NASA Technical Memorandum 86233

Satellite Remote Sensing for Ice Sheet Research

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FOREWORD

During the next decade several satellite missions will be overflying the polar regions collecting data potentially useful for ice research. These missions will provide an opportunity for compiling long time series of radar-altimeter, passive-microwave, infrared, and scatterometer data. In addition, synthetic aperture radar (SAR) data will be acquired from the space shuttle and from free-flying satellites. The SAR data will supplement high-resolution visible imagery from Landsat and SPOT satellites.

Because most of these data will be acquired by satellites that are flown primarily for ocean and land applications, over-ice data generally will require extensive reprocessing to yield information useful to glaciological research. The needs of the sea-ice research community have been addressed by working groups considering applications of passive-microwave data from sensors aboard Defense Meteorological Satellites, and SAR data from the European Space Agency's ERS-1 mission. This document assesses research applications of satellite data over the large continental ice sheets and ice shelves of Greenland and Antarctica.

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EXECUTIVE SUMMARY

Despite 25 years of intensive field work in Greenland and Antarctica, and the expenditure of billions of dollars, we are still unable to answer the most fundamental glaciological question: Are the polar ice sheets growing or shrinking? However, the many detailed investigations during this period have identified three important aspects of ice-sheet behavior:

1. The ice sheets are continually changing. Although the ice is either thinning or thickening within most of the areas studied, we cannot determine whether the observed changes represent redistribution of mass within the ice sheets, or mass exchange with the ocean. To answer this question, we need data from all of the major catchment basins. The most straightforward approach to determining the rate of thickening or thinning (the "mass balance") is to measure periodically the surface elevation at many points on the ice sheet. This can be done only from satellites using a radar or laser altimeter.

2. The ice sheets and the global climate have a complex cause-and-effect relationship operating on time scales ranging from months to millenia. In addition to direct relationships such as those between air temperature and ice ablation, or precipitation and ice accumulation, there are many indirect and poorly understood linkages. For example, sea ice has a modulating effect on the source of moisture that feeds the ice sheets with snow; ocean circulation and sea-ice cover around Antarctica strongly influence melt rates from beneath floating ice shelves which, in turn, regulate ice discharge rates from the continent. In order to identify and investigate these various feedback mechanisms, we need to monitor a selection of critical ice parameters: summer melt zones; surface temperatures; precipitation rates; ice-surface elevations and the positions of seaward margins of the ice sheets; and sea-ice extent. Most of this information can be obtained only from satellites.

3. In the annual layers of deposited snow, ice sheets contain a unique record of world climate and atmospheric composition over the past several hundred thousand years. Interpretation of this record requires an understanding of ice-sheet dynamics. This is because samples within an ice core have been displaced from their original deposition sites, and they have been thinned by varying amounts depending on past ice-sheet dynamics. A first step toward developing this understanding involves close analysis of present-day ice behavior which first must be described by a combination of global monitoring from satellites and detailed field investigations in areas of particular interest.

During the next 10 years, we shall have the opportunity to acquire data from altimeters; from visible, infrared, and microwave radiometers; scatterometers; and from Synthetic Aperture Radars (SARs) which will overfly the ice sheets. In order to assess potential research applications of these data and to determine which data should be acquired, NASA has asked a small group of glaciologists to address these issues. This report presents their recommendations, which the group believes to be representative of consensus opinion among the glaciological research community.

Actions recommended by the group can be summarized as:

- Surveys of ice surface topography by satellite altimeters should be repeated at intervals of approximately 5 years.

- Surveys of the seaward margins and near-coastal surface features of the ice sheets, using Landsat quality and/or SAR imagery, should be repeated every year.

- There should be long-term routine monitoring of ice-surface characteristics (temperature, accumulation rate, presence of surface melt) using infrared and passive-microwave radiometers for synoptic coverage and SAR for focused investigations of selected regions.

This research program will provide both the reconnaissance data that are sorely needed to describe overall ice-sheet behavior, and fundamental information on mass balance and environmental conditions that is essential to understanding present behavior and to the development of reliable predictive models. Results from this program will lead to more effective planning of *in situ* investigations by identifying areas that require focused study, and the interpretation of such intensive measurements from widely separated sites will be greatly facilitated by the overall picture of ice-sheet behavior provided by satellites.

We are on the brink of a major advance in ice-sheet research, and we must be ready to make effective use of the satellite measurements which will make this possible.

