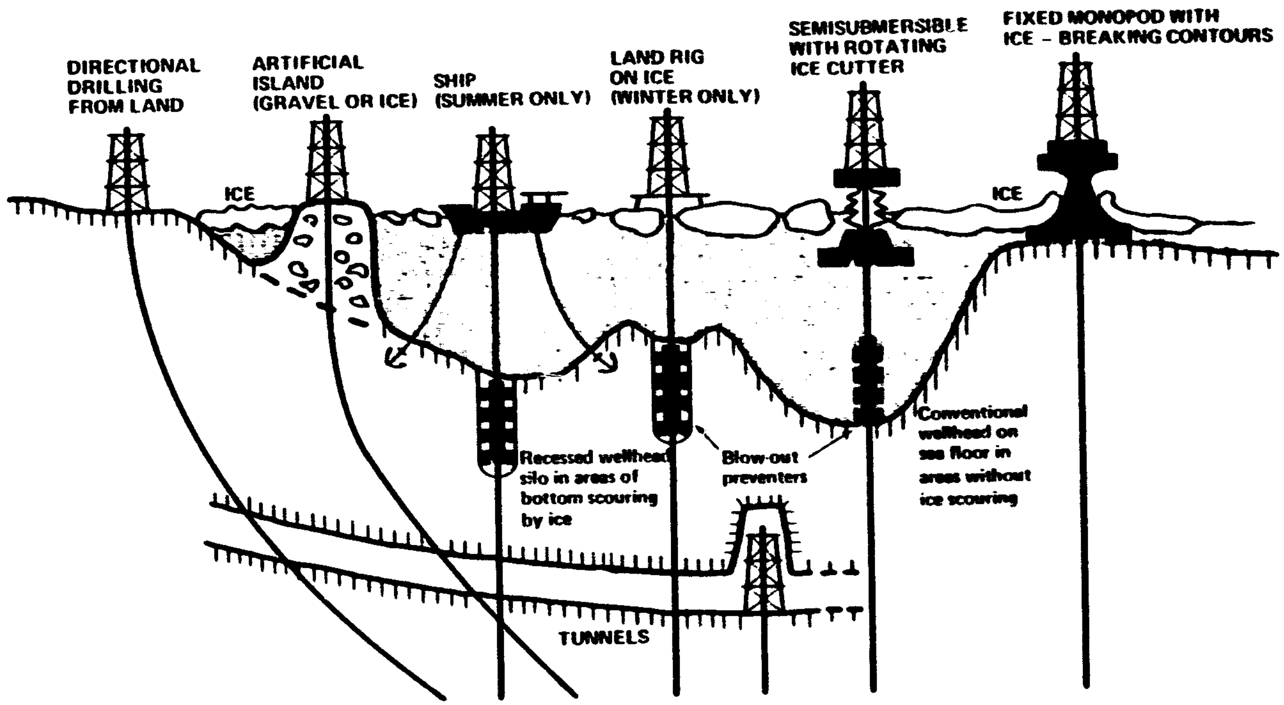


Figure 3-4. Methods of Drilling in the Arctic

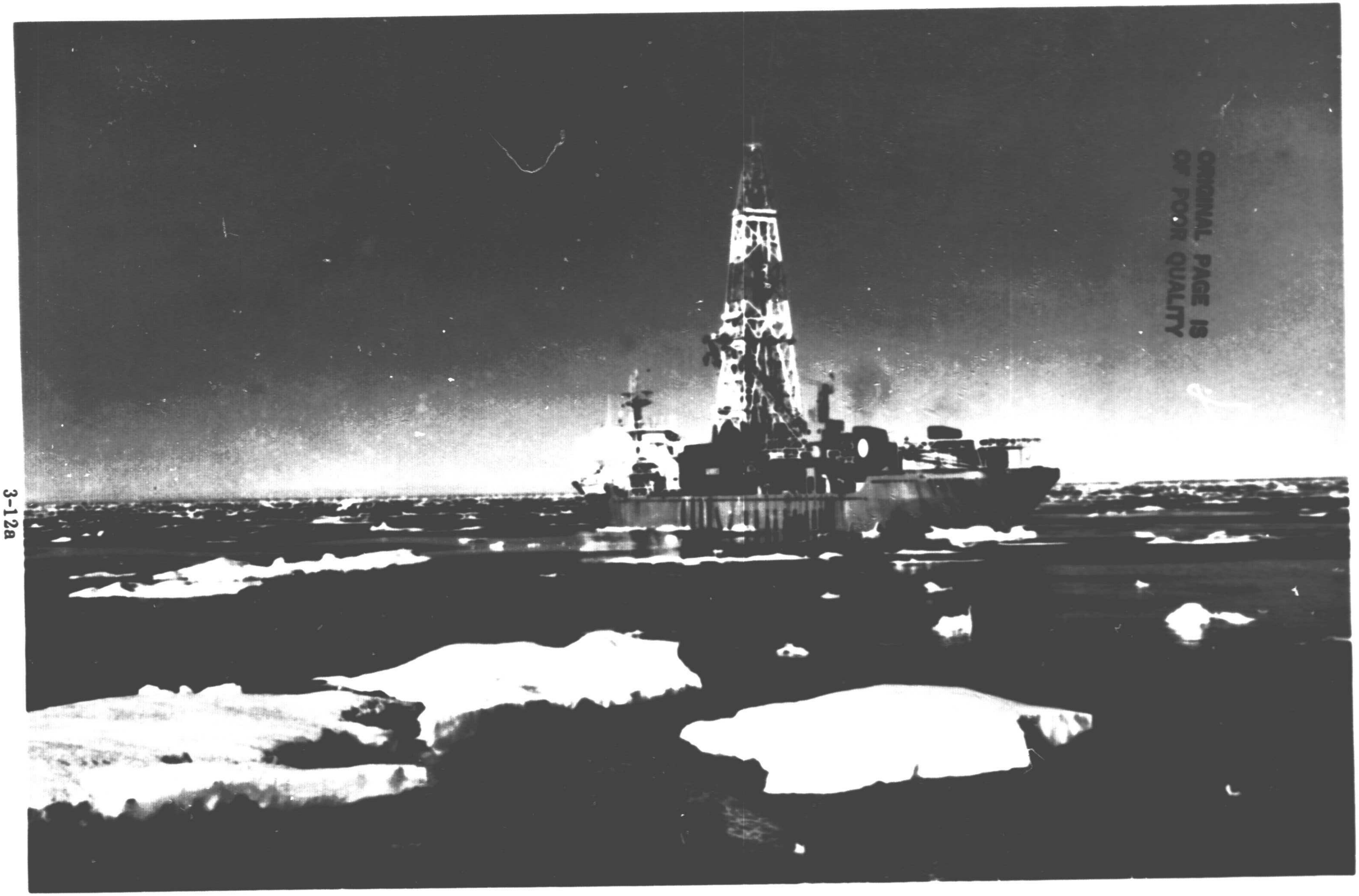


Figure 3-5. Ice Floes Near a Drilling Rig in the Davis Strait (Courtesy of MacLaren Marex, Inc.)

Sciences (NAS, 1974). Delineation of the geomorphology and land forms for permafrost terrain, a study of patterned ground and other physical surface features of this terrain, and electromagnetic probing below the surface is recommended.

3.4.2 ICE HAZARDS TO NAVIGATION

Marine shipping activities in Arctic waters are expected to increase rapidly during the next decade. Figure 3-6 is a projection, made in 1973, of this increased activity. Although the projections may be somewhat out of date, they probably still represent an approximate picture of future events.

Both sea ice and icebergs present serious hazards to shipping, and forecasting of their occurrence and movement are prerequisites to expanded shipping in the Arctic. While sea ice has already been discussed, icebergs have not. The latter present a serious hazard, especially near Newfoundland and Labrador.

Icebergs calved from West Greenland glaciers follow a route north to Baffin Bay, then west and south along the Labrador Coast to the Grand Banks of Newfoundland (figure 3-7), where they pose a threat to transatlantic shipping. The most notable marine disaster resulted when the RMS TITANIC collided with an iceberg on April 14, 1912 at the Tail of the Banks and sank with a loss of 1,513 lives. Consequently, the International Ice Patrol was formed at an international convention and has been operated by the U.S. Coast Guard since 1914. Since that time, many vessels have struck icebergs outside of the ice patrol area and other collisions have occurred with ships that venture into the stated limits of all known ice (Crowell, 1975). The most recent serious accident occurred in 1959 when the M/V HANS HEDTOFT presumably hit an iceberg and sank with the loss of all 95 persons aboard. Nonfatal collisions with icebergs as recently as 1973 and 1976 have imperiled the lives of mariners and severely damaged ships.

The presence of icebergs in the Northwest Atlantic shipping lanes is seasonal, with peak occurrence normally between March and July. The Grand Banks weather at this time is characterized by a high incidence of fog and low stratus cloud layer that hides icebergs from the usual method of visual aerial reconnaissance used by the ice patrol to find and track icebergs. Therefore, all-weather satellite surveillance is badly needed. Other forms of marine transportation in ice-covered waters include the important transportation routes on the Great Lakes, the Ohio and Mississippi River Systems, and the St. Lawrence Seaway. Several attempts have been made in recent years to improve techniques for moving commodities in the Arctic region, principally petroleum, from wellhead to market. For example, transportation of gas by pipeline from the Sverdrup Basin across Arctic islands in Canada is presently in the design stage. Transportation of oil by icebreaker vessels via the Great Circle Route, following results of the Manhattan Icebreaker Project, are still under consideration.

Processes such as glacier surges, the periodic drainage of glacier-dammed lakes, and the breakup of river ice require repeated short-term studies before, during, and after each event. The studies should reveal patterns and characteristics important in detecting and preventing flooding and possible shipping hazards.

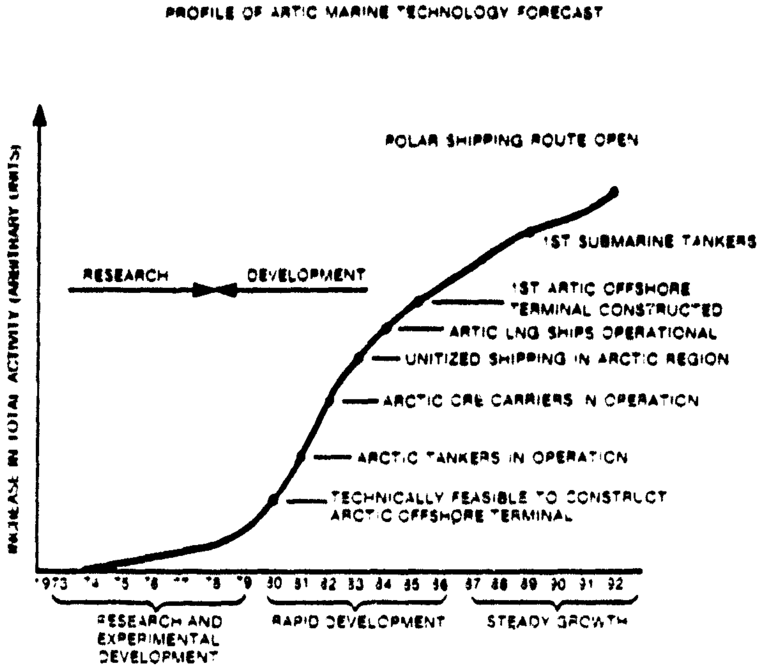


Figure 3-6. Projection of Marine Activities in Arctic waters (from Arctic Marine Commerce Study by AINA, sponsored by the Maritime Administration, 1973).

3.4.3 OTHER SNOW AND ICE HAZARDS

Snow is a hazard which costs both the United States and Canada billions of dollars annually. To illustrate this question of costs, a few examples are quoted. In the city of Chicago alone, it has been estimated that only 2 inches of snow on the highways increases fuel consumption by 50 percent and causes millions of commuters an average delay of 30 minutes, representing a substantial economic loss (Claffey, 1972). National expenditures to clear the road of snow by salting and plowing are enormous. Resulting salt-related highway damage is about $500 million per year nationwide, and damage to automobiles has been estimated at $119 million per year for the greater Boston area alone (Anderson and Austen, 1974).

Surging glaciers, tidewater glaciers with calving icebergs, and glacier-dammed lakes are serious hazards in Alaska, Canada, and elsewhere; these can be partially evaluated and monitored by ICEX. For example, rapid release of water from glacier-dammed lakes has caused loss of lives and extensive damage to roads, bridges, and houses in Alaska. The increase in water levels in these lakes could be monitored by ICEX to aid warnings of possible impending water release. The Columbia Glacier in Prince William Sound has recently caused considerable concern over the safety of oil transportation from the Port of Valdez. Calving from this glacier could prevent oil tankers from entering or leaving Prince William Sound, thus shutting off the supply of Alaskan oil to the contiguous states. ICEX could aid substantially in studies to monitor and evaluate this hazard.

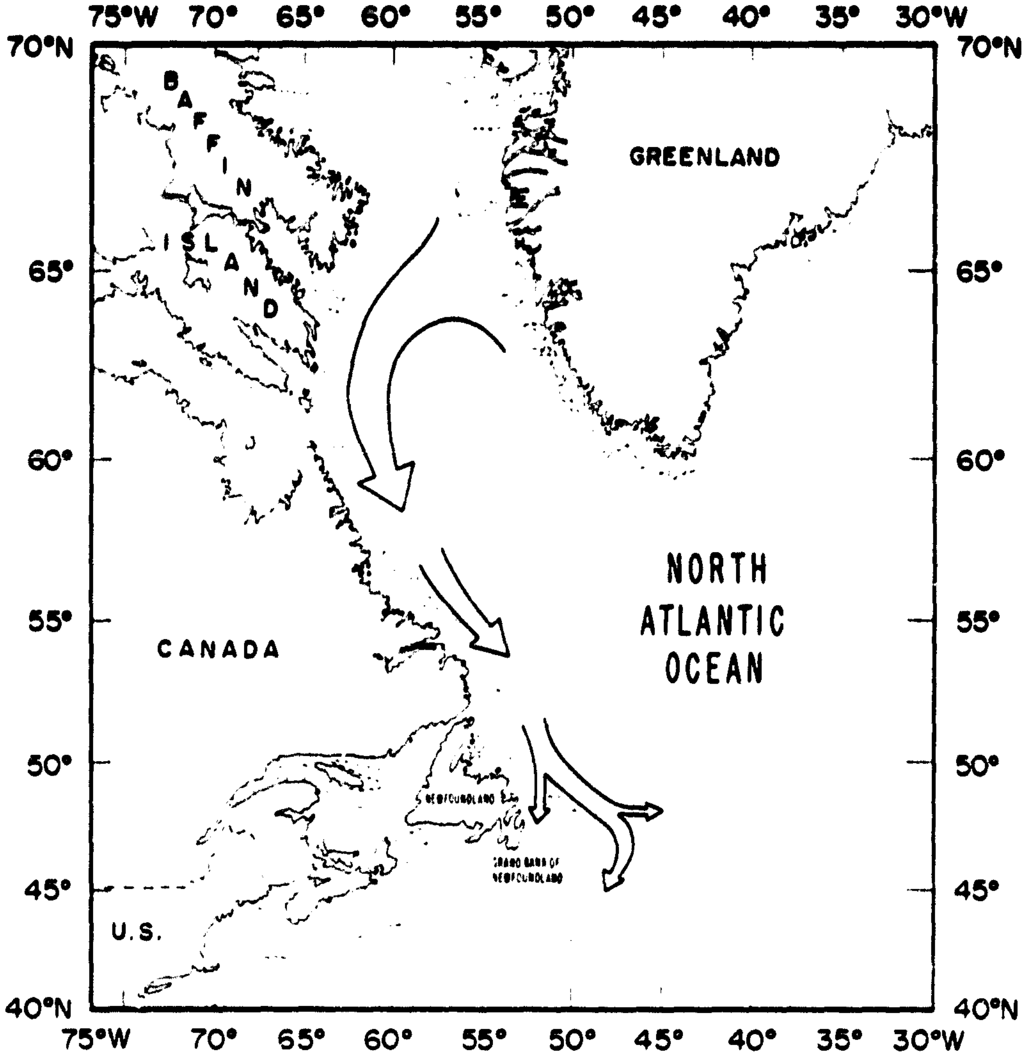


Figure 3-7. Iceberg Tracks Along the East Coast of Canada

The problems of the Great Lakes area and the St. Lawrence River Seaway have already been mentioned. Similar problems will need to be addressed in large northern rivers such as the Yukon River and the Mackenzie River because of expanding interest in resource development in these areas. The timing and extent of the ice cover, location of open water areas during winter, and sites of recurrent ice-jam floods can all be identified from ICEX imagery. Large lakes in the north of Canada and Alaska may also be used as transportation during resource development. Prominent northern lakes are Lake Illianna, Great Slave Lake, Great Bear Lake, and Lake Athabasca. ICEX imagery can be used to determine the timing and extent of the ice cover, location of open water areas during winter, sites where the ice overrides the shore, and the locations of ice piles. Information obtained from these lake ice studies should also be useful in evaluating potential ice problems in hydroelectric reservoirs such as the proposed Susitna Hydroelectric Project in Alaska.

3.5 ICE AS A RESOURCE

Ice and snow can be considered valuable resources in themselves. Water shortages are acute in many parts of the world. In an effort to supplement the snow pack of certain areas, cloud seeding has become a major effort. More radical are plans, which are gaining in respectability, to tow icebergs from the Southern Ocean to areas in the Southern Hemisphere where they could be melted and used as a source of freshwater.

3.5.1 SNOW HYDROLOGY

Optimal utilization of the snow resource in agriculture, hydroelectric power generation, and recreation requires extensive knowledge of the physics and geophysics of snow plus a method to monitor snow extent, both from spacecraft and from the ground. In the past decade, several reports (NAS, 1967; NAS, 1970; NAS, 1977; IHD, 1968; and Meriman, 1969) have mentioned the impact of snow on society and have stressed the need for basic research on the properties and processes associated with all forms of snow. Some of these impacts will be negative as, for example, floods caused by snow melting or the effects of salting roads; these were discussed in section 3.4.

Snow can easily be demonstrated to be a valuable resource. In the Northern Great Plains of the contiguous United States, 6 to 9 cm of precipitation in snowfall comprises about 20 percent of the total annual precipitation. The amount of snow has a great impact upon agricultural production for several reasons: (1) it provides protection against the winterkill of wheat and other plants, (2) it reduces soil freezing, and (3) it helps replenish water in the soil. Each cm of water above the threshold value (15 cm) represents a potential return of at least $75 million (based on 1974 market prices) from the Dakota wheat crop alone (NAS, 1977). Data on snow amount and distribution could aid crop production in the Great Plains, but acquiring the data is handicapped by a limited understanding of the basic dynamics of snow-distribution processes. Similar arguments can be advanced for other snow-covered agricultural areas.

The impact of snow on energy production is also extremely important. For example, the Columbia River Basin has 159 hydroelectric power plants with 21×10^6 kw of power-generating capacity (as of December 1974) which supply about 80 percent of the electrical energy needs of the Pacific Northwest (Limpert, 1975).

However, the annual runoff at the downstream station has varied between 149 and 316 x 10^9 m^3. Accurate runoff forecasting is needed in order to make optimum use of storage for flood regulation and power generation. If snow on the ground can be measured and the runoff predicted, the river sytems involved could be managed more efficiently.

Routine snow measurements and their interpretations for practical purposes depend on a better knowledge of the physics of snow and its properties. The study and application of electromagnetic sensing techniques is recommended to determine snow cover characteristics including snow depth density, free water content, water equivalent, grain size, layering, and areal variability of the snow cover. The basic problem is to observe synoptically the characteristics of the snow cover. Spacecraft can presently give the areal extent of the snow cover with few ambiguities (there are still some problems of differentiation between cloud and snow). However, the interpretation of all other parameters requires further research into snow physics, particularly the snow's characteristics as revealed by electromagnetic methods of remote sensing.

Some of the outstanding snow research topics are as follows (NAS, 1977):

a. The optical properties of snow, especially the albedo under a variety of conditions;

b. The determination of water equivalent of snow, by using remote sensing techniques;

c. The characteristics of snow covers, including snow depth, density, free water content, areal variability, grain size, and layering by using electromagnetic sensing;

d. The processes in the coupled soil-snow system and the permeability of the soil at the onset of snowmelt runoff;

e. The "ripening" of the snow cover (rapid grain growth, density increase, ice layer decomposition, etc.) throughout the melting cycle.

Electromagnetic sensing techniques employed from spacecraft have already aided these studies and will continue to do so throughout the ICEX program.

3.5.2 ICEBERG TOWING

In the polar regions, water supply from melting snow is presently of minor importance, both to agriculture and hydroelectric energy generation. Melting icebergs, on the other hand, represent a major potential water resource. The cost of obtaining potable and irrigation water in many areas of the world is increasing drastically—in parts of Saudi Arabia one cubic meter of drinking water costs $9. The idea of using nuclear desalinization techniques in countries bordered by seas is becoming less and less attractive as the activities of the few existing plants are studied. The waste disposal problems, the costs, and the thermal pollution of coastal waters are forcing many countries to look for alternate means of obtaining water. The towing of icebergs as a water resource, an idea which a decade ago was met with almost universal derision, is now under serious consideration as a means of alleviating water shortages. When one considers that 80 percent of all the freshwater on Earth is contained in ice sheets which are totally unused (the calved icebergs are melting in the ocean), one can understand why the idea is being considered.

The identification, tracking and studies of ablation of icebergs can most conveniently be conducted from spacecraft. A conference on iceberg utilization for freshwater production, weather modification, and other applications was recently held at Iowa State University (Husseiny, 1977). Other conferences will follow, and an actual attempt to tow an iceberg may be made in the near future.

CHAPTER 4. SCIENCE AND APPLICATION INVESTIGATIONS

CHAPTER 4. SCIENCE AND APPLICATION INVESTIGATIONS

4.1 INTRODUCTION

This section provides specific examples of possible investigations which would address the problems raised in Chapter 3. The particular scientific studies and development projects chosen illustrate the spectrum of research and development activities that be part of ICEX. They provide the basis for the observational and informational requirements discussed in the next chapter. In general, proposed spaceborne and other observations will provide unique and essential information which, when processed, analyzed, and modeled, can be expected to lead to major advances in our understanding of the snow and ice features and their related processes on Earth.

In the context of each scientific problem being investigated, the following sections address the environmental parameters to be measured; the ways in which ICEX is unique in its ability to measure these parameters; the general methods of processing, analyzing, and synthesizing the measured parameters into an understanding of physical processes or characteristics; and finally an assessment of the likely utility of the information so obtained.

4.2 SEA ICE INVESTIGATIONS

Sea ice processes occur on many different time and space scales. Scientific interest in the dynamic and thermodynamic behavior of ice encompasses the study of ice crystals, leads, pressure ridges, ice floes and eventually the entire pack ice of both polar regions. Similarly, short-term processes of ridging or other dynamic ice events are of as much interest as the long-term climate implications of sea ice which occur on time scales of millenia. Table 4-1 attempts to depict the major time and space scales of interest to sea ice research. Also indicated on this matrix are the various problem areas in sea ice research and the attendant temporal and spatial data requirements. The problem areas include the roles that sea ice plays in (1) fundamental geophysical processes, (2) ice forecasting, (3) hazards confronting offshore engineering design, and (4) climatic change and prediction. A few specific experiments, representative of the range of desirable investigations, to be conducted as part of ICEX, and are discussed in detail in the following pages.

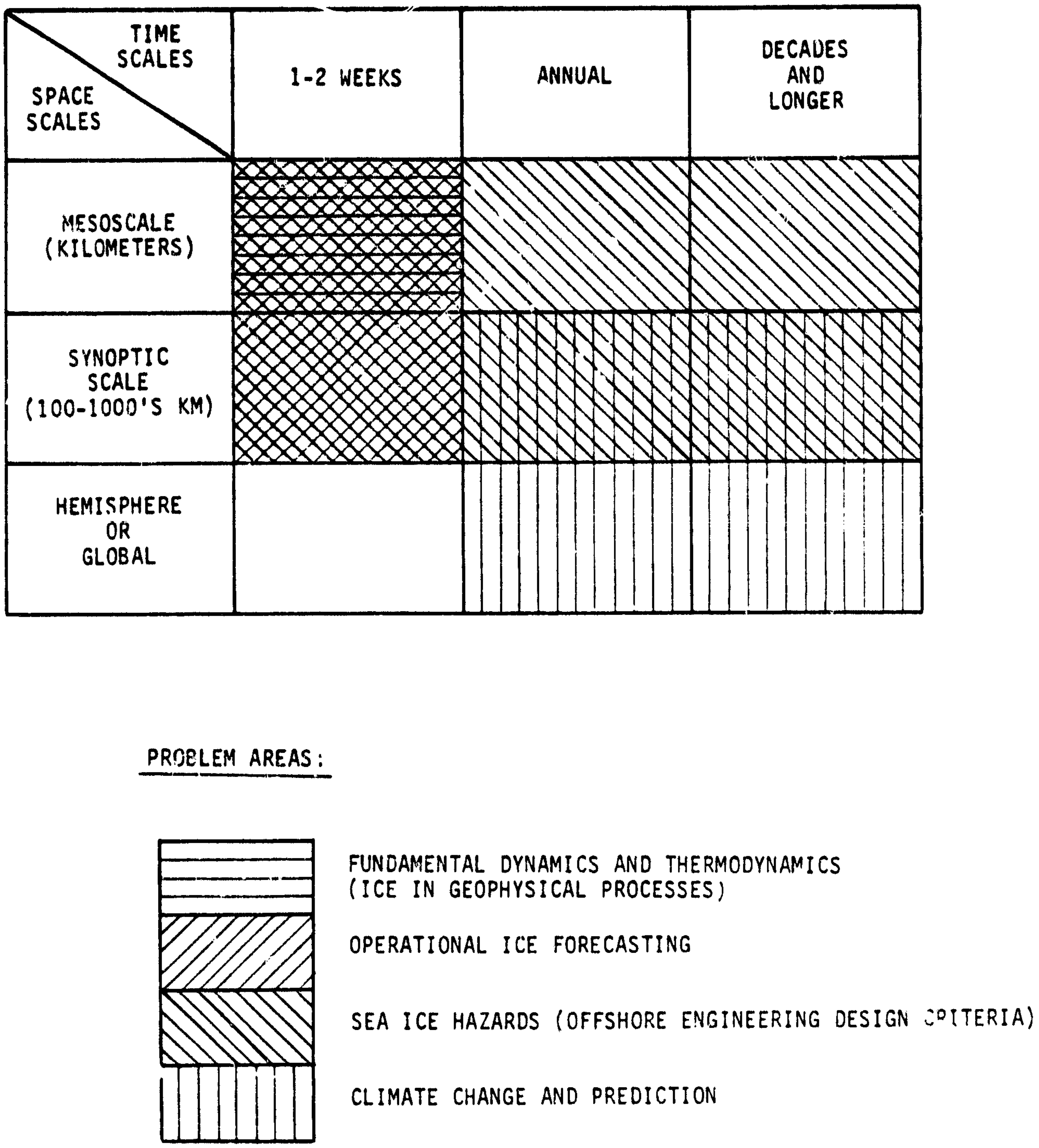
4.2.1 SEA ICE DYNAMICS AND THERMODYNAMICS

Activities proposed in the field of sea ice research can roughly be subdivided into three categories:

a. Studies that should be continued or commenced to make optimal use of presently existing data and to ensure the effective use of data to be obtained by ICEX (see subsection 4.2.1.1);

b. Studies of a fundamental nature that are now in progress, that should be accelerated, and that will be enhanced by ICEX (see subsection 4.2.1.2);

Table 4-1. Sea Ice Problems and Proposed Investigations on a Time/Space Matrix



c. Studies that will become possible only after the implementation of ICEX (see subsection 4.2.1.3).

The subdivision is made in accordance with the nature of the present document. All three categories contain activities defined in the customary terms of "monitoring," "process studies," and "modeling." Further, we reaffirm the statement made in this and other reviews of sea ice research that the most pressing need for advancement exists in two general areas:

a. The improvement of the precision of short-term ("operational") ice forecasts for specific regions,

b. The improvement of our understanding of sea ice as part of the global climate system, with the ultimate (if uncertain) goal of making seasonal or longer ice forecasts with a useful degree of skill.

4.2.1.1 Studies that Should Be Conducted Prior to ICEX. Historical data on the extent and distribution of sea ice span only a short period of time, compared with a number of other climatological records. Any existing data, especially those taken by satellites, should be processed and incorporated in the sea ice data set recently assembled by World Data Center A (glaciology).

The existing historical satellite data set is not only short but relatively unsophisticated, containing principally information on ice extent (with approximate and, in part, ambiguous definitions of "ice edge") and approximate classes of ice type and surface albedo. An effort should be made to refine this data set.

Sea ice data, currently being acquired by visual imagery, AVHRR, SMMR, and the recently deployed cloud-ice discriminating radiometer, should be processed and disseminated by well-standardized and documented procedures.

Considerable effort has been spent, and is being spent, to improve the understanding of the microwave radiative properties of sea ice. This work should be accelerated, with the purpose of providing unambiguous methods of determining surface temperature, surface state (frozen-melting-puddled), fraction of open water, and first-year/multiyear fractions by means of passive microwave images. It is likely that both theoretical studies and field experiments (surface and aircraft) will be required.

In view of the central importance of observing the ice velocity field on a wide range of scales (see subsection 4.2.3), high priority should be given to a test using Seasat SAR data. A suitable time sequence of geometrically corrected SAR images of the southern Beaufort Sea should be produced and used to derive ice displacement vectors on scales between the Seasat-SAR limit of resolution (20 m) and several kilometers. Special attention should be given to the repeatability of recognizable ice features to be used in measuring their displacement, the nature and frequency of discontinuities in the ice velocity field, effects of errors, and efficient methods of data processing and "compression." Data buoys with RAMS positioning were operated by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) during the summer of 1978, and should be used as an independent, if crude (position error radius approximately 1 km), control on the ice displacement.

The roughness of the surface topography of the sea ice is an important factor in determining the transfer of momentum (wind stress) from the atmosphere to the ice. Airborne laser altimeters have been used to measure this roughness. The backscatter of active radar waves impinging on the ice is also related to ice roughness; however, it is not clear in what way radar reflectivity and topographic roughness are related. Theoretical and field studies will be required to determine whether an operationally useful "calibration" of radar reflectivity in terms of aerodynamic roughness can be found.

Recent scatterometer and passive microwave images of sea ice from aircraft indicate that this new technique may be used to determine two important sea ice properties--roughness and ice type. Indeed, comparison of simultaneous scatterometer and passive microwave observations of various ice types reveals that the scatterometer may be an excellent complementary tool for discriminating ice type and mixtures. Also, scatterometry can provide radar backscatter cross-section measurements of sea ice that are necessary for interpreting radar imagery. Three tasks must soon be commenced. First, existing aircraft data sets of simultaneous SMMR, scatterometer, and radar images of sea ice combined with surface observations must be analyzed. Second, similar aircraft data sets must be obtained for types of sea ice not yet observed in this way--i.e., ice margins. Third, the Seasat-1 SMMR, SAR, and scatterometer data sets of the Beaufort Sea and Baffin Bay should be analyzed and compared with aircraft and surface measurements.

4.2.1.2 Ongoing Studies Aided by ICEX. An array of air-deployed data buoys observing atmospheric surface pressure, air temperature (during the dark season), and position (ARGOS) has been in operation since early 1979 in the Central Arctic (see figure 2-5). This buoy array provides the basis for computing the air stress field needed to "drive" dynamic large-scale sea ice models. It is of paramount importance, in accordance with recommendations made on the national (NAS, 1978) and international (GARP,1978) level, that this or a similar buoy network be maintained until it becomes possible to observe both ice displacement (velocity) and surface pressure to the required accuracy of $\pm$ 1 mb from space.

One of the main results of the Arctic Ice Dynamics Joint Experiment (AIDJEX) was the development of a dynamic ice model that relates external and internal forces acting upon the ice to a statistically defined ice thickness distribution. The nature of this relationship is exceedingly complex and only partially understood at this time. Further insight can be expected only from a series of long-term (many months) modeling studies that make use of the abovementioned, observed ice velocity and strain field and other pertinent data as, for instance, first-year/multiyear ice fractions that would be derived from passive microwave imagery.

The uppermost layers of the Arctic Ocean are more stably stratified than those of any other ocean, as documented by thousands of hydrocasts taken from numerous drifting ice camps since 1852. The existence of a sharp pycnocline at depths between 30 and 60 m is extremely important as it determines the depth of convective mixing and hence the ability of the upper ocean either to store or release heat. A comprehensive, descriptive analysis of the existing data is required along with a theory explaining the formation and maintenance of the "arctic mixed layer." Data analyses, theoretical studies, and, if necessary, additional field studies should be performed to understand the physical nature of the arctic pycnocline and to predict its evolution under variable external conditions.

Perhaps the most severe limitation of our understanding of the role of sea ice in the climate system is related to processes occurring at the outer edges of the ice-covered region in the seasonal sea ice zone. The ultimate measure of success in solving this problem will be a global general circulation model which describes atmosphere, ocean, and ice in these mutual interactions and feedbacks and which reproduces the annual variations of sea ice extent in both hemispheres as an "internal" variable without forcing or specification by ice data.

When examining atmosphere-ice-ocean interaction, it is desirable to pay particular attention to the most dynamic parts of the system. They are, in the Pacific region, the North Pacific Gyre (oceanic circulation) and the quasi-permanent Aleutian Low (atmospheric circulation and cyclogenesis). In the Atlantic region, corresponding features are the East Greenland and West-Spitsbergen currents and the Icelandic Low.

We propose that, in the context of ICEX, special attention should be given to these areas.

The impossibility of approaching the goal of completely understanding atmosphere-ice-ocean interactions by any single research strategy is well recognized. Therefore, a variety of sea ice studies is here suggested:

a. Stochastic analyses of sea ice variations and anomalies related to other geophysical parameters.

b. Field observations of oceanic heat transport in and near the seasonal sea ice zone.

c. Case studies of the synoptic meteorology of cyclone systems in relation to sea ice and their mutual interaction (heating patterns, moisture supply, baroclinicity, ice advection, etc.).

d. Regional studies of the annual sea ice cycle and its anomalies, especially in the confined and relatively tractable Bering Sea. Other important, though more complex regions are the Barents Sea and the East Greenland Sea/Fram Strait.

e. Theoretical and field studies of oceanic fronts, their association with the location of major ocean currents and the edge of the sea ice, upwelling and downwelling, and eddies with respect to their role in vertical heat flux and horizontal ice transport.

f. The relationship of sea ice cover and clouds, both in terms of mean (climatological) and synoptic meteorological (individual cyclones) conditions.

The Arctic Ocean contains the largest continental shelf in the world. The enormous land area of northern Eurasia discharges its fresh-water runoff onto that shelf (est. 3000 km^3 per year). This unique situation has received inadequate attention to date. For instance, lunar tidal currents in the shallow shelf waters reach magnitudes of one to several knots. The effects of those currents on ice motion, vertical mixing, and net horizontal water transport is far from understood. Theoretical computations of the co-oscillating lunar tide (Kowalik and Untersteiner, 1978; Kowalik, 1979) should be pursued further, buoy drift data from shallow-water regions should be examined for tidal components, and existing satellite images should be examined for potential information on tidal ice motions.

Tropospheric and stratopheric aerosols, i.e. particulate matter, in the Arctic affect the vertical temperature structure in the atmosphere, therefore affecting climate. This is a factor that has to be considered in the thermodynamic regions and the mass balance of the arctic pack ice; it is a problem that could be addressed by ICEX. Recent studies (Kerr, 1979; Rahn and McKaffey, 1979) have shown that aerosol concentrations in the Arctic are considerably higher than anticipated. These aerosols probably have industrial origins in Europe and North America, although desert dust and other "natural" contaminants have also been postulated as possible components of the aerosol. Numerical studies (Shaw and Stamnes, 1979) have indicated that the heating to be expected with our increase in aerosol concentration cannot be ignored in the mass balance changes of the pack ice.

4.2.1.3 Studies to be initiated as part of ICEX. The revised drifting data buoy network, with additional buoys in the Antarctic integrated into the system prior to ICEX's implementation, will be used for an exhaustive study of the scales of motion in sea-ice covered regions, both for the purpose of short-term "operational" ice forecasts and for the purpose of understanding the climatic role of sea ice. The principal tools for this task will be the combination of sequential SAR imagery and pressure fields derived from data buoys.

Routine monitoring of ice age and thickness, surface temperature, and velocity field will provide a comprehensive view of the mass balance of the entire Arctic sea ice region. This will explain local ice production and destruction in each region, advection from region to region, and volume of export into areas where sea ice never forms.

As a final comment, it is worth mentioning that by the time of implementation of ICEX, interactive global models of atmosphere and ocean are expected to have advanced considerably. Data and parameterization schemes as well as sub-models developed prior to and as part of ICEX will make their contributions to global climate modeling and other ice problems, both fundamental and applied.

4.2.2 STUDIES RELATING TO ICE FORECASTING

Many different types of experiments can be developed to demonstrate the general impact and the specific improvements that ICEX could bring to operational ice forecasting. Although these experiments would vary considerably, depending on the forecasting needs and the environmental setting of the different operations, they would have many elements in common. For instance, every experiment would use ICEX data to update information on ice conditions and to provide near-real-time imagery to forecasting stations and to in situ users for decision-making purposes. Related data would be used to drive the forecast models of all experiments and ultimately to check the "skill" of the forecasts.

The sample experiment described here is designed to forecast operational conditions just south of the ice edge, and within the pack in the Northern Bering and Southern Chukchi Seas. Possible participants in the experiment would include members of the U.S. fishing industry and groups from the oil and gas industry interested in obtaining predictions of ice and general operating conditions for locations well off the coast. Representatives of the shipping industry might also participate because of their concerns for optimal ship routing to minimize transit times.

The first step of the experiment would be to obtain a description of the environmental conditions at a given time. Salient parameters would be surface winds, sea surface temperatures near the ice edge, wave characteristics near the ice edge, the velocities of the ice, the orientation of leads, and estimates of the percentages of different ice types and associated thickness distribution. This information would then be transmitted as a local current "weather" report to the concerned user. SAR imagery would be useful to a ship attempting to work its way through heavy ice by following a lead system.

While the current "weather" report was being prepared, data would be fed into a numerical model, specifically tailored to produce short-term forecasts for the study area. This input data would also include surface pressure data obtained from buoys. Based on this information, forecasts would be made for a period of several days and these results transmitted to the user. The user would report back on the success of the forecasts. The forecasts would include the predicted location of the ice edge, the ice thickness distribution, the orientation of leads, the ice drift rate, and, when necessary, warnings of extreme ice motions or convergences. In addition, an associated oceanographic (open-water) and meteorological forecast would give wave heights and directions, water and air temperatures, surface winds, and visibility.

At some future time, perhaps 2 or 5 days later, this whole process would be repeated. For a given period of time, optimally a complete ice year, a comparison will be made between the conditions predicted and those which actually occurred. The comparison will reveal the efficiency and accuracy of the forecasts and how the models might be improved. For control, a similar set of forecasts should be prepared without using any ICEX data.

It would be profitable to conduct such operational ice forecasting exercises at a variety of different sites using diverse forecast models. One exercise would be to provide forecasts for shipping on the Great Lakes or on the St. Lawrence Seaway during the ice season. It is very important that the users be involved in the initial design of such experiments. It would also be useful to work through, and in cooperation with, existing ice forecasting centers.

4.2.3 STUDIES RELATING TO SEA ICE HAZARDS

Many investigations can be developed, using the data produced by ICEX, to advance our knowledge of ice as an environmental hazard. This section will briefly outline two studies which would improve our knowledge of the probability of encounter between large ice masses (such as ice islands, and different types of pressure ridges) and structures such as ships and offshore drilling platforms. The reason for interest in these subjects is clear; such collisions could totally destroy the structures causing both great financial losses and loss of life. It is also possible that such collisions could produce oil spills. In an environment where control at best would be difficult, the long-term damage of oil spills might be major.

4.2.3.1 Collisions with Ice Islands, Icebergs, and Floebergs. Permanent offshore structures, contemplated for the deeper waters over the continental shelves of the Beaufort, Chukchi, and Bering Seas, are susceptible to impacts with icebergs, ice islands, and floebergs. The origins of these last two types of ice features are quite different. Ice islands are tabular icebergs from the north coast of Ellesmere Island, while floebergs are thick masses of multiyear sea ice largely produced from intensely deformed pressure ridge systems that, in most cases, were grounded during their formation. These disparate ice forms nevertheless have several features in common: (1) they both show up as striking radar targets (the nature of their signatures is, however, quite different); and (2) little is known about their formation rates and distributions. In the early 1970's, hundreds of ice islands and ice island fragments were observed along the Beaufort Sea coast. In recent years, such signtings have been extremely rare. All that is known about floebergs is that they are a hazard and are produced by local grounding of pressure ridge keels. There is almost no information available on their frequency of formation or their present distribution in the polar pack.

A careful study of high resolution radar imagery coupled with short visits to several interesting and accessible ice masses would result in a major step toward resolving these questions. Data could readily be obtained on the numbers, the size, and the sequential locations of these ice features. In addition, such information could also be used to provide warnings to offshore operators when such hazardous ice masses are near the drilling site. However, there definitely will be floeberg and ice island fragments that cannot be shown through the radar imagery. Fortunately, these smaller ice fragments can be either "destroyed" or diverted.

A related experiment could be carried out for the region off the Labrador and Newfoundland coasts where large numbers of Greenland icebergs imperil both offshore drilling operations and transatlantic shipping. In this case the aircraft of the International Ice Patrol (IIP) could be used to visit iceberg targets that are identifiable from radar imagery produced by ICEX. The aircraft could also serve to note the characteristics of icebergs (if any) that are not identifiable from the imagery.