CONTENTS

I. INTRODUCTION

Nearly all ice on Earth occurs as large ice sheets in the polar regions. These ice sheets, reservoirs of more than 90 percent of the world's fresh-water supply, have remained poorly explored and little studied even through most of the present century. Yet now, with recent studies of their potential impacts on world sea level and global climate, their relevance to Man's activities on our planet is becoming apparent. The Antarctic ice sheet (Figure 1), containing over 90 percent of the world's ice, stretches over an area of 14 million square kilometers, making it larger than the United States. If the entire ice sheet were to melt, global sea level would rise by some 70 meters. Research in the polar regions has been hampered in the past by the vast size of the ice sheets, their remoteness, and the harshness of the polar environment. However, with the advent of satellite remote sensing providing broad spatial coverage, we can begin to investigate the polar regions without regard to severe weather conditions or long polar nights.

Increased awareness of the role of polar ice in modulating and responding to world climate, in controlling sea level, and in modifying ocean properties has exposed our lack of understanding of ice behavior. For example, we do not know whether the ice sheets of Greenland and Antarctica are growing or shrinking; we do not know how much snow falls on these ice sheets, how much melting there is, nor how much ice flows into the ocean to form icebergs. We cannot calculate accurately the forces that drive ice motion, and we cannot assess how strongly sea ice affects heat transfer between the ocean and atmosphere and hence influences both ocean properties and climate. The limited work that has been done shows that the polar regions are not dormant and unchanging. In the few areas where detailed measurements have been made, the ice sheet locally appears to be either thickening or thinning. Also, around the margin of the ice sheets, satellite data show enormous year-to-year changes in the sea-ice cover, and this is certainly indicative of changes in the source areas for the moisture that eventually feeds the ice sheets with snow. The extent and significance of the changes in the ice sheets and their environment needs investigation, and conventional field techniques are not adequate for this task.

In addition to intensive research in selected areas requiring *in situ* measurements, we need data from as large an area of the ice sheet as is possible in order to reconstruct the total pattern of ice-sheet behavior. For this reason the glaciological community was among the earliest advocates of remote sensing from satellites. Satellites in near-polar orbit can provide excellent coverage of the polar regions, but progress in ice research has been hindered by factors such as the assignment of a low priority to acquisition of Landsat images of the ice sheets, and limited availability of funds to process over-ice data to useful geophysical parameters. Nevertheless, a great deal of polar research has been accomplished using data from satellites such as Landsat, the Nimbus series, and Seasat that were launched for other purposes. Although none of these satellites was in a true polar orbit—passing over the poles—they each led to a major advance in our understanding of the polar regions.

Several satellite missions are planned during the next decade, primarily for ocean and land applications, that will extend data coverage of the polar regions and will provide a long time series of data over this increased area. Many of these missions will fly within 8 degrees latitude of the poles, providing coverage of almost all the Greenland ice sheet, and of the major Antarctic drainage glaciers where most of the "action" takes place. Ultimately, we need coverage at least to within 4 degrees latitude of the poles, and we look to NASA shuttle missions and the proposed Earth Orbiting System (EOS) to provide this coverage.

This report describes how satellite data from planned missions should be used to assess how the ice sheets affect climate and sea level, and how climate and sea level in turn affect the ice sheets. The glaciological community has a major responsibility to answer these questions, and to do this, appropriate satellite-determined data are essential.

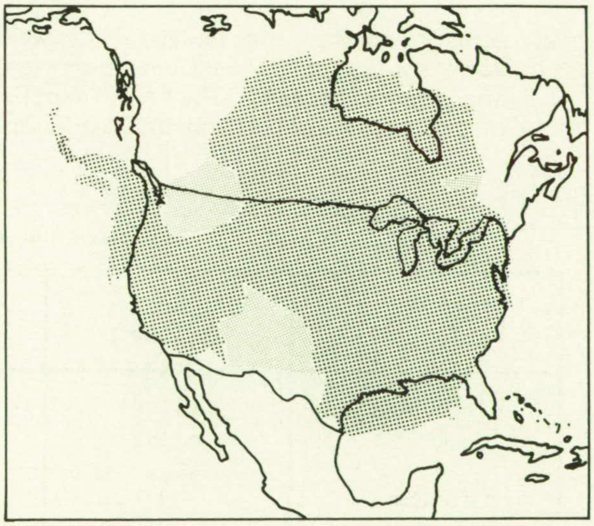


Figure 1. Antarctica superimposed over a map of the U.S. The lightly stippled areas are the floating ice shelves.