These simple studies should, in a short period of time, make a major contribution to our ability to provide quantitative estimates of the hazards involved in certain types of offshore, polar operations. It is even possible that, in the future, part of the air operations of the IIP could be replaced by a satellite-borne remote sensing system such as the one envisioned for ICEX.

4.2.3.2 <u>The Characterization of Pressure Ridging</u>. A most important aspect of sea ice is the near omnipresence of pressure ridges (the pile-ups of deformed ice that are produced as the result of compression and shearing motion between ice floes). Large pressure ridges are a major environmental hazard to ships and offshore structures because of their great mass and strength. In fact, the formidable floebergs that were mentioned in the previous section are but one "type" of pressure ridge. Pressure ridges are, however, not only important as a hazard; they are also of interest for a variety of other reasons. It is known that the major elements controlling the top and bottom topography of sea ice are pressure ridges. Therefore, the statistical characterization of ridging is needed to determe both air-ice and ice-ocean interactions, a determination that would serve as valuable input to ice drift and deformation models. Information on ridging is also needed as input to models for the routing of surface-effect vehicles and ships. The intensity of ridging is also needed to predict the rate of sound attenuation in ice-covered oceans (the scattering of sound at the base of the ice pack is largely caused by pressure ridges). This information is of interest to submarine navigation and reconnaissance as well as to science. Finally, a knowledge of the degree of ridging is essential to estimate both peak and fatigue ice loads.

Current knowledge of seasonal and spatial variations in the intensity of ridging and in the geometry of ridging in the polar oceans is very rudimentary. The present method of collecting such data (laser profilometry) is both expensive and slow and the data is tedious to analyze. However, current results do show that the nature of the ridging changes noticeably with season, with location, and presumably from year to year. What is needed is a way to rapidly survey large areas of the polar oceans to determine the parameters that describe the distribution of ridge heights.

It should be possible to make such measurements by using the instrument package that has been suggested for ICEX. For instance, the radar altimeter will provide continuous information on variations in mean surface height, RMS roughness, and total mean surface slope from a 9.3 km diameter footprint. The laser altimeter provides similar data for a much smaller footprint—70 m in diameter. In addition, the WSIR imagery will provide information on the two-dimensional geometry of the ridging (ridging patterns) and on that percentage of the total area viewed that is composed of deformed ice.

What is needed are data that will allow correlations to be developed between the radar and laser altimeter results and ridge height distributions and RMS roughness as determined by aircraft-borne laser profilometry. This can easily be achieved by using an aircraft equipped with both a laser profiler and a camera to underfly a few satellite passes. Test locations would be selected from a preliminary analysis of the altimeter data. Locations should be statistically homogeneous. Appreciable differences in the degree of ridging between locations are also desirable. It is anticipated that correlations could be developed with either the Hibler-Mock one-parameter distribution, the Wadhams (1976) expotential distribution, or the Hibler-Weeks-Mock distribution (1972). Maps could be prepared on a quarterly basis using these ridging correlations. The maps would present the characteristics of the pressure ridging over the complete polar oceans. Armed with such information plus WSIR data on representative rates of ice drift, confident estimates could finally be made of the return intervals for different sizes of large pressure ridges at different offshore locations.

4.3 ICE SHEET DYNAMICS INVESTIGATIONS

4.3.1 DEFINITION AND PURPOSE

The purpose of the ice sheet investigation is to monitor the mass balance (growth/decay rate) and to determine the potential for surging (accelerated ice flow) of the Greenland and Antarctic ice sheets. It is well known that continental ice sheets covered much of North America and parts of Eurasia during the recurrent ice ages. About 15,000 years ago the ice sheets of the last glaciation began to melt rapidly and flow into the ocean. At present it is simply not known whether the ice sheets on Greenland and Antarctica are growing or shrinking or actually are capable of surging.

The mechanisms and dominant processes involved in the ice sheet changes, the inherent stability or instability of large ice masses and their responses to various climatic conditions—these are elements of major importance to the understanding of long-term climate and the environmental changes imposed by large ice masses. The ice sheet dynamics investigations range from direct observations of the current state of the ice sheets to studies of the glaciological processes and ice dynamics modelling experiments.

4.3.2 DISCUSSION

One role of the ice sheets is that of a component of the climate system with a slow response but a large influence. Large increases in sea level have occurred during major climate warmings, due to melting of the ice sheets. Massive ice buildups on land have occurred during coolings, with a lowering of sea level.

Another potential role, about which there has been considerable speculation (e.g. Wilson, 1964), concerns the possibility of inherent instabilities in large ice masses resulting in accelerated ice flow into the oceans. This increased ice flow would cause major changes in global sea level, oceanic cooling, and changes in global climate. Computer models of ice sheet dynamics (Budd and McInnes, 1979) and other studies indicate, but do not prove, the potential for greatly accelerated ice sheet flow. On the other hand even a small mass imbalance, less than the errors in present estimates of ice sheet mass input minus output, would be sufficient to cause the apparent current rise in sea level of about 1.5 cm/decade (Hicks, 1979).

Although the ice sheets probably respond slowly to global warmings or coolings, an important question concerns the changes in the mass balance that might result from a CO_2-induced climate warming. On a longer time scale, the temperature increase that started some 15,000 years ago is still propagating through the present ice sheets, possibly leading to accelerated ice flow as the temperature increase reaches the critical lower levels near the ice sheet base (Whillans, 1978). Considering either case—a gradual mass imbalance or accelerated flow--ice volume changes corresponding to changes from 15 cm/century to several m/century in sea level are indeed possible and would be significant in terms of global impact.

New remote sensing concepts proposed for ICEX offer the capability to determine the mass balance of the ice sheets, to measure many of the parameters required for modeling the dynamic character of the ice sheets, and to monitor the ice sheets for surges or significant changes in ice volume. In particular, the surface elevation measurements expected from laser and radar altimeters should be of sufficient accuracy to measure directly the change in the ice volume and, thus, the mass balance. To complement this capability, a realistic model of ice sheet flow that incorporates satellite-derived parameters and other ice measurements is needed to evaluate and understand the significance of any changes that might be observed in the ice sheets.

The observational requirements for ice sheets are described in detail in Chapter 5. Some of the required parameters describe the basic size, shape, and other boundary conditions such as mass input (ice accumulation rate). Others describe the ice deformation and flow, which are two characteristics of particular importance. The rate of ice deformation is a function of ice temperature, internal stress, and other factors such as ice crystal size and orientation. Ice flow is also strongly influenced by the conditions of the ice-bedrock interface. Some of the desired ice sheet properties can only be obtained from field studies or ice modeling experiments such as those which have been undertaken by various scientific investigators in recent years. The ICEX ice sheet investigations will be a coordinated extension of previous ice sheet modeling and observational experiments with emphasis on understanding the time-dependent characteristics of the ice sheets. The three principal elements of the ice sheet investigations are baseline measurements, modeling experiments, and complementary field studies.

4.3.3 BASELINE MEASUREMENTS

The objectives of the baseline measurements are to obtain ice sheet parameters from satellite observations, determine their accuracy, and evaluate their glaciological significance. The results will be of direct use for describing the ice sheets. They will provide baseline data on current conditions for comparison with future measurements, and will provide data for modeling experiments.

Primary information will be obtained from the accurate elevation maps and the elevation-change maps. The elevation maps alone will delineate the major features of the ice flow--ice divides, ice domes, ice drainage basins, ice streams, outlet glaciers, and ice shelves. Surface undulations from meters to tens of meters will be characterized and their origins investigated. Elevation-change maps will be used to determine whether the undulations are stationary surface features, as may be generated by bedrock irregularities; or migratory, as may be caused by snow drift or kinematic surface waves.

The elevation-change maps will add a new dimension to ice sheet studies and will be used to investigate a variety of phenomena and theories. The time-dependent characteristics of the surface may be related to mass balance, surging, or other changes in mass input or ice flow. Such changes could be caused by long-term variations in the rate of ice accumulation, bedrock conditions, ice temperatures, or other factors. The magnitude and spatial distributions of any changes will provide important clues regarding their causes. Some areas, such as the region near the grounding line where the floating ice shelves join the inland ice, may be particularly sensitive and exhibit rapid changes in elevation and surface slope. In other regions an increase in elevation may be related to decreases elsewhere and be indicative of non-steady-state flow or mass imbalance.

The mass balance of the various drainage basins and the overall balance of the ice sheets will be investigated. Initially, as sequential elevation maps are obtained, an upper limit will be placed on ice volume changes. As additional measurements at longer intervals are obtained, the accuracy of the mass balance determination will improve. In addition to analysis of the accuracy of elevation measurement techniques, various glaciological processes such as firn compaction must be investigated to dismiss potential causes of elevation changes unrelated to mass balance.

Suspected intermittent surging of ice streams, glaciers, and even whole drainage basins are of particular interest. Between surges, the surface elevation would increase in the upper parts of the ice mass and decrease in the lower parts, whereas during a surge the reverse would occur as the excess ice from the upper portion is rapidly transferred to the lower portions. If surges do occur in the ice sheets, corresponding variations in the surface elevation profile would be readily apparent. However, because the probability of initiation of a surge during any period of observation is very small, it is important to search for evidence of previous surges, unusual ice flow patterns, or elevation characteristics that might precede a surge. In this manner, it may be possible to assess the potential for future changes in ice flow.

Although the elevation measurements are emphasized here, measurement of other parameters such as accumulation rates will also be important for understanding the ice sheet dynamics. Recent studies have shown that the passive microwave emission from the ice sheets is related to the size of the ice crystals in the firn, which is in turn dependent on the rate of accumulation of new firn (Zwally, 1977). Therefore, the physical basis for remote measurement of a parameter for mass balance studies has been established. While the various measurements alone will provide new insights, modeling of the dynamic relationships among the various parameters is needed to understand fully the significance of the observations.

4.3.4 MODELING EXPERIMENTS

The objective of the modeling experiments is to simulate the dynamic behavior of the ice sheets and significant features of the ice flow. The models will incorporate observed and simulated ice sheet parameters and be used to study the processes involved in ice sheet mass balance and dynamic changes. As additional data on surface elevation, accumulation rates, ice velocity, and other parameters are acquired, numerical models of the ice flow will be used to test various hypotheses concerning the state of the ice masses, as well as various assumptions, approximations, or unknown parameters in the model. In particular, the possible elevation changes described in the previous section would be investigated to develop an understanding of their potential causes and significance.

Although a variety of models have been used to study ice sheet dynamics, the entire effort in ice sheet modeling has been quite small. It has also been limited in the scope of questions it can answer because of the insufficiency of data for input to the models and for verification of model outputs.

The ICEX modeling experiments will utilize new data and extend previous modeling efforts. Since the temperature distributions within ice sheets are of principal interest, the first ice sheet models obtained steady state vertical temperature profiles from an integration of the one-dimensional heat conduction equation (e.g. Jensen and Radok, 1963). This modeling was extended by using the equation of mass continuity along ice flow lines to derive various physical characteristics such as areas of melting or freezing at the bedrock (Budd, Jensen, and Radok, 1970). Much of the effort on glacier modeling has been directed to temperate glaciers where the ice is isothermal near the freezing point throughout the glacier. For the non-isothermal ice in ice sheets modeling is more complex because the flow law relating deformation to stress must reflect the large temperature variations in the ice sheets. The first attempts at glacier modeling in three dimensions were made and extended to modeling surges of an isothermal glacier by Campbell and Rasmussen (1969). Other recent developments have included modeling of ice sheet surging (Budd and McInnes, 1979), three-dimensional modeling of the Greenland ice sheet (Jensen, 1977) and modeling of detailed changes in surface elevations of a temperate surge-type glacier including comparison with field measurements (Bindschadler, 1978).

The development of a variety of models by various investigators will be stimulated by ICEX. The actual development may in part be guided by the ICEX observational results and by future studies designed to provide new insights into various flow phenomena such as ice streams. A three-dimensional, time-dependent model of the major ice sheet drainage basins is needed to study individual basins such as the West Antarctic-Ross Ice Shelf region. Changes on the scale of the major drainage basins would have significant impacts on the global system. Modeling experiments on this spatial scale are also appropriate because the ice behavior in each region is generally independent and the flow characteristics and mass balance may vary considerably from one region to another. The model should be constructed to be compatible with the accurate surface elevations from ICEX in particular, and other new data from ICEX and associated field studies in general. Various modeling experiments will examine the relationships between observed and simulated surface elevations, surface slopes, ice flow rates, surface climate, and mass balance.

4.3.5 FIELD STUDIES

Ongoing national and international glaciological projects in Greenland and Antarctica can be expected to continue their investigations of ice sheet dynamics and provide complementary data not obtainable from satellites. The major projects have been the Greenland Ice Sheet Project (GISP), the Ross Ice Shelf Project (RISP), and the International Antarctic Glaciological Project (IAGP) in East Antarctica. In general, these projects have provided data from surface measurements, aircraft remote sensing, and ice drilling. Bottom topography and ice thickness of most of Greenland and about 50 percent of Antarctica have been obtained from aircraft radar sounding.

Flow rates at selected points have been obtained by a combined satellite and surface-based positioning system. Also, some internal ice and bedrock properties have been obtained by drilling and by aircraft and surface based surroundings. Accumulation rates and ice temperatures have been obtained at selected points, but some regions have few if any measurements.

In connection with ICEX, additional field studies are needed for several purposes. Some studies on the dielectric and physical properties of the ice sheet firn are needed to develop the remote sensing techniques. Others are required to provide complementary or control point data. Field activities are required for ice velocity measurements using the satellite laser ranging with surface targets and the satellite-surface receiver positioning techniques. However, the most important field activities will probably be those which will be planned and undertaken to investigate, in greater detail, specific regions or phenomena based on the initial ICEX results. For example, if the surface elevation measurements from ICEX show unusual or unexpected behavior of the ice, extensive field studies may be required to provide an adequate explanation of the observed phenomena.

4.4 SNOW STUDIES

Monitoring of hydrological properties of snow pack by microwave remote sensing has received considerable attention. Low frequency microwaves have snow-penetrating capabilities which enable the internal characteristics of snow to influence the microwave signature. Remote observations of snow-covered regions have been made with ESMR's on board Nimbus-5 and 6 satellites. Several other passive microwave studies have addressed (a) the theoretical estimation of microwave emission from snow, (b) comparison of model calculations with satellite-observed T_B's from polar firn, (c) snowfield thermodynamic temperature, (d) determination of crystal size by the use of multifrequency microwave radiometer measurements, and (e) correlation estimation of microwave emission to water equivalent, depth and free water content.

For dry snow conditions on the high plains, significant relationships between snow depth or water equivalent and microwave T_B were developed (figure 4-1, Rango et al., 1979). A flat, relatively homogeneous area of ESMR FOV was necessary for the dry snow study because the ESMR surface resolution was coarse. Thus, the estimation of snow depth under dry snow conditions is possible and feasible. Further data sets are needed to extend the relationship over a greater range of snow depth. Relationships similar to the one in figure 4-1 would have to be derived for use in other areas of study.

The presence of melt water in the snowpack radically changes the microwave emission characteristics--resulting in as much as 35 K increases in T_B over dry snow conditions. Such changes allow easy detection and monitoring of melting snow pack, and the estimation of the timing of snow-melt runoff. Ground truth for such microwave experiments from space might be obtained from low altitude gamma ray techniques, which are quite useful for obtaining snow water equivalent over a snowfield within the satellite FOV.

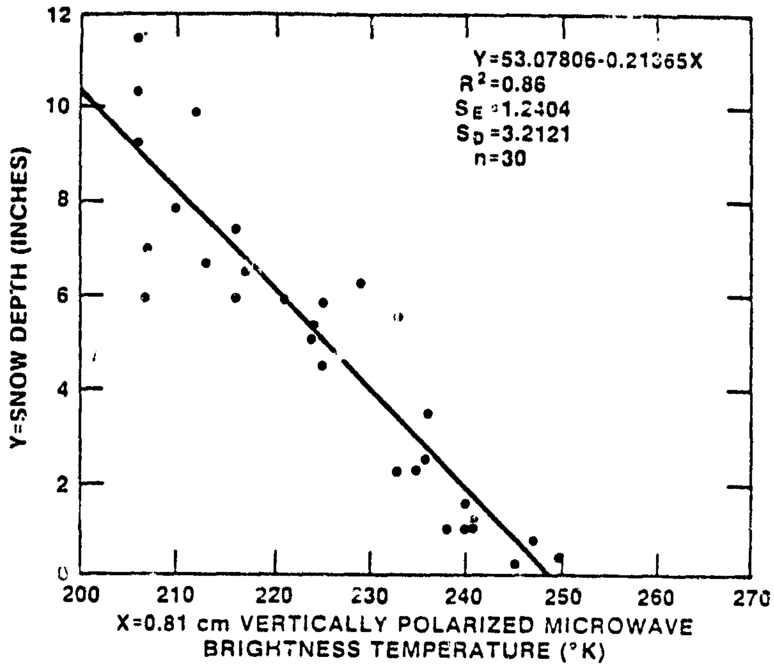


Figure 4-1. Nimbus-6 Vertically Polarized Microwave Brightness Temperature Versus Snow Depth on the Canadian High Plains. (Snow depth data from 15 March 1976 summarized over same ground.) Data included from short and high grass prairie areas only (Rango et al., 1979).

In order to verify the relationships obtained to date on the Canadian and United States high plains, a coordinated series of experiments is required. Several study sites should be chosen in order to obtain a range of snow depths and snow cover conditions. Approximately 4 to 5 sites would be required where coordinated ground truth and underflights would take place. Although resolutions of up to 7 km with new radiometers and 100 m with the radar imagery (WISR) will be available, the use of large homogenous test areas will still be required. Possible study areas include the high plains of southern Alberta-Sascatchewan in Canada and the Montana-North Dakota area in the United States, the Alaskan interior or north slope, and Scandinavia. At the chosen study sites, a ground truth effort coordinated with the satellite overpass should be mounted. The effort would entail conventional snow depth and density measurements as well as the digging of snow pits for characterizing snowpack-internal properties (including wetness) and underlying soil moisture. Associated with this intensive ground truth acquisition effort would be the need for truck and aircraft-mounted multispectral microwave measurements for comparison and calibration of the spaceborne systems. In order to obtain snow depth and water equivalent data over large areas associated with the FOV of the remote sensors, it is recommended that low altitude gamma radiation aircraft flights be made at the time of satellite overpass in each study area. The duration of these experiments would cover about two months--extending from the winter dry snow period to the beginning of snowmelt.

Analysis of the spacecraft data will focus on a comparison of the multispectral radiometer and scatterometer data with the area-wide ground truth data in order to verify previously established snow mass and T_B relationships. The high resolution X-band radar will also be analyzed extensively in view of its potential use in important mountain snow areas. Changes in height of the snowpack associated with precipitation events or melting will be monitored with the radar altimeter/laser profiler. Results of these studies should answer the following questions:

a. How well can the snow mass be estimated?

b. To what extent are the snow parameter versus T_B relationships transferable between various study areas?

c. What is the most useful combination of future sensor systems for operational monitoring of snow distribution?

CHAPTER 5. OBSERVATIONAL AND INFORMATION REQUIREMENTS

CHAPTER 5. OBSERVATIONAL AND INFORMATION REQUIREMENTS

5.1 INTRODUCTION

The research and applications problems and experiments described in previous chapters require the observation of a variety of snow and ice parameters. In this chapter, the fundamental geophysical parameters are specified in terms of their required accuracies, spatial resolutions, and temporal resolutions or samplings. In some cases, these requirements are substantially the same for basic ice research, for climate studies, and for commercial and operational applications, as indicated in the tables. A brief description of each parameter and the rationale for the requirements is given.

The ability to fulfill these requirements will depend on a comprehensive data collection and analysis program including ground truth studies, conventional surface measurements, and the continued development of remote sensing and information extraction techniques. Also assessed is the capability of the sensing system (described in Chapter 6) to determine each parameter. In several cases, data from more than one sensor will be combined to derive the geophysical parameter.

5.2 SEA ICE PARAMETERS

Sea ice is a regulator of the atmospheric heat engine directly influencing energy and momentum exchange processes at sea; the parameters chosen reflect these balances on daily and climatic scales. The effectiveness of an ice-laden sea as a reflector of solar energy depends mainly on cloudiness and the sea ice extent, (the latter being determined by its edge or boundary), the fraction of the sea covered with ice (concentration), and the albedo of the sea ice itself.

The direct exchange of heat, water vapor, and momentum between atmosphere and ocean depends upon the surface area shared between them. Variations in sea ice concentrations directly affect both the overall albedo of the sea and the nonradiative energy exchange between the atmosphere and ocean. Resultant momentum and energy exchange variations can cause rapid modification in air mass and ocean characteristics.

Sea ice is in a state of almost continuous motion. The motion of sea ice changes the insulation it provides against ocean and atmospheric exchange processes, by forming leads (open channels), altering ice concentration, and producing ridges. The motion may export ice to warmer regions. Discrete slabs (floes) of sea ice which move freely into warmer seas will melt; floes which are unable to escape are eventually frozen together again in a matrix of new ice. The history of sea ice as well as its future growth is indicated by ice type (multiyear or first year). Sea surface and ice surface temperatures are crucial to the interactions in both the growth of sea ice and its initial formation.