II. THE GEOPHYSICAL ROLE OF ICE SHEETS

Ice sheets exist as a consequence of climate; yet over large areas of the Earth's surface, ice sheets control the climate. The high albedos of ice and snow interact with other factors to produce feedbacks that influence the overall sensitivity of the climate system. Ice sheets radiate heat to space, and their effectiveness in achieving this varies with their areal extent and surface elevation. The biggest ice sheet—that of Antarctica—is intimately linked to the circulation of the ocean and atmosphere and even the depth of the world's seas.

Although permanent ice sheets cover about 10 percent of the land surface area of the Earth, they are even today the least-studied and least-understood major components of Man's environment. Very little has been done to determine the exact dimensions or to record variations of the Greenland and Antarctic ice sheets. Table 1 summarizes what is known and shows the overwhelming scale of the great ice sheets compared with the sum total of all other glaciers.

ICE SHEET CLASSIFICATION

There are three major types of ice sheet:

1. A terrestrial ice sheet rests on land which, for the most part, is above sea level and would be well above sea level if the ice sheet were removed and isostatic recovery were to take place. The Greenland ice sheet (Figure 2) and most of the East Antarctic ice sheet are terrestrial ice sheets.
2. A marine ice sheet rests on land that is well below sea level, and would remain so even after removal of the ice. The West Antarctic ice sheet and two of the major drainage basins in East Antarctica are marine ice sheets (Figure 3).

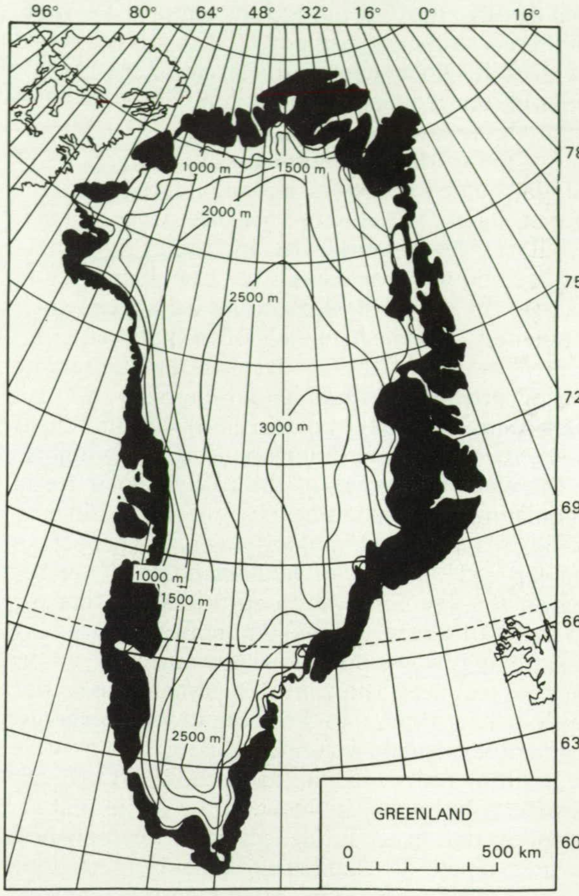
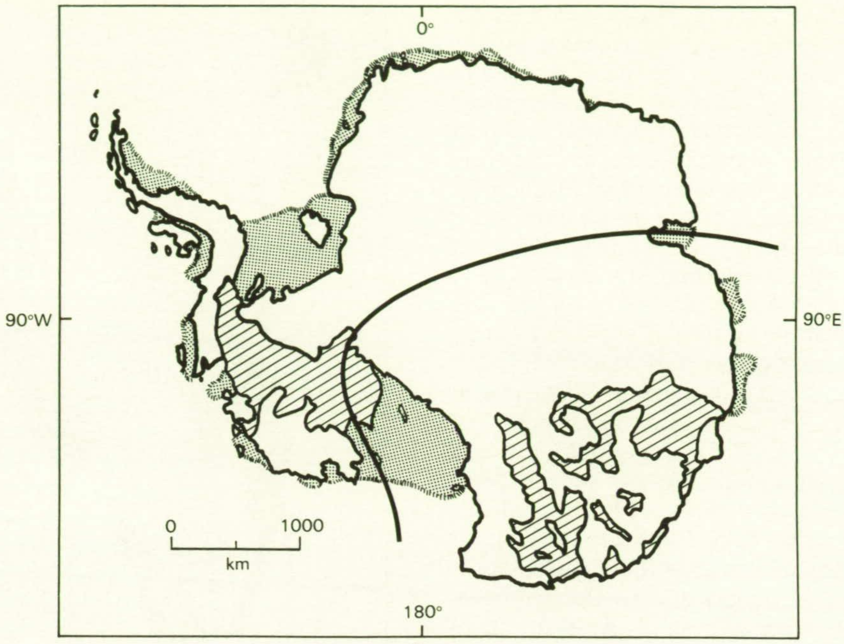


Figure 2. Greenland, showing surface-elevation contours over the ice sheet. Exposed rock predominates in the black areas.