5.2.1 COMMENTS ON SEA ICE PARAMETERS PRESENTED IN TABLE 5-1

5.2.1.1 Boundary - Accurate serial boundary measurement is perhaps the most important sea ice observation for offshore operations, especially for fishing and oil exploration. Both coarse and fine resolution data are required.

Table 5-1. Sea Ice Observation Requirements

PARAMETER	CATEGORY			TYPE OF OBSERVATION	OBSERVATION REQUIREMENT						CODE	PROPOSED MEASUREMENT CAPABILITY
					ACCURACY		RESOLUTION					
							SPACE		TIME			
	BASIC	CLIMATE	OPN/COMM		DESIRED	MIN.	DESIRED	MIN.	DESIRED	MIN.		
SEA ICE												
Boundary	I	I		Line Position	5 km	20 km	5 km	20 km	1 day	3 days	A	LAMMR
			II	Line Position	500 m	5 km	500 m	2 km	1 day	1 day	B	WSIR, IEAS
Concentration	I	I		% of Area	2%	5%	25 km	25 km	1 day	3 days	A	LAMMR, SCAT
			I	% of Area	10%	20%	5 km	25 km	1 day	3 days	A	LAMMR
			II	% of Area	2%	5%	1 km	10 km	1 day	3 days	B	LAMMR, WSIR
Albedo	I	I		Area Average	0.02	0.04	25 km	100 km	3 days	2 weeks	A	PIMR
Motion	II			Point Displ.	100 m/d	1 km/d	5 km	100 km	1 day	7 days	A	WSIR
			II	Point Displ.	50 m/d	1 km/d	1 km	10 km	6 h	7 days	B	WSIR,
Ridging												
Density			II	Number/Area	10%	50%	50 m	100 m	7 days	1 month	B	WSIR, SCAT
Orientation			II	Orientation	10°	30°	NA	NA	7 days	1 month	B	WSIR
Height			II	Height	1 m	5 m	NA	NA	1 day	1 month	C	WSIR, SCAT
Ice Type	I	I	II	Frac/Area By Type	5%	10%	1 km	25 km	7 days	1 month	A	LAMMR/SCAT, WSIR
Leads												
Fractional Area	III		II	Frac/Area	10%	50%	50 m	100 m	1 day	3 days	B	WSIR
Orientation	III		II	Orientation	10°	30°	NA	NA	1 day	3 days	B	WSIR
Floe Position			II	Point Location	20 m	100 m	20 m	100 m	6 h	2 days	B	WSIR
Surface Melting		II		Frac/Area	Wet/Dry	Wet/Dry	25 km	25 km	1 day	3 day	A	LAMMR
Surface Temperature	I	I		Area Average	1°K	3°K	25 km	100 km	1 day	3 day	A	LAMMR/PIMR

Table 5-1. Sea Ice Observation Requirements (cont.)

PARAMETER	CATEGORY			TYPE OF OBSERVATION	OBSERVATION REQUIREMENT						CODE	PROPOSED MEASUREMENT CAPABILITY
					ACCURACY		RESOLUTION					
							SPACE		TIME			
	BASIC	CLIMATE	OPN/COMM		DESIRED	MIN.	DESIRED	MIN.	DESIRED	MIN.		
Ice Thickness	III	III		Area Average	20 cm	1 m	25 km	100 km	7 days	1 month	D	Limited thickness information can be inferred from ice type.
			III	Area Average	20 cm	1 m	50 m	1 km	1 day	3 days	D	
Surface Pressure	I	I	II	Point Value	0.5 mb	1.0 mb	25 km	50 km	1 day	3 days	—	DCS/Data Buoy
Wind Velocity	III	III	III	Area Average	10^0	20^0	25 km	50 km	1 day	3 days	B	SCAT over oceans only.
Sea Surface Temperature	II	I		Area Average	0.2^0K	2^0K	10 km	25 km	1 day	3 days	B	LAMMR over oceans only.

Sampling Key

I - Continuous
II - Frequent
III - Occasional
IV - Infrequent

Code

A - Desired requirement can be met.
B - Substantial part of requirement can be met.
C - Measurement concept, capability not well determined.
D - Useful measurement but limited.

5.2.1.2 Concentration - An ensemble of ice concentration measurements at different spacial resolutions and time intervals is required because ice concentration is the prime factor in determining the ocean-atmospheric heat flux. In the winter, the variations in the small amounts of open water may cause large relative changes in the heat balance. Significant differences in concentration are known to occur over space scales of 1 km and in times of one day.

5.2.1.3 Albedo - Small albedo differences are clues to many ice processes: thickness variations in thin ice, the onset of surface melting, the formation of new leads, and the date of the newest snow fall, among others.

5.2.1.4 Motion - ICEX serial radar imagery will permit the measurement from space of ice deformation with an accuracy presently obtainable only from manned drifting stations using NAVSAT. It also allows such measurements to be made covering large regions and at requisite time scales. If four measurements could be made a day, it also would allow the measurement of inertial oscillations that occur in sea ice.

5.2.1.5 Ridging - Little is currently known about the seasonal and spatial variations in ridging, except that there appears to be systematic variations in the intensity of the ridging with location at a given time. Time consistency of these variations with season and from year to year are as yet unknown. Pressure ridges are obstacles to ice-breaking ships, and can be extremely dangerous to offshore structures.

5.2.1.6 Ice Type - Ice type changes slowly except in regions of strong divergence where large areas of open water can form and be converted to thin ice within a few hours. Current ESMR data suggest that large thin ice areas may be present occasionally near the North Pole although direct observational verification of this suggestion is still lacking.

5.2.1.7 Leads - Lead patterns provide information on the mode of recent deformation. For many applications high spatial resolution is required, since leads may be very narrow, yet be useful to a beset ship.

5.2.1.8 Floe Position - The concern here is the identification of large multiyear ice floes or ice islands in the vicinity of offshore activities. In addition to improving short-term planning and responses, the statistical data base developed will be important in defining the collision risk levels in various geographic regions. This problem is particularly severe in the summer where large daily ice movements may occur near the edge of the ice pack.

5.2.1.9 Surface Melting - Two types of melt phenomena are important to observe—the pattern of snow melt and, after snow melt has occurred, the pattern of the formation and ultimate refreezing of the meltponds that develop on the bare ice surface. Such observations are required only during the melt season (from May to September for the Northern Hemisphere).

5.2.1.10 Ice Surface Temperature - The ice surface temperature varies from zero to minus 45°C. Temperature is a useful parameter in studies of the mesoscale ice energy budget and in certain engineering applications, where the ice properties, which are strongly temperature dependent, are important.

5.2.1.11 Ice Thickness - Ice thickness is an important parameter in almost every type of problem that involves sea ice. Unfortunately it does not appear to be currently possible to measure ice thicknesses from space with the accuracy and the spatial resolution that are desired. However, limited thickness information can be inferred from ice type.

5.2.1.12 Surface Air Pressure - All sea ice numerical models are driven by wind stress fields, which are, in turn, deduced from the surface atmospheric pressure field.

5.2.1.13 Wind Velocity Over Open Water - This can be used both as a substitute for, and as a check on, surface wind estimates based on the atmospheric pressure field.

5.2.3.14 Sea Surface Temperature - Precise measurement of this parameter permits the identification of ocean fronts and circulation features. Air temperature and sea surface temperature can also be used together to estimate the exchange of heat.

5.3 ICE SHEET, ICE SHELF, AND ICEBERG PARAMETERS

The dynamic relationships among boundary conditions for ice sheets are determined by the internal flow properties of the ice and its interaction with the bedrock. The ice dynamics are described by the ice velocity and strain fields. Similar considerations apply to ice shelves. Boundary conditions include the three-dimensional surface and bottom topographies, the surface and bottom temperatures or heat fluxes, the ice mass input from the atmosphere in the form of precipitation, and the mass output by iceberg discharge, surface melting near the margins, melting at the bottom, evaporation, and blowing snow transport.

Since it is not necessary to measure all these parameters, emphasis is placed on those measurements, such as change in surface elevation, needed to describe and understand the time-dependent characteristics of the ice sheets and shelves.

For operational and commercial applications, the only ice sheet requirements explicitly listed in table 5-2 are related to iceberg studies for water resources and iceberg detection as an environmental hazard. Other required parameters, such as change in surface elevation and surface melting of the ice sheets, are also needed for the study of advanced concepts such as the possibility of hydroelectric power generation using meltwater runoff from the Greenland ice sheet (Partl, 1977).

5.3.1 COMMENTS ON THE ICE SHEET, ICE SHELF, AND ICEBERG PARAMETERS PRESENTED IN TABLE 5-2

5.3.1.1 Surface Elevation. The most basic attainable measurement is a map of the surface elevations of ice sheets to an absolute accuracy of 1 m. This accuracy will make it possible to distinguish the various drainage basins and to determine the direction and magnitude of the surface slope within those drainage basins. The direction and magnitude of the surface slope indicates the direction and speed of ice flow. Even more importantly, detailed elevation measurements will permit accurate delineation of the ice streams and outlet glaciers. Although these

Table 5-2. Ice Sheet, Ice Shelf, and Iceberg Observation Requirements

PARAMETER	CATEGORY			TYPE OF OBSERVATION	OBSERVATION REQUIREMENT						CODE	PROPOSED MEASUREMENT CAPABILITY
					ACCURACY		RESOLUTION					
							SPACE		TIME			
	BASIC	CLIMATE	OPN/COMM		DESIRED	MIN.	DESIRED	MIN.	DESIRED	MIN.		
ICE SHEETS, ICE SHELVES, AND ICEBERGS												
Elevation of Surface	IV			Line Profile	1 m	10 m	5 km	50 km	NA	NA	A	IEAS
Elevation Change	III	III		Change in Line Profile	10 cm	50 cm	5 km	5 km	90 days	10 years	A	IEAS
Boundary	III	III		Line Position	100 m	100 m	100 m	100 m	1 year	10 years	A	WSIR (Alternate Landsat)
Thickness	IV			Line Profile	10 m	50 m	5 km	50 km	NA	NA	—	Aircraft
Ice Accumulation Rate	III	III		Area Average	10%	50%	10 km	100 km	1 year	10 years	B	LAMMR/PIMR, Scat
Surface Temperature (Annual Mean)	III	III		Area Average	$0.2^{o}K$	$1^{o}K$	10 km	100 km	1 year	10 years	B	PIMR/LAMMR, Scat
Surface Horizontal Velocity	III	III		Point Value	10 cm/yr	1 m/yr	Select Points	NA	5 years	10 years	B	IEAS/Surface Target
	III	III		Point Value	50 m/yr	100 m/yr	Select Points	NA	5 years	10 years	C	WSIR/Surface Target
Strain Rate	III	III		Relative Point Displacement	10^{-6}/yr	10^{-5}/yr	Select Lines	NA	5 years	10 years	C	IEAS/Surface target
Surface Melting	II	II		Area Average	10 cm/yr	Yes/No	10 km	100 km	1 day	3 days	B	LAMMR
Surface Roughness	II			Area Average	10 cm	1 m	10 km	100 km	90 days		C	IEAS

Table 5-2. Ice Sheet, Ice Shelf, and Iceberg Observation Requirements (cont.)

PARAMETER	CATEGORY			TYPE OF OBSERVATION	OBSERVATION REQUIREMENT						CODE	PROPOSED MEASUREMENT CAPABILITY
					ACCURACY		RESOLUTION					
							SPACE		TIME			
	BASIC	CLIMATE	OPN/COMM		DESIRED	MIN.	DESIRED	MIN.	DESIRED	MIN.		
Iceberg Volume Discharge	III	III	III	Regional Average	5%	20%	NA	NA	90 d	10 years	B	WSIR/IFAS
Iceberg Detection			II	Point Location	5 m	100 m	5 m	100 m	6 hours	2 days	B	WSIR
Internal Properties and Bottom Conditions	III			Point Values, Vertical Profiles, Area Averages							—	Surface sensors, drilling, and aircraft projects

Sampling Key

I - Continuous
II - Frequent
III - Occasional
IV - Infrequent

Code

A - Desired requirement can be met.
B - Substantial part of requirement can be met.
C - Measurement concept, capability not well determined.
D - Useful measurement but limited.

phenomena comprise only a small fraction of the total area of an ice sheet they carry most of the ice outflow.

5.3.1.2 Surface Elevation Change. Any mass imbalance of the ice sheet will produce a change in the elevation. The key requirement is the relative accuracy of sequential elevation measurements. The best estimate for Antarctica as a whole gives a positive mass balance of about 20 percent implying that the average surface elevation is increasing by 3 cm yr^{-1} (average mass input is about 15 cm yr^{-1} of ice). However, present estimates are based on scant measurements of snow accumulation and a limited knowledge of ice discharge. From measurements of surface elevation to an accuracy of 10 cm, an overall mass imbalance of 20 percent could be detected over a three to five year period. However, in many places the elevation change is probably greater than 10 cm yr^{-1}, and it may be either positive or negative. For example, inland of Shirase Glacier, the Japanese have measured a decrease in surface elevation of as much as 1 m yr^{-1}, whereas recent calculations for the Ross Ice Shelf sector have indicated an average increase in ice thickness on the order of 15 cm yr^{-1}. Significant results could be made with less accuracy than 10 cm, but the time interval needed between repeat measurements would increase accordingly.

5.3.1.3 Boundary. The requirement for locating the horizontal position of the boundary to a precision of 100 m is consistent with the surface elevation requirement of 0.1 m, because typical horizontal to vertical dimensions are in a ratio of 1000 to 1. Changes in the position of ice sheet boundaries may be indicative of changes in mass balance or other factors affecting the ice flow rate. Measurement of the boundary of the floating ice shelves to this accuracy is also needed to study the balance between ice flow in the shelves and the calving rate and production of tabular icebergs.

5.3.1.4 Ice Thickness. High accuracy is not needed for ice thickness measurements -- within 1 percent is sufficient and such measurements have been obtained by airborne radar sounders. However, sufficient closely-spaced coverage is needed to permit the meaningful interpolation between sounding lines. For regional mapping, a line spacing of 50 to 100 km would probably suffice.

5.3.1.5 Ice Accumulation Rate. The ice accumulation rate or mass input to an accuracy of 50 percent would provide a significant improvement over present knowledge in some regions. The desired accuracy of 10 percent for mass input is compatible with the limits imposed on the mass balance determination by a 10-cm accuracy for ice elevation change. The values should be averaged over 10 km or more horizontally to average out anomalous local variations. It is also important to average over several years because of substantial differences in the accumulation for individual years. The ice accumulation rate varies from a few hundredths of a meter to as much as one meter per year (the latter only in limited areas near some coast lines). Typical figures for interior regions are 5 to 20 cm yr^{-1} for East Antarctica, 10 to 50 cm yr^{-1} for West Antarctica and the major ice shelves, and 15 to 80 cm yr^{-1} for Greenland.

5.3.1.6 Annual Mean Surface Temperature. The mean annual surface temperature is an important boundary condition which partially determines the temperature distribution within the ice sheet and the rate of ice deformation. Anomalies and variations occur on spatial scales similar to those for accumulation rates. The listed accuracies are suitable for model inputs and for determing long-term trends of the surface climate.

5.3.1.7 Surface Velocity (Horizontal). The ice velocity in the interior and near the margins of the ice sheets and ice shelves varies a great deal from place to place. For instance, velocities in the interiors of the large ice sheets are only a few meters per year or less. Along the fronts of active ice shelves, the ice is moving at a rate of 1 km yr^{-1} or more. Outlet glaciers and ice streams typically exhibit speeds of hundreds of meters per year. On the other hand, along the margins of grounded ice sheets, between ice streams, the movement rate may be only a few tens of meters per year.

It is desirable to know the velocity of ice movement around the entire margin of the major ice sheets. It would also be useful to determine the variation of that velocity as a function of time. Grounded ice, in particular, moves at a speed that may vary seasonally and even diurnally in some places.

5.3.1.8 Strain Rate. When examining large-scale dynamics of the ice sheets, it is important to measure strain rates over distances of tens or hundreds of kilometers. Typical strain rates are 10^{-5} yr^{-1} to 10^{-4} yr^{-1}, i.e., a few meters per year increase in length of a line a hundred kilometers long.

5.3.1.9 Surface Melting. Observation of the spatial extent and duration of surface melting during the ablation season is needed to study year-to-year variations in water runoff.

5.3.1.10 Surface Roughness. The height and orientation of sastrugi and waves on the surface are interest for studies of snow drift and inversion winds.

5.3.1.11 Internal Properties and Bottom Conditions. Information on internal ice temperatures, ice fabrics, melting at the bottom of ice shelves and ice sheets, and other properties are also needed, but at present can only be obtained from surface, helicopter and aircraft measurements or by drilling into the ice.

5.3.1.12 Iceberg Discharge. Knowledge of iceberg discharge from both Greenland and Antarctica is required for two purposes. Iceberg discharge provides a major mass output for both of these regions. Changes in the rate of discharge would be directly related to changes in the ice flow rate. Also, little is known about the size distribution, spatial distribution, dynamics, and decay rate of icebergs. This is particularly true in the Antarctic seas where such information is needed to assess the possibility of iceberg towing for water resources. Sequential observations of horizontal area and freeboard of icebergs would also be useful in studing decay rates.

5.3.1.13 Iceberg Detection. Detection and tracking of icebergs is of prime importance for shipping and oil operations throughout the western North Atlantic. Presently, off the coast of Labrador, icebergs that drift close to off-shore oil rigs are towed away to avoid impacts, an expensive and logistically difficult task. A near real-time, all-weather means of accurately observing iceberg drift trajectories over the entire area would greatly improve forecasting abilities.

5.4 SNOW PARAMETERS

At high latitudes in summer, the difference in albedo between snow and soil is 0.65, and the average daily insolation is 500 w/m^2--about one-half of which reaches the ground (Sellers, 1973). A snow cover change of approximately 5 percent therefore corresonds to a heat flux change of 10 w/m^2.

Snow water content in the winter is a useful predictor of soil moisture and hydrologic conditions in the spring and even summer months. An accuracy of 1 cm water equivalent is desirable for water supply used for agricultural purposes.

Runoff from melting snow provides more than 65 percent of the total streamflow across most of the mountainous western United States. The characterization of the snowpack by various types of physical measurements allows for the prediction, of snowmelt runoff and better multipurpose management of the this important water supply. In the upper midwestern United States and Canadian high plains, knowledge of snow pack characteristics is extremely valuable for forecasting floods in the early spring.

In order to adequately monitor the snow resource for runoff prediction the measurement of various parameters is critical, namely, snow-covered Area (SCA), depth, density, snow water equivalent (S_n), and free water content. In addition to the snow properties, the condition of the underlying soil is especially significant for estimating the amount of melt water that will reach the stream channel as runoff. Historically, most snow observations in the western United States have provided depth, density, and S_n estimates. Measurements are invaribly taken at prelocated snow courses, on or near the beginning of each month from approximately February through May. Continuous automatic monitoring of S_n is now performed at many locations as forecasting requirements have increased to include short term runoff, as well as seasonal streamflow. The telemetering of such data in real time through conventional "line of sight" radio, meteor burst, and satellite transmission has also proved useful in employing snowmelt for runoff forecasting.

Conventional S_n measurements are representative of a given point in a watershed. Seldom are there a statistically significant numbers of point measurements in a specific basin. The regression analysis approach to seasonal streamflow forecasting somewhat compensates for this deficiency by treating the S_n measurements as indices. The point measurements are assumed to be representative of large sub-basin areas or the entire watershed. Such assumptions may be false, resulting in erroneous calibration of the watershed models. Faulty calibration may in turn produce models which are erroneous in specific situations.

Since 1973, SCA has been successfully mapped from space by various investigators using data from Landsat and NOAA satellites (Rango, 1975; Meier, 1975; Meier and Evans, 1975). A remote sensing technique to estimate snow depth or S_n over an entire basin would add considerably to the already existing SCA capability. Such a technique, by itself, would provide much more detailed knowledge of the snowpack in both mountainous and flatland basins for runoff prediction purposes. Combining both techniques would permit a large area estimate of total snow volume. Such an estimate would specify the maximum potential of snow water production and also locate that water in relation to the various elevation zones or sub-basins of the watershed.

Passive microwave measurements of snow packs have received considerable attention recently because the microwave radiation is emitted by the entire thickness of the snow pack (at sub-freezing temperatures), allowing sensing of internal characteristics. The Nimbus-5 and 6 ESMR radiometers have provided useful snowpack observations (Section 4.4). Several passive microwave studies have investigated snow microwave characteristics and their correlations with water equivalent, depth, and free water content.

5.4.1 COMMENTS ON THE SNOW PARAMETERS PRESENTED IN TABLE 5-3

5.4.1.1 Percentage Coverage. This is the most important snow parameter that is presently obtainable by satellite. In as much as such measurements can find immediate use in hydrological forecasts, it is important to obtain such data to an accuracy of approximately 1 percent and to a high spatial resolution. Repeat observations every 3 to 7 days appear adequate.

5.4.1.2 H_2O Content. This is also an extremely important parameter. However, its determination is, although apparently possible under certain dry snow conditions, much more problematic.

5.4.1.3 Albedo. In snow as in sea ice, small albedo changes provide important cludes to the occurence of a number of processes. Of particular interest here is the onset of surface melting.

5.4.1.4 Snow Depth and Density. It maybe possible to determine snow density using multifrequency radiometry, but more research will be necessary. Similarily, the laser altimeter may provide estimates of the snow depth in certain regions. It should be remembered that the determination of any 2 of the 3 parameters H_2O content, snow depth, and snow density automatically permits the estimation of the third parameter.

Table 5-3. Snow Cover Observation Requirements

PARAMETER	CATEGORY			TYPE OF OBSERVATION	OBSERVATION REQUIREMENT						CODE	PROPOSED MEASUREMENT CAPABILITY
					ACCURACY		RESOLUTION					
							SPACE		TIME			
	BASIC	CLIMATE	OPN/COMM		DESIRED	MIN.	DESIRED	MIN.	DESIRED	MIN.		
SNOW COVER												
Percent Coverage	III	II		Area Average	5%	5%	10 km	50 km	7 days	7 days	B	PIMR/LAMMR, Scat
			II	Area Average	1%	5%	1 km	10 km	3 days	7 days	C	PIMR/LAMMR, WSIR
H_2O Content		II		Area Average	1 cm/cm^2	3 cm/cm^2	10 km	50 km	7 days	7 days	C	LAMMR/PIMR, Scat
			II	Area Average	1 cm/cm^2	3 cm/cm^2	1 km	10 km	3 days	7 days	C	LAMMR/PIMR, WSIR

Sampling Key

I - Continuous
II - Frequent
III - Occasional
IV - Infrequent

Code

A - Desired requirement can be met.
B - Substantial part of requirement can be met.
C - Measurement concept, capability not well determined.
D - Useful measurement but limited.

CHAPTER 6. SYSTEMS APPROACH

CHAPTER 6. SYSTEMS APPROACH

6.1 INTRODUCTION TO THE ICEX SYSTEM

Previous chapters have outlined in great detail the objectives and requirements of the ICEX program and the experiments needed to meet these objectives. The total candidate system that will perform the experiments and analyze the results consists of sensors to be flown in space and on aircraft, buoys to be placed both in the water and on the ice, data transmission and relay systems, ground processing systems, and, finally, data analysis and distribution systems.

This chapter addresses various elements of the system, with emphasis on remote sensing from space; space-to-ground data relay and transmission systems; surface data acquisition; and the ground system required to process, analyze, and use the data obtained from the various sensors.

Aircraft sensors are discussed within individual experiment plans. This document does not discuss specific space platforms, because implementation of the actual space segment will be determined by programmatic considerations involving various candidate spacecraft. However, certain sensors must acquire data simultaneously to be most effective for ICEX purposes. Thus, the Large Antenna Multifrequency Microwave Radiometer (LAMMR) and the scatterometer must share the same platform, as must the two elements (laser and radar) of the Ice Elevation Altimeter System (IEAS). The WSIR will provide ice motion and the LAMMR ice concentration, and both these parameters are needed for study of the interrelated dynamics and thermodynamics. The spacecraft segment developed for ICEX will ensure that such sensors fly either on the same platform or on separate platforms in the same orbit.

6.2 SPACECRAFT INSTRUMENT DESCRIPTIONS

The atmosphere through which spaceborne remote sensors must view the surface is complex and dynamic, being subject to rapid variations of parameters such as temperature, pressure, humidity, wind velocity, and cloud cover. Because most of the observables that can be measured by remote sensors are functions of several of these variables, an interactive, multitechnique approach is necessary to interpret the sensor data. The ICEX sensor system incorporates both active and passive instruments and utilizes many bands of the electromagnetic spectrum, ranging from radio frequency to visible light. The data obtained by these different measurement techniques will be interpreted interactively to extract those parameters which have been specified as requirements in Chapter 5.

The ICEX will also provide a test bed for experimental sensing techniques and will permit the cross-calibration of qualitatively different techniques for measurement of the same parameters. By using the ICEX sensor system in a synergistic fashion, self-consistency checks will be used to refine data extraction techniques and to increase confidence in the reliability of the results.

The ICEX sensor system contains the following six remote sensing instruments:

a. Large Antenna Multifrequency Microwave Radiometer (LAMMR)

b. Wide Swath Imaging Radar (WSIR)

c. Scatterometer (SCAT)

d. Ice Elevation Altimeter System (IEAS), Radar

e. Ice Elevation Altimeter System (IEAS), Laser

f. Polar Ice Mapping Radiometer (PIMR)

It also contains a Data Collection and Location System (DCLS) to collect data from buoys and other in situ sensors, and a GPS receiver to obtain real-time satellite position data. Table 6-1 provides details of parameters and other data to be acquired by each of these sensors.

The LAMMR is a passive multichannel radiometer which will measure the radiation T_B of the surface in seven bands ranging from 1.4 GHz to 91 GHz. The WSIR is an X-band synthetic aperture radar which produces images of the surface with a basic pixel size of 100 m over a swath of 360 km or 25 m over a 90 km swath for special investigations. The scatterometer is a side-looking radar with the capacity to measure the scattering cross section at 14.6 GHz. The IEAS is an altimeter which can measure ice altitude profiles with two complementary instruments: a microwave radar to provide continuous coverage over the nadir track and a laser ranging system with commandable pointing to provide precision altitude determination, off-axis mapping, fine scale profile resolution, and ranging to reflectors placed on the ice. The PIMR is a passive, multichannel infrared radiometer which can map cloud cover, determine cloud parameters, measure surface temperature, and aid in distinguishing surface ice and snow clouds.

The footprints for each of the instruments, as obtained from the 700 km, near-polar ICEX orbit, are shown in figure 6-1. The interactive functions of these instruments are highlighted in table 6-1; the individual instruments are described in greater detail in the following text.

6.2.1 LARGE ANTENNA MULTIFREQUENCY MICROWAVE RADIOMETER (LAMMR)

The LAMMR provides dual-polarization radiometric measurements in seven frequency bands between 1.4 and 91 GHz over a swath 1600 km wide. Its ground instantaneous field-of-view (FOV) varies between 7 and 103 km, depending on frequency. The sensor consists of seven channels feeding a common 3-6 m antenna. The antenna axis is pointed 45° away from nadir. The LAMMR scan is produced by rotating the entire antenna about the nadir axis.

An offset Cassegrain paraboloidal reflector antenna design was selected because of its compact configuration and its ability to function over a wide frequency range with high beam efficiency and low RF losses. The Cassegrain feed design places the feedhorn cluster and electronics package near the drive mechanism. This tends to alleviate the problem of dynamically balancing the estimated

Table 6-1. ICEX Sensor System Information

	Observable Parameters	Extracted Parameters	Other Data Used or Provided
LAMMR	Surface brightness temperatures in seven microwave bands	Composition and state of surface; sea ice concentration, boundary, type, sea surface temperature, ice sheet accumulation rates, snow parameters	Utilizes surface temperature and cloud cover data (from PIMR) and surface roughness data (from scatterometer)
WSIR	High resolution microwave radar images	Sea ice motion, ice sheet motion, surface properties and large iceberg locations	Utilizes low resolution LAMMR images to provide emissivity data
Scatterometer	Microwave scattering cross section	Surface scattering characteristics, ridging, ice sheet boundaries, sea ice concentration and type	Provides surface roughness information to aid the interpretation of other microwave data
IEAS, Radar	Range profile along satellite track with a wide footprint	Ice sheet elevation, boundaries, and slope. Provides continuous coverage	Utilizes laser for calibration and fine scale altitude and profile determination
IEAS, Laser	Range profile along a selectable track with a narrow footprint, centimeter level range to retro-reflector targets	Precision orbit determination, small-scale surface roughness, off-nadir altimetry precision profiling, horizontal motion	Performs cross-track scanning to resolve ambiguities in microwave altimeter data, scans off-track profiles, provides calibration data

Table 6-1. ICEX Sensor System Information (cont.)

	Observable Parameters	Extracted Parameters	Other Data Used or Provided
PIMR	Reflected solar radiation in four near-IR bands, emitted-IR radiation in atmosphere window	Surface temperature, surface albedo, and cloud properties	Provides surface temperature and cloud cover maps with fine resolution to interpret data from other instruments
DATA COLLECTION	Location of in situ platforms; receives telemetry giving surface pressure, air and water temperature, wind velocity, humidity, etc.	Surface pressure, temperature and surface wind fields	Provides "surface truth" checks on remotely sensed data in specific locations

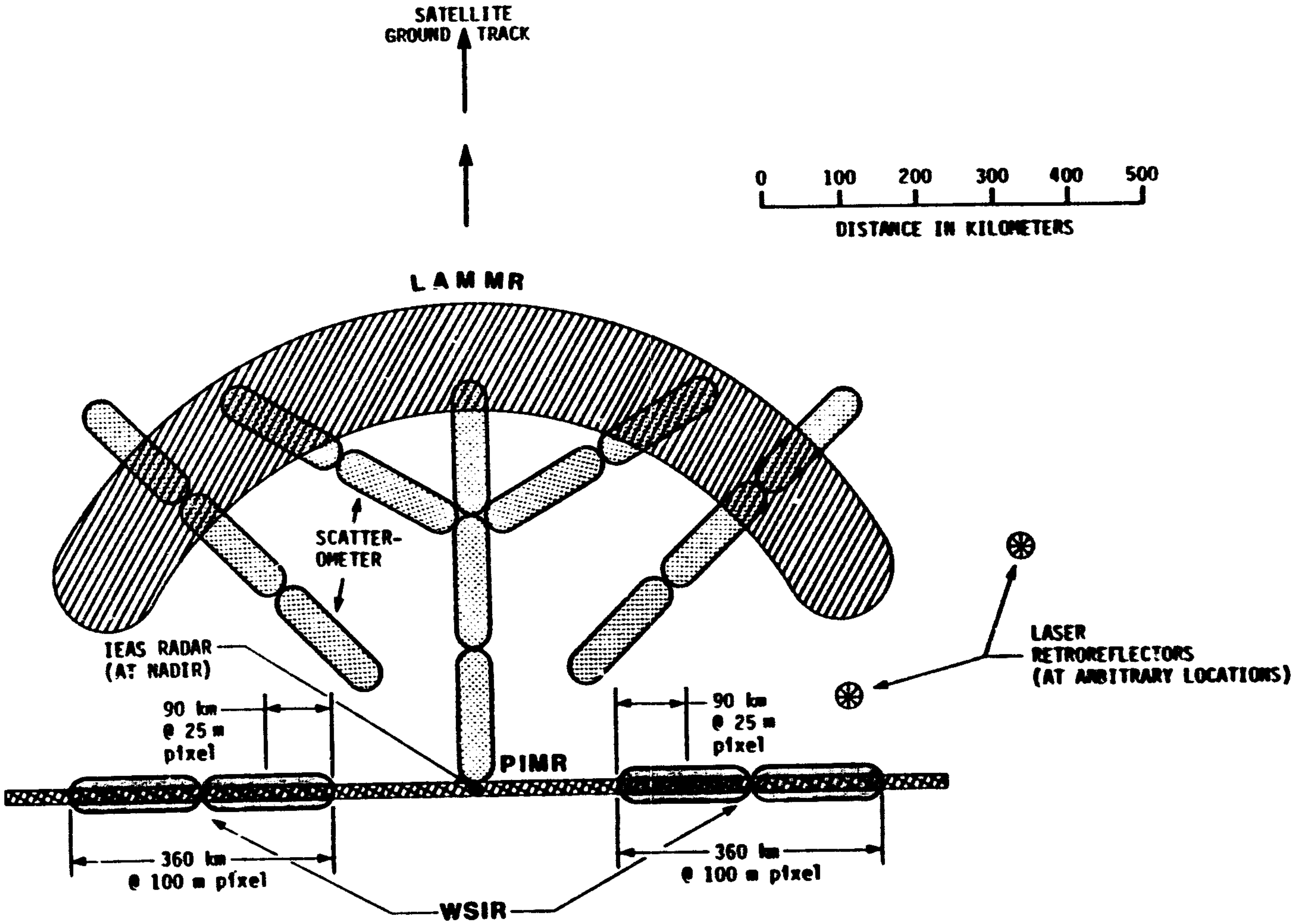


Figure 6-1. Footprints for Each ICEX Instrument

300-pound structure, which is rotated at one rev/s. A counter-rotating wheel compensates for the rotational momentum of the sensor.

The radiometers are operated during a 120° segment of the 360° scan which is centered on the spacecraft velocity vector. Calibration occurs once per scan during 30° of the remaining 240°.

Each radiometer channel contains two receivers, one for each polarization. Except for the 1.4 GHz channel, the receivers are of the total power type, and calibration is accomplished by switching the inputs alternately to an ambient load and cold sky horn during the calibration interval. The 1.4 GHz channel uses a null-balanced noise injection system for calibration to minimize weight and volume. The receivers below 18 GHz are a tuned radio frequency design using field-effect transistor amplifiers. The receivers in the upper four channels (>18 GHz) use balanced mixers followed by low-noise IF amplifiers. This approach and near-state-of-the-art design is expected to meet the extreme temperature sensitivity requirements (σ 1° K) demanded by the short integration times associated with high surface resolution.

Table 6-2 presents the key performance parameters proposed for the LAMMR. The beamwidths at the 37 and 91 GHz channels are achieved using less than the full 4 m aperture. This is accomplished by under illuminating the reflector to provide contiguous imaging at the selected scan rate. At 91 GHz, the ground footprint along-track is further enlarged by using two overlapping beams for each polarization. Hence, there are four rather than two receivers for that channel.

6.2.2 WIDE SWATH IMAGING RADAR (WSIR)

The ICEX WSIR is an X-band (9.6 GHz) imaging radar system using synthetic aperture radar techniques to obtain high resolution radar imagery. The system is designed to obtain continuous imagery with a 360 km swath and a 100 m pixel size from a 700 km orbit. In addition, a 25 x 25 m pixel size with a 90 km swath width may also be selected.

The spaceborne portion of the radar system consists of a dual antenna subsystem and a sensor subsystem. Each of the two antennas consists of a pair of 19 x 0.6 m planar arrays oriented parallel to the spacecraft velocity vector. Their normal axes are boresighted at an angle of 28.6° and 37.9° to the local nadir. One of the antenna pairs is oriented to the right of the spacecraft and images one of the polar regions. The other pair is used to image the other pole. The FOV of each antenna array is about 9.25° and the two arrays of each pair are time shared to generate two 180 km wide contiguous swaths of radar imagery. A processor on the ground merges the two 180 km images into a single continuous swath image.

The pulsed coherent radar sensor employs linear FM coding (chirp) to achieve high range resolution. Digital ground processing effectively (synthetically) achieves a higher azimuthal resolution than would be expected from the antenna's physical size.

The nominal peak radiated power (PRF) is 4 kw and the PRF is either approximately 900 or 1050 Hz, depending on the antenna used. The antenna in use and the PRF are alternated every 75 ms. Location information from a Global Positioning System (GPS) receiver on board the spacecraft is used in controlling the WSIR. Based on the GPS data and ground commands, a microprocessor directs the

Table 6-2. LAMMR Key Performance Parameters

Frequency	GHz	1.4	4.3	10.65	18.7	21.3	36.5	91
Beamwidth	deg	3.8	1.23	.49	.28	.25	.25	.13
Resolution (IFOV[1])	km	103	34	14	8	7	7	3.5
Integration Time	ms	23	7.7	3.1	1.8	1.6	1.6	.8
RF Bandwidth (BW)	MHz	28	200	100	200	200	1000	2400
Predetection BW	MHz		200	100	100	100	500	1000
System Noise Temp (T_S)[2]	^oK	400	400	500	400	400	800	1200
Sensitivity (ΔT)	^oK	.4	.2	.9	1.3	1.4	1	1.6
Radiometer Type		NULL BALANCED	TOTAL POWER					
Receiver Type		TUNED RADIO FREQUENCY			SUPERHETERODYNE			
Polarization		DUAL						
Number of Receivers		2						4
System Calibration Accuracy	^oK	±1						±1.5

Note: 1. IFOV major axis dimensions of elliptical fortprint.

2. $T_S = T_{Receiver} + T_{Ant}$: Assume $T_{Ant} = 200^oK$.

WSIR system to obtain contiguous swath coverage of the desired region. Also under microprocessor control, the radar video is digitized, combined with GPS and spacecraft attitude data and time, and tape recorded for later transmission via Tracking and Data Relay Satellite System (TDRSS) to a radar correlator and pixel processor. Table 6-3 is a summary of the WSIR characteristics.

Table 6-3. ICEX WSIR Characteristics

Wavelength	3.1 cm (X-band)
Incidence Angles	27 to 49 degrees
Output Image Pixel Size	100 X 100 meters or 25 X 25 meters
Number of Looks	5.6
Swath Width	360 kilometers (100 X 100 m pixel) or 90 kilometers (25 X 25 m pixel)
Polarization	H H
Range of σ_0	-23 dB to 0 dB
Dynamic Range (commandable)	3 to 6 bits per sample
Contrast Ratio	10 dB or better
Data Rate	18 megabits/sec
Data Cycle	30% per orbit
Data Format	Continuous
Data Turnaround	24 hours or less
Data Products	Images on film, high density tape
Image Quality	Geometrically correct, radiometrically linear
Location Accuracy	100 meters

6.2.3 SCATTEROMETER

The ICEX scatterometer is an active microwave instrument for measuring the normalized radar cross section (σ_0) of the surface in the polar regions. The basic scatterometer design is an upgraded version of the Seasat scatterometer. The operating frequency is 14.6 GHz.

The scatterometer will generate active measurements that are collocated with the passive measurements of the LAMMR. The data obtained will also provide a library of σ_0 versus incidence angle for various types of ice surface. The scatterometer's electronically-steerable antennas will together cover a swath nearly 1500 km wide, with resolution cell size of 10 to 25 km. The overlapping swath from sequential orbits will enable measurements of σ_0 of the same area at up to five different incidence angles.

The basic scatterometer's antennas are five 3 m x 15 cm rods, oriented parallel to the ground and either at 90° or at 45° to the spacecraft velocity vector. The pattern of each antenna is an electronically steerable narrow fan beam. Resolution cell size is under software control. The antenna pattern produces a swath width of 1480 km, which overlaps both the LAMMR and WSIR swaths.

An optional scatterometer configuration, employing seven antennas instead of five, would enable measurement of wind direction and speed over open ocean. Those measurements were taken by the Seasat scatterometer. Another developmental alternative could give a resolution cell size of 1 x 10 km.

Detailed performance characteristics of the scatterometer are given in table 6-4.

Table 6-4. Scatterometer Characteristics
(Based on Preliminary Configuration Study)

Frequency	14.59927 GHz	
Bandwidth	+ 500 kHz	
Pulse Width	4.8 ms	
Peak Transmit Power	110 w	
Average Transmit Power	20 w	
Pulse Repetition Frequency	34 Hz	
Receiver Noise Temperature	1000° K	
Antenna Gain	36 dB	
Polarization	H & V Copol., Crosspol.	
Data Rate	4 kb/s	
Number of Antennas	5	7*
Average DC Power	187 w	198 w *
Mass	262 kg	333 kg *
Volume	1.4 m^3	1.8 m^3 *

* Optional configuration to measure ocean wind speed and direction as well as ice σ_0

6.2.4 ICE ELEVATION ALTIMETER SYSTEM (IEAS)

The IEAS consists of two complementary subsystems: a radar altimeter and a laser altimeter/ranger. The radar altimeter is a nadir-directed sensor that generates a continuous profile of the ice and provides measurements of ice topography, surface slope, and roughness. The laser subsystem performs high-precision altimetry in both nadir and off-axis modes, and it produces correlative data useful for calibrating the radar altimeter and for resolving ambiguities. In addition, the laser can be commanded to track retroreflectors placed on ice sheets and at other locations throughout the world. This would provide data for both ice motion tracking and accurate orbit determination.

6.2.4.1 Radar Altimeter. The radar altimeter design draws heavily upon the Seasat altimeter design. The radar altimeter operates at 13.5 GHz. It utilizes a parabolical reflector antenna 2 m in diameter, which produces a 3-dB ground footprint that is 9.3 km in diameter. The transmitter generates chirped 25.6 μs pulses with 20 W of peak power. The frequency modulation of the pulses and the digital processing of returns are under microprocessor control.

The microprocessor continuously optimizes the radar altimeter system to provide the best height resolution consistent with the surface topography. One significant enhancement to the Seasat altimeter design is proposed for the ICEX radar altimeter. This adaptive feature utilizes a dynamic microprocessor analysis of the instantaneous radar returns to provide a continual optimization of the IEAS radar system characteristics. This enhancement allows the altimeter to adaptively track the large slopes found on ice and land. The adaptive feature is essential to maintain tracking during changing surface conditions. Such a feature was not needed on the Seasat altimeter because the mean ocean surface slope is near zero.

To ensure that the entire return is always contained within the tracker's dynamic range (the window), the width of the window is varied according to the shape and range extent of the return. The number of range cells (or quantization steps) is kept constant, so that changing the window width is equivalent to varying the range resolution.

The mean surface height, RMS roughness, and total mean surface slope are extracted from the processed radar return records after appropriate pulse-to-pulse averaging. The unambiguous determination of the slope direction requires laser altimeter data to resolve a left-right ambiguity, which remains in the radar altimeter data.

Other parameters determinable from radar altimeter data include: (a) significant wave height and wind speed in ice-free oceanic areas, (b) the location and velocity of polar ocean currents, and (c) sea-ice boundary location. Additionally, comparing summer and winter altimeter measurements may allow a determination of the floating ice thickness. Table 6-5 summarizes the proposed measurement capabilities of the radar altimeter.

6.2.4.2 Laser Altimeter. The laser subsystems of the IEAS operate in two modes: (1) high-precision on-nadir altimetry, and (2) cross-track ranging to the ice surface and to retroreflective targets. In the altimeter mode, the laser altimeter provides height and surface roughness measurements. These will be compared with similar measurements made by the radar altimeter to determine the tropospheric and ionospheric biases in radar data. The cross-track ranging mode will provide data to resolve the slope ambiguity of the radar altimeter. Ranging measurements to "fixed" retroreflectors will be used to accurately determine the spacecraft orbit. Repeated observations of reflectors placed on ice will provide a history of ice sheet motion.

The NdYAG laser generates short (200 ps) pulses of 25 m energy. It operates with a .532 μm wavelength at a 10 to 20 pps rate. The transmitted beam divergence is 20 arc seconds, which from a 700 km altitude produces a nadir ground footprint 70 m in diameter. The receiver uses 28 cm optics and two sensors: a circular-scan streak tube with 40 ps timing precision and a coarse-timing photomultiplier with counter. The latter resolves the ambiguities of the streak tube. The timing of both the transmitted and received pulses is measured by the same receiver system to minimize measurement biases. The system will provide measurements of average surface height to a 5 to 10 cm accuracy. For the cross-track ranging function, a two-axis gimballed mirror points the beam over a wide FOV. Pointing accuracy of better than 6 arc seconds is achievable using 20-bit encoders together with a sensitive integral gyro package and periodic on-orbit calibrations.

The return signal, which in the altimeter mode has an expected value of 35 photoelectrons, is analyzed on board to find the average surface height and the RMS roughness within the footprint. This analysis resolves the arrival time of each

Table 6-5. Proposed Radar Altimeter Measurement Capabilities

Measurement	Accuracy	Comments
Height	$\pm$ 1m	Precision (RMS): 3-10 cm (smooth/level) < 50 cm (rough/tilted) Spatial Resolution: 700 m
Surface Slope	$\pm 0.1^{o}$	Range: $0\text{-}5^{o}$
Surface Roughness (RMS)	$\pm$ 12.5 cm or $\pm$ 2.5% (whichever is greater)	Range: 0-5 m
Surface Reflectivity	$\pm$ 0.5 dB	Range: -4 to 45 dB
Sea/Ice Boundary Location	$\pm$ 700 m	
Polar Ocean Current Location	$\pm$ 1-3 km	

photoelectron and calculates the height and roughness estimates using standard statistical techniques.

6.2.5 POLAR ICE MAPPING RADIOMETER (PIMR)

The PIMR is a 5-channel scanning infrared radiometer. It has four near infrared channels which measure reflected solar radiation in spectral bands optimized for the study of clouds, snow, and ice. The fifth channel, a thermal infrared channel at 11 μm, provides temperature maps of the Earth's surface with a radiometric resolution of 0.1° K. The pixel size is approximately 1 km for the thermal channel and for one of the near IR channels; it is 3 km for the remaining near IR channels. The swath width can be made to coincide with that of the LAMMR, i.e., 1600 km.

The five channels are centered at 0.754, 0.863, 1.14, 1.64, and 11 microns. The first channel (.754) has a very narrow bandpass and is located on the edge of an oxygen absorption line. It is used to infer the altitude of cloudtops. The second channel (.863) is used for fine-resolution near IR images and as a reference for interpreting the other channels. The channels at 1.14 μm and 1.64 μm are important for the differentiation of snow, clouds, and ice. Clouds have a very high reflectance in all of the near IR channels. Snow and ice have relatively high reflectances in the 0.754 μm channels and low reflectances (typically 0.1 to 0.2) in the fourth channel. As ice melts or ages, its near infrared reflectance decreases significantly.

Snow, ice, and water all have emissivities which are nearly unity at 11 μm. . contrast, the microwave emissivities of snow and ice are significantly less than unity and are quite variable depending on the snow and ice type and physical condition. Therefore, the PIMR will provide T_B maps that present an accurate measure of surface temperature and may be used to deduce microwave emissivities and ice parameters from the LAMMR's T_B maps.

The PIMR is a modified version of the existing AVHRR-2 and therefore utilizes many components and subsystems which have already been proven in space flight. It has a 20 cm aperture and uses a beryllium elliptical scan mirror rotating at 360 rpm. The PIMR requires a two stage passive radiant cooler to operate three of the IR detectors at a temperature of 105° K.

Table 6-6 summarizes the capabilities of the PIMR.

Table 6-6. PIMR Capabilities

Channel	λ(μm)	Δλ(μm)	IFOV (mr)
1	0.754	0.001	3.9
2	0.863	0.275	1.3
3	1.14	0.07	3.9
4	1.64	0.06	3.9
5	11.0	1.00	1.3

6.2.6 DATA COLLECTION AND LOCATION SYSTEM (DCLS)

A DCLS will be included on the ICEX mission to accommodate ice science and application requirements for in situ surface measurements. The DCLS will satisfy requirements for both data transfer and position location of remote, unattended platforms and balloons. In addition, the system may be used to provide an estimate of the velocity of platforms averaged over a period of approximately 100 minutes. DCLS is generically related to the Nimbus/RAMS and TIROS-N/ARGOS systems. DCLS will be compatible with existing ARGOS platforms presently using the TIROS-N data collection system. The primary characteristics of the DCLS are shown in table 6-7.

The DCLS consists of three major components:

a. The Remote Data Collection Platforms,

b. The Spacecraft Instrument,

c. The Ground Processor.

Table 6-7. Characteristics of the DCLS

System Capacity:	200 platforms within view of spacecraft 2000 platforms total globally distributed	
No. of Measurements/Day/Platform:	60^{o} lat.	10 minimum 14 maximum
Platform Location Accuracy:	3 km RMS minimum 5 km RMS maximum	
Platform Velocity Determination Accuracy:	0.5 m/s minimum 1.5 m/s maximum	100 minutes average
Data Capacity/Platform:	32 bits minimum 256 bits maximum	

The spacecraft instrument makes frequency measurements of each platform during each burst transmission. The results of these measurements are stored along with the data collected from the platform. After some period of time, the stored data from the spacecraft are transferred via TDRSS to the ICEX Processing Center. The data are processed to derive position and velocity data from the doppler shift evident in each platform's frequency measurement data. The resultant information may be stored in the data base, transferred to regional ice centers or relayed to local users via the Advanced Information Transmission System (AITS)(See Section 6.6.2). The DCLS will also be used by AITS local users requesting image data from the ICEX data base.

DCLS also makes use of the command and data handling system interface with TDRSS.

6.3 SURFACE DATA ACQUISITION

6.3.1 INTRODUCTION

To derive maximum effectiveness from the ICEX system, a network of surface data collection platforms, e.g., buoys, will be deployed in both the Arctic and Antarctic regions. Drifting sea ice buoys will be used to measure atmospheric surface pressure, temperature, and ice positions. The pressure measurements will provide good estimates of the surface winds which are the primary forcing function for moving the ice. Surface air temperature is a measure of primary thermodynamic forcing. Measurements of ice positions provide the velocity and deformation fields of the ice for comparison with model results.

6.3.2 BUOY ARRAY DESCRIPTION

It is anticipated that, for adequate coverage of the Arctic Basin, an array of 20 to 25 buoys would be deployed on a 500 km grid roughly patterned after the present FGGE network shown in figure 2-5. The Antarctic requires an array of approximately 25 buoys located primarily in the Weddell Sea area, which would include the Weddell Sea Polynya. Scales of 500 km would suffice except for possible ice margin experiments requiring a more dense array. Figure 6-2 represents this coverage.

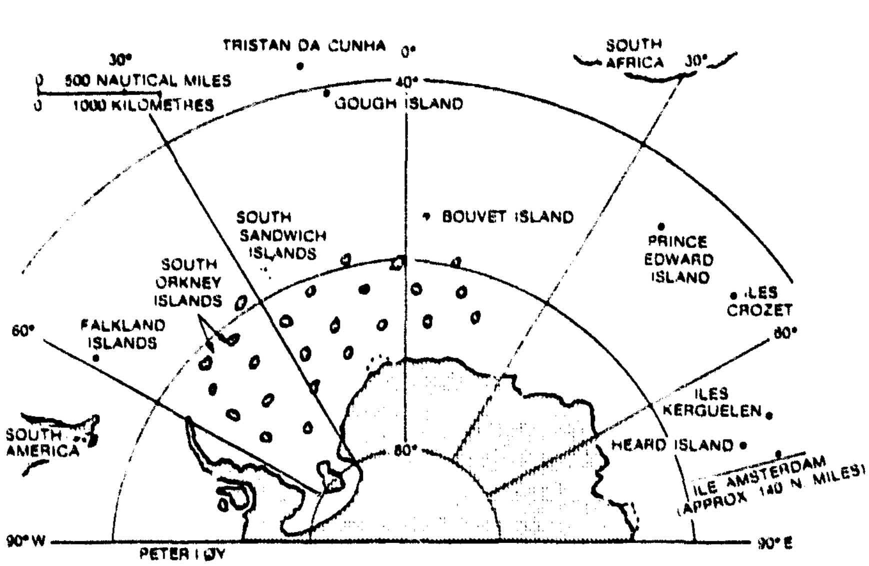


Figure 6-2. Location Map of a Buoy Array for a 500 km Separation

The data buoy is the highly successful TIROS Arctic Drifter (TAD) Buoy (Air Droppable) presently being utilized in the FGGE array in the Arctic. These buoys are designed to be air dropped over any type of terrain, and are watertight. They measure atmospheric pressure, temperature, and location. The 401.6 MHz transmitter and suitable digital encoding of the TAD buoy permit reception by the DCLS receiver system described in subsection 6.2.6. Barometric pressure is measured over a range of 900 to 1050 millibars with .1 mb resolution. The inside buoy hull temperature is measured over a range of -50°C to +14 with greater than .25°C resolution. The present buoys are powered by inorganic lithium batteries with an average life of approximately 12 months. The buoy design incorporates a self-leveling gimbal system which ensures that the antenna will be vertical not only upon landing but also during any subsequent disturbances from wind or ice surface changes. Each buoy is deployed by parachute, which is automatically disconnected upon impact.

Not enough is known presently about the stability of the buoy sensors over long periods of operation. Experience with the present FGGE buoy array is expected to indicate whether sensor stablity over the life of the buoy will be sufficient to obviate the need for difficult and costly recalibration in the field.

Desired changes to the present buoy design would be (1) longer battery life; (2) the addition of an external ambient temperature probe; and (3) the addition of a wind sensor which measures surface wind directly (at height of approximately 10 m).

No method presently exists for remotely observing the ocean environment beneath the ice cover. A data set composed of simultaneous measurements taken under and over the ice cover would be of great value. A buoy design meriting serious exploration is one that would be air-droppable, would penetrate the ice, and would lower a set of drogued oceanographic sensors (e.g., hydrophone, thermistor string, conductivity cell). A surface buoy with ice drilling/ice penetrating capability is presently under design by the Naval Ocean Research and Development Center.

6.3.3 DATA ACQUISITION

Data transmitted from the surface buoys will be received on board the satellite, added to the main data bitstream, and forwarded to the Ice Processing Facility via the TDRSS link. At the processing facility, the data will be analyzed in conjunction with satellite sensor data and can be immediately relayed to local users via AITS or stored in the data base at the facility. Subsection 6.6.2 describes the AITS in detail.

6.4 ORBIT CONSIDERATIONS

6.4.1 INCLINATION AND ALTITUDE

The orbit proposed for ICEX has an altitude of approximately 700 km and an inclination of 87° or 93°, so the spacecraft passes by the poles within 3 degrees of latitude.

The need for polar viewing sensors requires a high inclination orbit, while the proposed altitude is the result of a compromise which involves atmospheric drag, transmitter power output from the active elements of the payload (WSIR, Scatterometer, IEAS), resolution, and area coverage. The atmospheric drag component and area coverage deteriorate with decreasing altitude. Required transmitter output is higher, and sensor resolutions also deteriorate with increasing altitude.

The particular orbit inclination chosen is determined by observational requirements placed on those instruments with the narrowest field of view, namely the WSIR and the IEAS. For sea ice dynamics investigations, the WSIR is required to provide high-resolution imagery of the whole north polar region, including the pole itself. The proposed WSIR has a swath width of 360 km, with the closest point of that swath at 310 km from nadir and the farthest at 670 km. Each degree of latitude represents about 111 km on the Earth's surface and thus, an orbit that passes the poles somewhere between 2.8 and 6 degrees is needed to provide the required WSIR coverage.

One of the prime purposes of the nadir-looking IEAS is to measure the ice sheets of the Antarctic. To encompass its most important areas, such as the Ross Ice Shelf and the West Antarctic ice sheet, the nadir point of the spacecraft should approach the South Pole to within approximately 3° of latitude, thus providing coverage of about 98% of the continental area.

These selected orbit parameters apply even if the payload is carried on more than one spacecraft. In that case, the spacecraft must be placed in orbits having the same altitude and inclination to provide compatible data from the imaging sensors (WSIR, LAMMR, Scatterometer, PIMR).

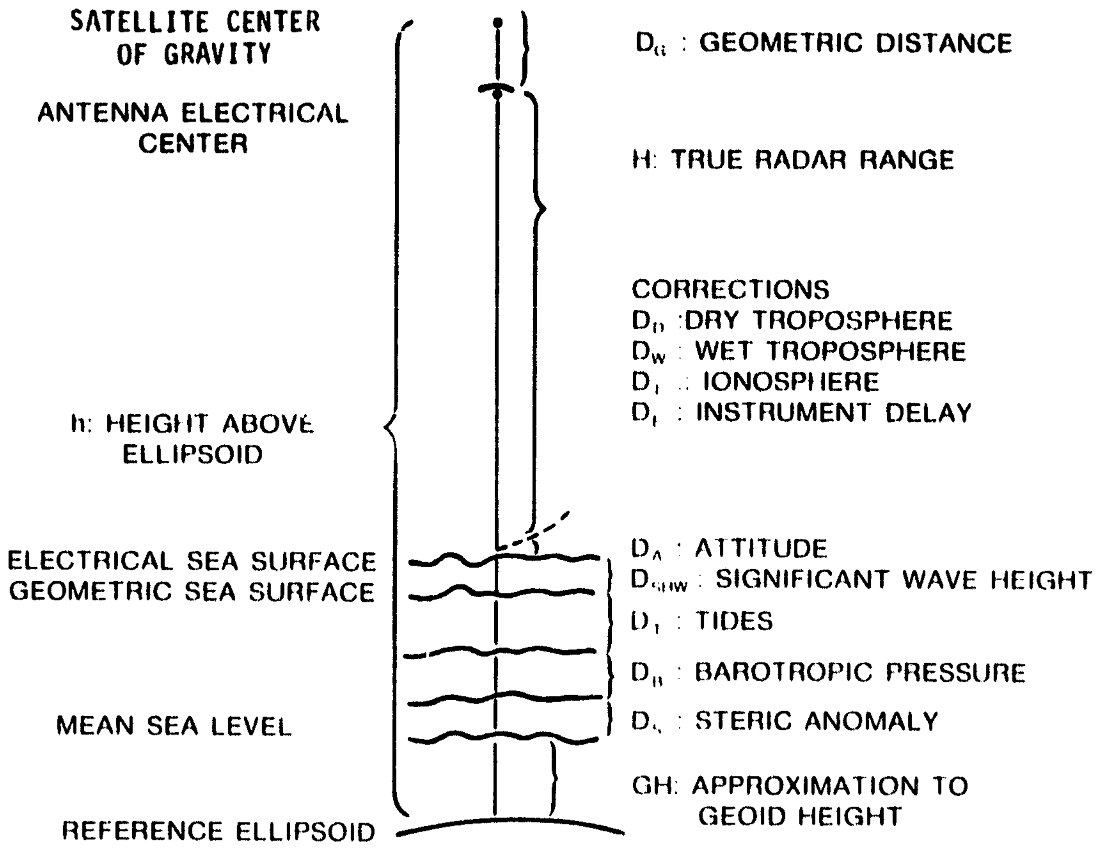
6.4.2 PRECISION ORBIT DETERMINATION

Precision orbit determination will be an important facet in the analyses of the altimeter experiments planned for the ICEX mission. Figure 6-3 depicts the concept of satellite altimetry. In order to reference the altimeter data to a common coordinate system, the data are reduced to the heights of the sea surface above (or below) an ellipsoid with the origin at the center of mass of the Earth. This is accomplished by subtracting the altimeter measured heights of the satellite above the sea surface from the computed heights of the satellite above the reference ellipsoid. The "computed heights" are the result of fitting the best orbit to all available observational data on the satellite. For the ICEX mission, observational data are expected from ground-based lasers, and the spaceborne laser and electronic systems.

Considerable progress has been made in the advancement of the state-of-the-art in precision orbit determination as a result of efforts associated with the GEOS-3 and Seasat missions. This progress has been the result of improved software, instrumentation, physical modeling, and the development of improved and new techniques in the orbit determination process. The present radial accuracy achievable on a global basis for the GEOS-3 and Seasat satellites is about 1 m. The altimeter system proposed for the ICEX mission will have an accuracy of better than 10 cm.

Thus, further progress is required between now and the mid 1980's. Past analyses using simulated as well as real tracking and altimetry data have indicated that residual orbital errors in the modeling of the perturbing forces acting on the spacecraft manifest themselves with a dominant periodicity of one orbital revolution. An example of this effect is shown in figure 6-4 which presents the amplitude

SATELLITE ALTIMETER MEASUREMENT



$$GH = h - D_G - H + D_D + D_W + D_I + D_I - D_A - D_{SWH} - D_T - D_B - D_S$$

Figure 6-3. Factors Involved in Satellite Radar Altimetry Measurements spectrum of the altitude errors for Seasat based upon a simulation of the errors due to drag, solar radiation pressure, and the gravity model of the Earth over a 3-day period. This is important because errors of this type will appear as systematic long-wavelength trends in the altimeter data. It may be possible to develop techniques to utilize the altimeter data to empirically model these long wavelength errors.

Historically, gravity resonance effects have been a major source of model error for the computation of precision spacecraft orbits. For example, resonance perturbations due to spherical harmonic coefficients above degree and order 36 could amount to several tens of meters if the orbit is not selected optimally. Such perturbations can be minimized if care is taken in the selection of the critical orbit parameters.

Intensive studies are currently underway for Seasat in the areas of improving the modeling of nonconservative forces such as atmospheric drag and solar radiation pressure. Since the proposed ICEX spacecraft will most likely have an area-to-mass ratio even larger than Seasat and the shape will be irregular and time varying with respect to the solar angle, complex modeling of these forces will be even more critical than for Seasat. Studies are required to assess the utility of new models currently under development and to further expand upon existing techniques.

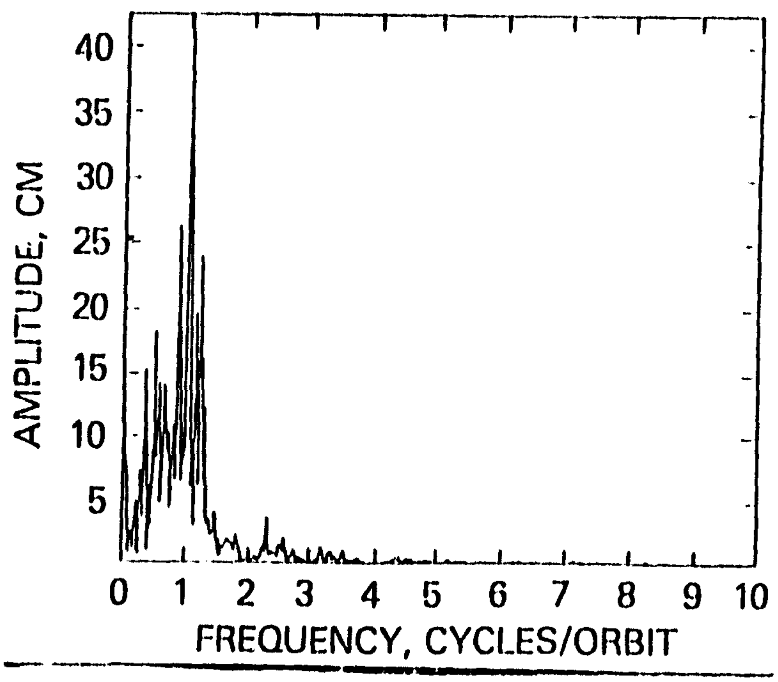


Figure 6-4. Amplitude Spectrum of Seasat Altitude Errors. Simulated errors due to gravity, drag, and solar radiation pressure on a three day arc.

In this regard, accelerometers have been successfully used in other spacecraft for measuring subtle nonconservative orbital perturbations. The utility of the present accelerometer technology as applied to the measurement and modeling of these forces is being assessed for the ICEX mission.

6.5 INFORMATION PROCESSING AND ANALYSIS FACILITY

The ICEX Data Processing and Analysis Facility (IDPAF) will support scientific analysis of ICEX data in near-real time and also provide data storage and manipulation capability for longer term research programs. Investigators will use the data sets through interactive analysis terminal systems. These terminals will be similar to the terminals developed for the Atmospheric and Oceanographic Information Processing System (AOIPS) and the Landsat Assessment System (LAS). In addition to data received from ICEX, the facility will provide direct links to the Climate Data Base and to the Applications Data Service (ADS) for two-way data communication. The degree of data processing and "compression" falls, in most cases, into the categories defined in table 6-8. These categories are in keeping with definitions elaborated for the Global Atmospheric Research Program (GARP). Raw data, preprocessed data, derived parameters, and orbit and attitude data will reside in the facility data base and will be available instantly to on-line users and to the ADS and Climate Data Base users. Data retransmission from the facility will allow experimental data products to be evaluated for accuracy, timeliness, and application to operational situations. Output data products will also be recorded on film for technology transfer and nonreal-time scientific analysis.

Figure 6-5 is a block-diagram showing functional data flow to and from the IDPAF.

The following are primary IDPAF processing requirements:

a. Archiving WSIR, LAMMR, scatterometer, IEAS, and PIMR data for selected periods of time (estimated at 80 days per year);

b. Producing computer compatible tapes and photographic images of selected areas;

c. Supporting interactive research and analysis of archived and near-real-time data sets;

d. Producing derived parameter data sets;

e. Disseminating data by satellite retransmission and the Applications Data Service (ADS).

Figure 6-6 is a system block diagram showing the data flow and analysis processing functions.

Data input communications will be performed by the Domsat interface. Incoming data rates from the LAMMR and WSIR will be 25 mbps (2 percent duty cycle) from each source. Data will be recorded on two high density tape recorders (HDDT) for archiving and serving as a data rate translator. After the pass is recorded, the HDDT's will be slowed down for low data rate playbacks into the sectorizers and data processing computer systems. The third HDDT will be used for tape staging, input of previously archived data, and as a backup to the other two HDDT systems. The sectorizers will limit data flow to the processors by passing desired data to the

Table 6-8. Classification of Data Sets

Data Type	Description
Raw Data	Raw telemetry data from observing instrument.
Level I (physical quantities)	Calibrated data such as brightness temperature, radiances. Extracted from raw data under rigorously controlled and documented procedures.
Level II (parameters)	Parameters at highest available spatial and temporal resolutions. Extracted from Level I data under rigorously controlled and documented procedures.
Level III (gridded parameters)	Spatially and temporally averaged parameters, including statistical information. Extracted from Level II data under rigorously controlled and documented procedures.
Level IV	Data sets combining different parameters, spacially or temporaly averaged or correlated and selected to test a specific theory, hypothesis, or scientific interpretation.
Experimental Data Sets	Data at Levels I, II, or III, but not under rigorous control. Intended for algorithm development purposes.

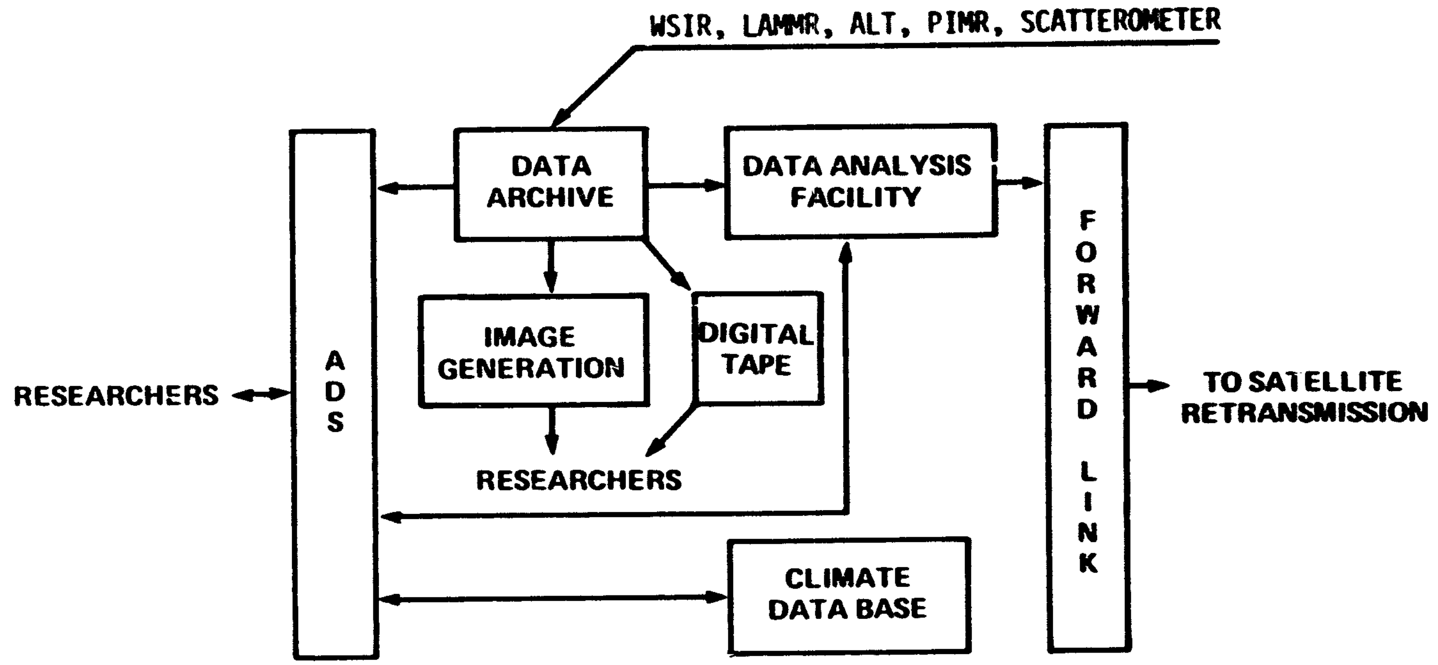


Figure 6-5. Schematic of the ICEX Data Flow Processing and Analysis Facility

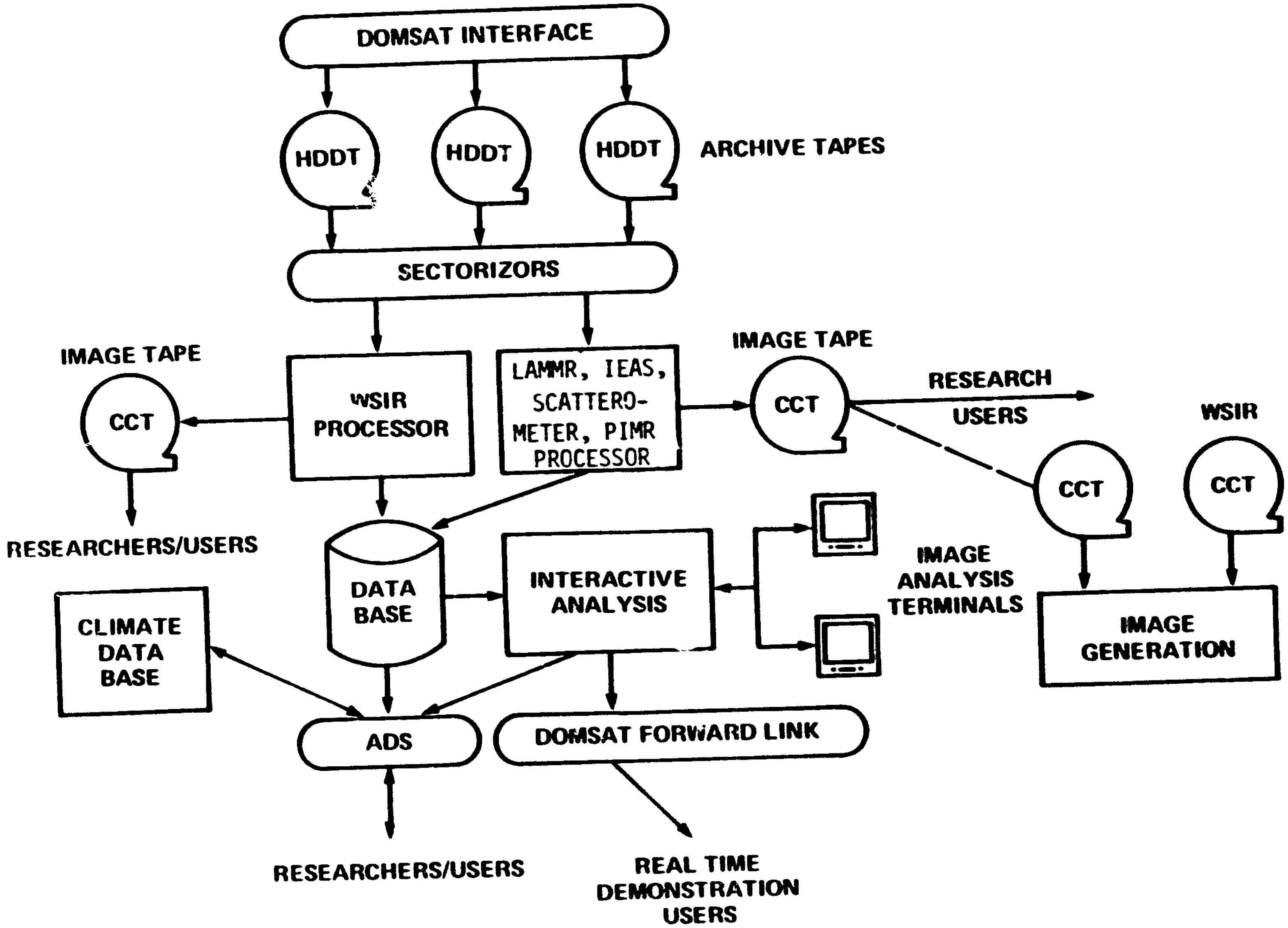


Figure 6-6. Detailed Schematic of the ICEX Processing Facility

systems and excluding unwanted data. This feature reduces data processing requirements significantly, since only needed data will be ingested by the processors.

The WSIR and LAMMR, scatterometer, IEAS, and PIMR processors will perform bulk parameter extraction and prepare data sets for recording on computer-compatible tape (CCT). The processors will also perform data base management functions as required to supply data sets to the interactive analysis system and the external user community (including the climate data base) through the ADS and satellite data links.

The interactive analysis computer system will perform data manipulation and parameter extraction functions required for analysis of archived and near-real-time data. Significant features of the system will be the following items:

a. Ease of use - "Menu" driven system which users can learn quickly and respond to easily;

b. Rapid response - most computations performed in seconds; therefore truly interactive analysis will be achieved;

c. Black and white and color displays of data;

d. Standard television display compatibility;

e. User data "on-line" for instant availability.

The two sophisticated image analysis terminals will link the user to the data bases and the parameter extraction hardware and software. Black and white and color display of ice flow motion vectors, pressure ridges, ice classification, and other ice parameters will be provided.

The image generation system will produce photographic images of satellite data and derived parameters for the user community. Image generation will be performed off-line to minimize loading on the processing systems.

The three processors in the facility will be 32 bits/word computers. Each will have 1 megabyte of memory, an array processor, and 700 megabytes of disk storage. Applications software development will be initiated early in the program to provide analysis capability prior to launch and to support instrument check-out prior to integration with the spacecraft.

6.6 DISTRIBUTION AND RELAY SYSTEM

Several separate links to site-specific users are included in the ICEX data distribution and relay system, because of the lack of reliable terrestrial and satellite communications with the polar regions. The first system is a near-real-time, low-data-rate system broadcasting LAMMR T_B's to the ground over a 1,400 km swath with 7 to 25 km resolution. Being a Metsat-class automatic picture transmission (APT) system, it operates at a data rate of 1.4 kbps. Ground terminals for the system are inexpensive and require only a simple omnidirectional antenna.

AITS, the second system, broadcasts WSIR pictures and other data to two (or perhaps more) users per polar pass. These pictures and data are processed, annotated, and interpreted on the ground, transmitted to the spacecraft using the forward link of TDRSS, and stored before broadcast. Requests for data are transmitted to the spacecraft through the Data Collection System (DCS).

The third system for site-specific users is similar to the Landsat-D real-time X-band link. It will transmit raw WSIR data at 17.8 Mbps through a 42-watt transmitter to Landsat-D remote terminals. The users will have to provide their own ground computational capability similar to the WSIR processor at White Sands, but with a capability that is not as rapid as that of the WSIR. The fourth system is primarily a voice relay for communications by field expeditions.

6.6.1 ADVANCED INFORMATION TRANSMISSION SYSTEM (AITS)

In order to satisfy requirements of local users and investigators located in the polar areas (i.e., latitudes greater than 60°), a near-real-time data forwarding transmission system will be utilized. These local users require a variety of image products ranging from full resolution WSIR results to two-tone ice contour maps. AITS will provide data to local users participating in ICEX, upon request, with a time lag of 3 to 48 hours. In the event that WSIR imagery is desired, this turnaround time assures that a current image is in the ICEX data base and is forwarded to the local user.

Figure 6-7 shows the data flow for AITS. The local user requests data via the ICEX DCLS using a modified data collection platform transmitter. The requests for data products (made with station ID's) are merged on board ICEX with other spacecraft data and periodically relayed via TDRSS to the ICEX processing center. In the process of collecting local user data requests, the DCS also locates the position of the user (since users may be nonstationary). Once the ID of the user has been validated, the ICEX processor uses the position data and the ICEX data base to construct a 100 km x 100 km image located on the current user position. Local user images are then relayed to the ICEX spacecraft via TDRSS and stored on board. Images are subsequently transmitted directly to local users via a UHF link during a flyover.

Figure 6-8 presents the trade-off between image resolution (pixel size) and retransmission time to the local user (which establishes overall system capacity). At a square pixel size of 100 m, the retransmission time of 470 seconds (7 min 50 sec) is required. This resolution requirement would set the system capacity at 2 images/pole/orbit. A system capacity of 20 images/pole/orbit is feasible for a low-resolution ice contour map representing large areas.

The AITS spacecraft hardware primarily consists of a high power UHF transmitter and antenna for the local user downlink and a random access storage medium (a new technology development). Technology candidates for the latter are video discs or bubble memories. AITS also makes use of the ICEX data collection system and the command and data handling system interface with TDRSS.

The local user ground terminal consists of a modified ARGOS type data collection platform transmitter, a UHF telemetry receiver, an omni-directional

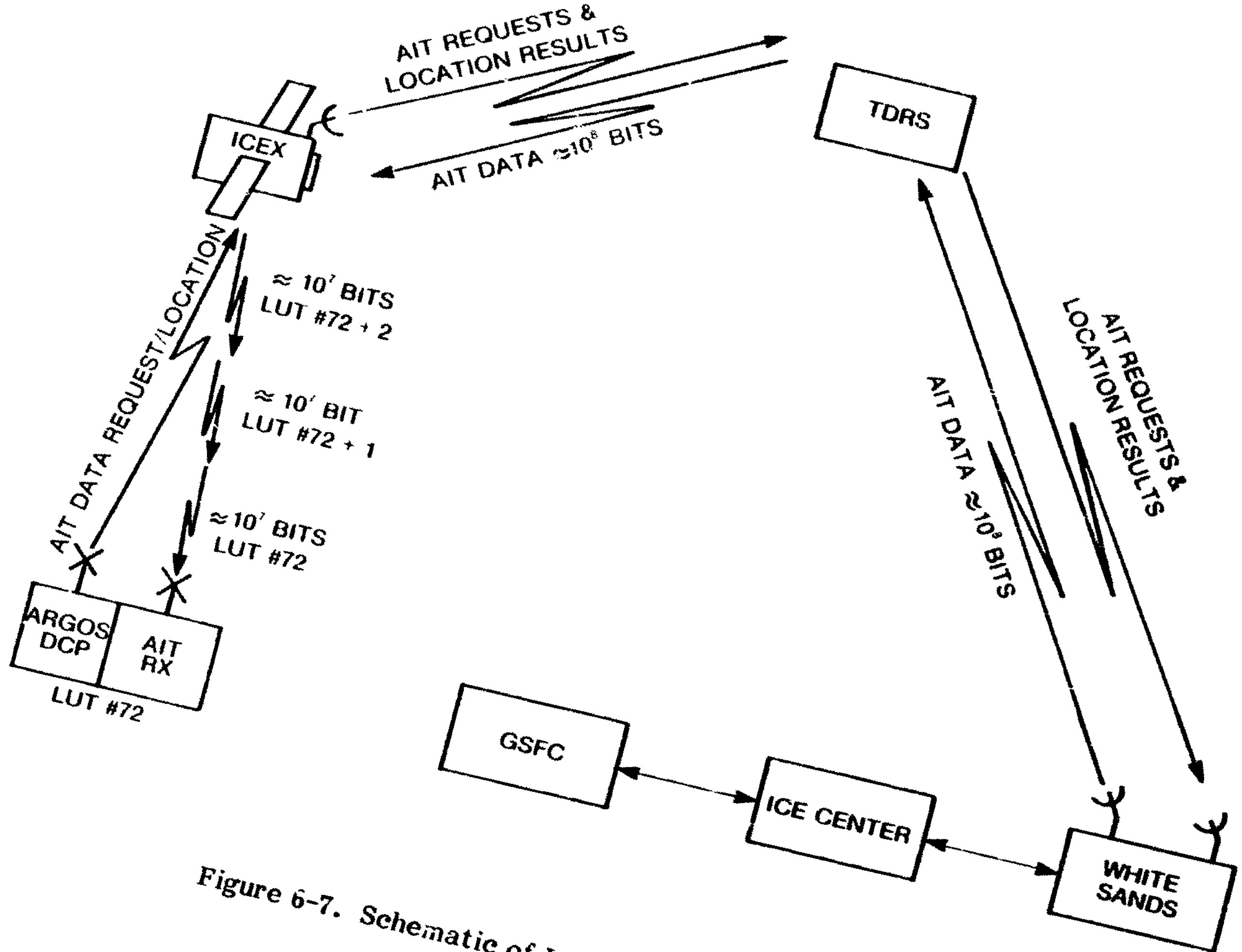


Figure 6-7. Schematic of ICEX Data Relay and Transmission System

UHF antenna common to both, and an image recorder. The transmitter, upon local user request, will forward the following information to the ICEX processing center:

a. Date and time of request (inserted by the spacecraft),

b. User identification (I.D.),

c. Desired data product,

d. A data and/or comment field,

e. Local user longitude and latitude (determined by DCLS system).

AITS local user data products may include:

a. High Resolution WSIR Data:

(1) 100 km X 100 km square image

(2) 100 m/pixel

(3) 1 in 32 grey scale resolution

(4) Image lags real-time by 48 hr max

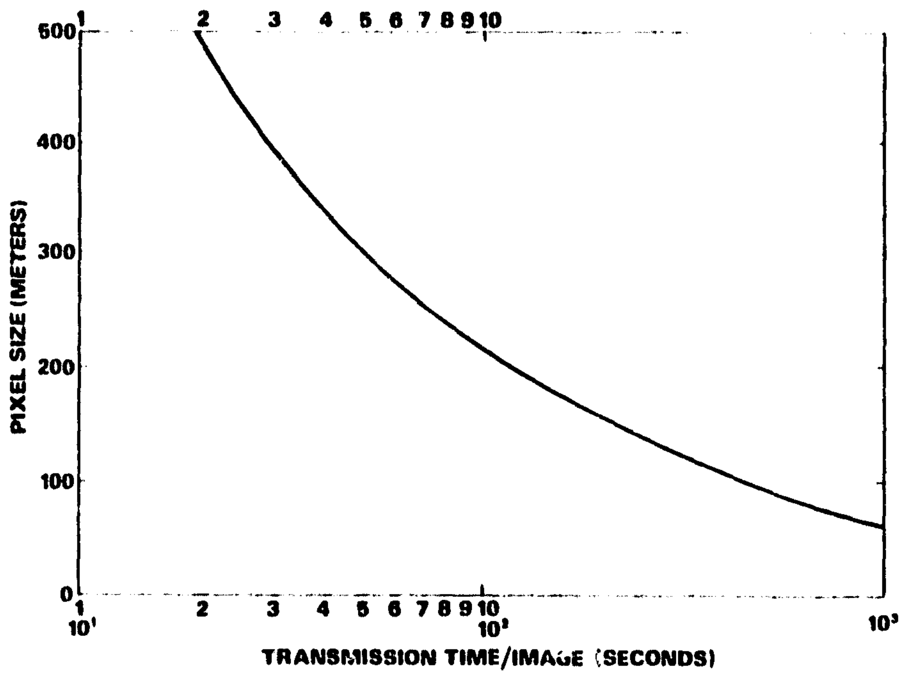


Figure 6-8. Pixel Size Image Transmission Time on AITS for 100 km^2 WSIR Image

b. Ice contour map/weather map:

(1) 1500 km X 1500 km square image

(2) 1500 m/pixel

(3) 1 in 2 grey scale (black or white)

(4) Image lags real-time by 2 orbits and lag in map generation

c. Other data products or data fields yet to be specified. Any data existing in the data base could presumably be forwarded to the user. Special data products could be supplied upon request if user-supplied processing algorithms were available at the ICEX processing center.

Costs for a local user ground terminal are estimated to be no more than twice that of an existing meteorological satellite Advanced Picture Transmission (APT) receiver. During the design phase, all efforts will be made to ensure that the data collection platform may, if desired, also serve as an ARGOS sensor platform. Attempts will be made to maintain receiver compatibility with standard APT transmissions.

6.6.2 WSIR REAL-TIME X-BAND LINK

The ICEX mission will utilize a high resolution X-band picture transmission system, similar to the one to be flown on Landsat-D, to provide direct real-time WSIR data to interested users. The digital data format will incorporate all image data from the wide swath imaging radar. It transmits this data in real time on an 8.2 GHz (X-Band) downlink. While the WSIR instrument produces data at a rate of 17.8 MBPS, the downlink data rate will be nominally 85 MBPS. This data rate and the format are selected to be compatible with the Landsat-D/Thematic Mapper real-time X-band link. By so doing, users with receiving stations for Landsat-D real-time imagery may also receive ICEX/WSIR imagery at a minimum additional cost.

The space hardware consists of a high speed formatter to assemble WSIR data into data blocks and an X-band transmitter and antenna. Assuming a 42 W transmitter at 8.2 GHz and the ground station as defined below, the spacecraft X-band antenna may be omnidirectional and would allow acceptable links to users within a 2200 km radius.

The ground station equipment will be equivalent to that required for the Landsat-D direct reception X-band link:

a. Dish Diameter: 10 M

b. Antenna Gain: 58 dBi

c. System Noise Temp.: $263^{o}K$

d. Receive System G/T: $33.8\ dB/^{o}K$

e. Antenna Beam Width: 0.1^{o} (3 dB)

It is assumed that the Landsat user expense for WSIR data from ICEX is then the cost of the WSIR processor system.

6.6.3 VOICE AND DATA RELAY CAPABILITY FOR ICEX

A severe limitation to the scientist performing research at remote sites in the Arctic or the Antarctic is the dependence upon HF communications, usually as his or her only link to a support station. In times of ionospheric disturbances when HF "black-out" occurs, no means of communications between scientists in the field and the support camps exist unless they are within the limited range of VHF communication. This lack of ability to communicate has serious implications from the standpoint of safety and of efficient conduct of field work. Weather and other environmental conditions must be communicated to aircrews who are the lifeline of support between support stations and the scientists in the field. A modest voice and data relay capability on ICEX would offer an excellent solution to these limitations.

Such a voice and data relay capability for the ICEX would be similar to that in the OSCAR (Orbiting Satellite Carrying Amateur Radio) repeater satellite--an extremely cost effective, efficient, and practical means of relaying information. The primary requirement for any two stations communicating via this repeater is that both stations be simultaneously within the footprint of the satellite. The OSCAR repeater provides several modes of operation, all of which are designed for multiple simultaneous users.

Readily available commercial components can be utilized by the communicating ground stations for both transmitting and receiving. Practically any commercially available receiver with good sensitivity, a preamplifier, and simple circularly polarized low gain antenna would suffice. Transmitting equipment should be capable of 80-100W effective radiated power. The spacecraft antenna would be a simple 10 meter linearly polarized antenna.

Because ICEX will be in a near polar orbit, every pass of the satellite will be visible for some period at the poles. Coverage is reduced as the latitude of the station decreases and as the distance between stations increases. For applications in polar regions, assuming both communicationg station are between latitude of 75° and 90° north or south, the period of communications coverage (both stations within satellite footprint) is estimated to lie between 15 and 30 minutes for each of the 12 to 14 daily passes. During these peiods voice or data could be passed between any of the research stations or field parties. A modest onboard storage capability would permit scientific data from any location to be stored and dumped (direct readout) to any chosen ground station along the satellite subtrack. Such a capability would relieve the system of the requirement that two stations be simultaneously within the footprint of the satellite before information can be transmitted.

The above proposed relay capability would complement the TIROS-N ARGOS data collection sysem and permit maximum flexibility in terms of what sensor data and other information is passed, to where, and when.

CHAPTER 7. RECOMMENDATIONS CONCERNING RESEARCH AND COORDINATION

CHAPTER 7. RECOMMENDATIONS CONCERNING RESEARCH AND COORDINATION

In the preceding parts of this document we have attempted to describe the scientific background of ICEX, its objectives in basic and applied science, and the technical means of implementing it. We have shown that the program is timely and feasible and that significant new insights and operationally useful data and procedures will result, provided that, as an integral part of the program, a massive effort is mounted and maintained to compress and disseminate the data.

An important question remains to be asked: Will the scientific and technological communities be able to use effectively the enormous volume of information generated by ICEX?

The mechanics of our national system of funding scientific research are such that the amount of money available to do certain kinds of work is generally not greatly out-of-balance with the number and demands of scientists who want to do that work. Learned societies and their advice, mission agencies and their requirements, academic communities and their programs, industry and its technologies--all contribute to a trend of mutual adjustment between a given "constituency" and the amount of support available. In this connection it appears useful to briefly reflect on the nature of the "constituency" of ICEX.

A few decades ago glaciology was the science of glaciers, taught typically as a sideline in geology departments, with an emphasis on glacial geology and geomorphology. After World War II the growing international glaciological community defined its subject area as "the study of ice in all its forms," thus adding to its traditional pursuit studies of the mechanics and thermodynamics of ice and snow, as well as their interactions with the lithospheric, atmospheric, and hydrospheric environment.

Throughout that evolution there has been in existence a community of "polar scientists." Although ice dominates the polar environment, their interests cover the entire range of terrestrial and biological sciences. The legitimacy of being identified with a geographical region rather than a scientific discipline has been questioned repeatedly and reaffirmed each time: the operational cost and difficulty of doing work at high latitudes provides an overriding element of commonality, and working together is a simple matter of practical expediency.

The increasingly global view of meteorology, climatology and oceanography, brought about by Earth-orbiting spacecraft mainly during the last decade, has embraced snow and ice and the polar regions under the key concept of "cryosphere." The term cryosphere appears in all relevant national and international geophysical planning documents of the past few years. Semantic precision and traditional connotations aside, we believe that this has been a useful and constructive development, as it departs from traditional disciplines or groups of scientists and deals with scientific substance. It is based on the recognition that the interactive system atmosphere-hydrosphere-cryosphere should be the prime object of our quest for understanding of the processes governing weather and climate.

It is important, therefore, to view ICEX not only in the context of the activities and interests of the individuals who collectively prepared this document but as one of a number of programs serving basic and applied Earth science. Regardless of what appears as the present "constituency" of ICEX, the program must be responsive to a much wider community of interested individuals and groups.

We offer several specific recommendations to NASA:

a. The years between the decision to proceed with the project and its actual implementation should be used to prepare for the flow of data and its use by researchers. The Information Processing and Analysis Facility (IDPAF), in particular, must be set up well ahead of the satellite launching. It must be closely associated with a high quality in-house research group so that it will be generally responsive to the research and development needs of the entire community.

b. The planning and funding of ICEX R&D efforts, both inside and outside NASA, should be started immediately, with special emphasis on the interpretation and utilization of sample ICEX-type data now in existence, sensor development, and the search for efficient methods of data processing, compression, and dissemination.

c. Expenditures, in-house and out-of-house, should be made not only for their specific results but also with the purpose of stabilizing and strengthening existing teams and activities, for supporting relevant advanced teaching programs, workshops, seminars, assistantships, fellowships, and, in general, with the purpose of mobilizing and augmenting scientific manpower.

d. An inter-agency agreement should be formulated that commits block funding for ICEX research (presumably using the vehicle of an Announcement of Opportunity and drawing on the experience gained in similar projects).

e. A firm commitment should be sought from other Federal in-house research units (NOAA, DOD, DOE, USGS, USCG, DOI...) which dedicates an identifiable fraction of their research to the utilization of ICEX data.

f. An overview committee should be established and charged with promoting cooperation, and information exchange, reviewing data dissemination and archiving, and seeking outside advice on research priorities (e.g., NAS-NRC).

g. The role of industry (notably oil, gas, and shipping) as a user and a contributor should be better defined and expanded.

h. Foreign countries and scientists with an interest in snow and ice research should be kept abreast of developments and encouraged to participate in a fashion suitable and advantageous for both the United States and the other country.

The scientist who wants to know what is knowable, the technologist who wants to do what is doable, and the government official who must decide what is needed, generate the essential forces to be balanced in any major research project. We anticipate that NASA's exemplary record on how to perform this task will be continued in ICEX.

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ICEX GLOSSARY

Artificial Islands - manmade gravel mounds constructed in shallow water to support drilling rigs.

AVHRR - Advanced Very High Resolution Radiometer; an instrument used on NOAA meteorological satellites with high resolution in both the visible and infrared channels.

Baroclinicity - the state of stratification in a fluid in which surfaces of constant pressure intersect with surfaces of constant density.

Bathymetric Contours - variations in water depth depicted on contour maps.

Beaufort Sea - part of the Arctic Ocean north of Alaska.

Bering Sea - part of the Pacific Ocean immediately south of the Bering Strait.

BESEX - joint U.S./U.S.S.R. Bering Sea Experiment on remote sensing of the marginal sea ice region of the Bering Sea in Spring 1974.

Bottom Water - the deep, cold water masses of the world's oceans that do not participate in the rapidly-fluctuating, mainly wind-driven circulation systems of the upper ocean.

Brightness Temperature - a measure of the microwave energy emitted by a surface.

Buoys - floating data collection platforms used to measure atmospheric surface pressures, temperature, winds, and subsurface ocean parameters.

Chukchi Sea - part of the Arctic Ocean north of the Bering Strait.

Climate Modeling - the activity of creating and testing mathematical representations of interactions hypothesized to affect or to determine climate.

Coriolis Force - the inertial force caused by the Earth's rotation that deflects a moving body to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

Cryosphere - the most changeable physical constituent of the Earth's surface, consisting of six elements; 1) seasonal snow on land, 2) sea ice, 3) permafrost, 4) river and lake ice, 5) ice sheets, and 6) glaciers.

DCLS - Data Collection and Location System; a candidate ICEX function, DCLS will provide in situ surface measurements to satisfy ice science and applications requirements. It will be used to transfer data and locate the position of remote, unattended platforms and balloons.

Inertial Oscillations - a wave-like or circular motion, with a period ranging from infinite at the Equator to 12 hours at the poles.

Dual Polarized - able to measure or sense both horizontally and vertically-polarized components of electromagnetic radiation.

Eddies - a circular motion of air or water, usually embedded in a mean current.

Ekman Layer - a boundary layer in air or water affected by surface friction.

Ellesmere Island - Canadian island in the Arctic Ocean, west of Greenland.

Emissivity - the relative ability of a surface to radiate energy as compared with that of an ideally black surface under the same conditions.

ESMR - Electronically Scanned Microwave Radiometer; the first passive microwave imager flown on a satellite, it has facilitated several breakthroughs in the remote sensing of ice including the ability to (1) distinguish between sea ice and water and between multiyear and first year ice, and (2) measure ice concentrations on hemispheric scales, regardless of clouds.

ESSA - Environmental Science Services Administration, predecessor to National Oceanic and Atmospheric Administration (NOAA).

Eustatic Changes - of or pertaining to changes in sea level throughout the world, resulting, for example, from extensive formation or melting of ice sheets.

FGGE - First Global GARP Experiment, a worldwide coordinated effort to study the physical processes of the troposphere and stratosphere. (see GARP)

Firn - snow which has increased in density as a result of recrystallization and compaction.

First-Year Ice -	floating ice of not more than one year's growth, characteristically level where undisturbed by pressure ridging.
First-Year Ridges -	pressure ridges formed of first-year ice.
Floebergs -	thick masses of sea ice largely produced from intensely deformed pressure ridge systems that, in most cases, were grounded when they first developed.
Floe -	a piece of floating ice other than fast ice or glacier ice. Floes are subdivided by size as follows: ice cakes are less than 10 m across; small floes, 10-100 m; medium floes, 100-1000 m; big floes, 1-10 km; vast floes, over 10 km.
FOV -	Field of View
GARP -	Global Atmospheric Research Programme, a program for studing physical processes in the troposphere and stratosphere for the purposes of increasing the accuracy of short-term forecasting and improving the understanding of the physical basis of climate.
GCM -	General Circulation Model, a mathematical representation of the global atmosphere and its variations. This activity should ultimately model both the global atmosphere and the world's oceans.
GEOS-3-	Geodynamic Experimental Ocean Satellite.
Geostrophic -	pertaining to fluid motion in which all forces are in balance.
Geothermal Heat Flux -	heat from the deep layers of the Earth.
Glacier Ice -	any ice in or originating from a glacier, whether on land or floating in the sea as icebergs.
Glacier -	a mass of snow and ice continuously moving from higher to lower ground or, if afloat, continuously spreading. The principal forms of glaciers are ice sheets, ice shelves, ice caps, ice piedmonts, and various types of mountain glaciers.
GPS -	Global Positioning System, a worldwide, all-weather navigation system.
Heat Balance -	heat gained minus heat lost from a given region.
Heat Sink -	an area of heat loss, a cold region, or the low temperature element of a thermodynamic engine.

Hydrosphere - all the water on the surface of the Earth, including oceans, lakes, rivers, etc.

Iceberg Towing - plan to tow icebergs from the Southern Ocean to areas in the Southern Hemisphere where they would be used as a source of fresh water.

Ice Concentration - ratio of the percentage of sea ice to the percentage of water for a given area.

Ice Island - form of tabular iceberg found in the Arctic Ocean, with a thickness of 30 to 50 m and from a few thousand square m to 500 square km in area. Ice islands often have an undulating surface, which gives them a ribbed appearance from the air.

Ice Sheet - mass of ice and snow of considerable thickness and area. Ice sheets may be resting on rock or floating. Ice sheets of less than about 50,000 square km and resting on rock are called ice caps.

Ice Types - ice classification based on various criteria: age, salinity, compactness, crystal structure, etc.

ICEX - Ice and Climate Experiment - a proposed program to study the Earth's snow and ice.

ICSI - International Commission for Snow and Ice.

IDOE - International Decade of Ocean Exploration.

IDPAF - ICEX Data Processing and Analysis Facility, a proposed facility to support scientific analysis of ICEX data in near-real time and also to provide data storage and manipulation capabilities for longer-term research projects.

IEAS - Ice Elevation Altimeter System, a proposed instrument system which can measure ice altitude profiles with two complementary instruments: a microwave radar altimeter and a laser altimeter.

IFOV - Instantaneous Field of View.

IGY - International Geophysical Year - 1957-1958.

Insolation - the radiation from the Sun received by a surface, especially the Earth's surface; the rate of such radiation per unit of surface.

ITOS - Improved Tiros Observational System.

Katabatic Outflow - a cold, shallow layer of air moving downslope.

Krill - small shrimp-like crustaceans (mainly Euphausia superba) considered by many fishery experts to be the world's largest untapped source of natural protein.

LAMMR - Large Antenna Multifrequency Microwave Radiometer, a candidate ICEX instrument used to measure radiation of the surface in seven bands ranging from 1.4 GHz to 91 GHz.

Leads - open channels in sea ice.

Marginal Cryosphere - geographic regions experiencing snow or ice during part of the year.

Mass Balance - (for ice sheets) this is the relationship between the rate of mass gain from snowfall and of mass loss from melting and outflow.

Meanders - winding or convolutions, as of a stream.

Meltpool - small body of water resulting from water melting on top of ice.

Microwave Sensors - class of instruments sensitive to electromagnetic radiation with wavelengths longer than a few millimeters -classified as passive or active.

(a) passive looks only at the naturally-emitted source of radiation.

(b) active involves sending a pulse of radiation and monitoring the reflected or scattered radiation return from that pulse, e.g., radar.

Monopod - a drilling platform resting on a single structural column.

Multiyear Ice - type of ice which has been present for more than one year typically having lower salinity and higher density than first-year ice.

NAVSAT - Navigation Satellite (deployed by U.S. Navy).

Nimbus 5,6 & 7 - series of NASA experimental meteorological satellites.

NORSEX - Norweigan Sea Experiment conducted in Autumn, 1978 and 1979.

NOSS - National Oceanographic Satellite System - a satellite proposed for operational ocean monitoring.

Nuclear Desalinization - technique of using nuclear power to remove salt from ocean water to produce drinking water.

NdYAG laser - laser formed of a standard material base composed of neodymium, yttrium, arsenic, and gallium.

Pack Ice - any area of sea, river, or lake ice other than land, or fast ice, no matter what form it takes or how it is disposed. Pack ice cover may be reported in tenths, or may be described as very open pack (1/10th to 3/10ths), open pack ice (4/10ths to 6/10ths), close pack ice (7/10ths to 9/10ths) and very close pack ice (practically 10/10ths, with very little if any water visible).

Permafrost - perenially frozen ground which underlies about 20 percent of the Earth's land surface.

PIMR - Polar Ice Mapping Radiometer - this candidate instrument system can map cloud covers, determine cloud parameters, measure surface temperatures, and aid in distinguishing surface and snow from clouds.

Pleistocene - designating, or of the first epoch of, the Quaternary Age in the Cenozoic Era, characterized by the spreading and recession of continental ice sheets and by the appearance of modern man.

POLEX - Polar Experiment, an element of FGGE.

Polynya - any water area in pack ice or fast ice other than a lead.

Pressure Ridges - pile-ups of deformed ice that result from compression and shearing motion between ice floes.

Profilometry - measurement of altitude profile.

Pycnocline - boundary between water masses of differing density, in polar regions typically the boundary between low-salinity surface water and more saline deeper layers.

Quaternary Period - the geologic period following the Tertiary in the Cenozoic Era; present geologic epoch starting approximately two million years ago.

Remote Sensing - the collection of information about an object without being in physical contact with it—restricted to methods that employ electromagnetic energy to detect and measure target characteristics.

Ross Ice Shelf - a large, tapered "plate" of floating glacier ice descending from the interior of Victoria Land and Marie Byrd Land into the Ross Sea of Antarctica.

SAR - Synthetic Aperture Radar, an active microwave imaging sensor recently flown on Seasat-1.

Sastrugi - long, wavelike ridges of hard snow, typically formed perpendicular to the direction of the wind and common in polar regions.

SCA - Snow Covered Area.

Scatterometer - side-looking radar with the capacity to measure the scattering cross section. It shows surface scattering characteristics, ridging, ice sheet boundaries, and sea ice concentration and types.

Scouring - moving pack ice rubbing vigorously against the ocean bottom in some cases forming gouges measuring 6 m deep.

Sea Ice - any form of ice found at sea which has originated from the freezing of sea water.

Seasat-1- a satellite designed to measure ocean parameters.

Shirase Glacier - outlet glacier on the East Antarctic ice sheet where recent ice elevation measurements have been made.

SMMR - Scanning Multichannel Microwave Radiometer -a five-frequency, dual-polarized version of an ESMR flown on Nimbus-7 and Seasat-1.

Spitsbergen Island - the largest island of the Svalbard archipelago (Norwegian).

SSIZ Workshop - Seasonal Sea Ice Zone Workshop held in 1979.

Storm Tracks - patch of low-pressure weather systems.

Surge - a relatively rapid or accelerated flow of glacier ice resulting in an advance of the terminus or ice front and a thinning of the upper portions of the glacier or ice sheet.

SURSAT - Canadian Surveillance Satellite Experiment conducted in Winter and Spring, 1978 and 1979.

Synoptic - presenting or involving data on weather and atmospheric conditions over a wide area at a given time.

Tabular Berg - a flat-topped iceberg. Most tabular bergs form by breaking from an ice shelf.

TAD - Tiros Arctic Drifter, an air-droppable buoy system presently employed in the Arctic which measures atmospheric pressure, ambient temperature, and location.

T_B - brightness temperature.

TDRSS - Tracking and Data Relay Satellite System. This system will provide telecommunications services and relay communication signals between the user spacecraft and user control and/or data processing facility.

Thermodynamics - branch of physics dealing with the reversible transformation of heat into other forms of energy.

Troposphere - the atmosphere from the Earth's surface to the tropopause, about 10 km high at the poles and 18 km at the Equator. In this stratum, clouds form, convective disturbances take place, and the temperature usually decreases with altitude.

Upper Troughs - area of low barometric pressure in the upper atmosphere.

Weddell Sea - section of the Atlantic Ocean east of the Antarctic Peninsula.

WSIR - Wide Swath Imaging Radar, a candidate ICEX instrument system. It is an X-band synthetic aperature radar which produces images of the surface with a basic pixel size of 100 m. WSIR will be used to obtain parameters of sea ice motion, ice sheet motion, surface properties, and large iceberg locations.