Table 1
Area and Volume of Glaciers

	Area (10^6 km^2)	Percent	Volume (10^6 km^3)	Percent
Mountain Glaciers	0.5	3	0.3	1
Greenland	1.7	11	2.6	8
Antarctica	13.9	86	30.1	91
Total	16.1	100	33.0	100

3. Ice shelves are floating extensions of the grounded ice sheets. They form where ice flows into the sea. The Ross and Filchner/Ronne ice shelves are the largest, occupying major embayments in the Antarctic coastline. There are no large ice shelves in the Arctic.



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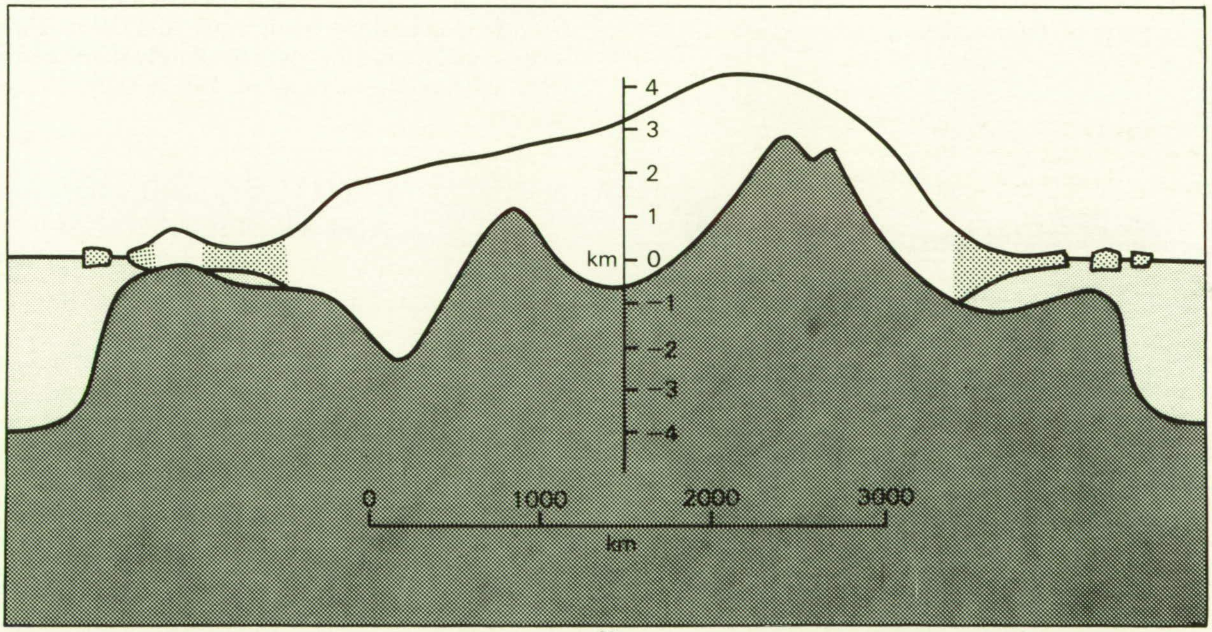

3b

Figure 3. Antarctica, showing ice shelves (stippled) and hachured areas where bedrock is more than 500 meters below sea level. A section along the bold line in 3a is shown in 3b.

GREENLAND

The Greenland ice sheet, with a maximum surface elevation greater than 3,000 meters (Figure 4), has depressed the underlying land, but only small areas lie at depths greater than 250 meters below sea level. Ice is lost by surface melting, which accounts for about half of the wastage, and by icebergs calving from glaciers that pass through the rim of mountains surrounding the ice sheet. Some of the glaciers move at speeds up to several kilometers per year and they are severely crevassed, so that icebergs calving from them break up rapidly to become comparatively small fragments. The average snow accumulation rate is equivalent to approximately 30 centimeters of water per year (Figure 5). Comparing estimates of snow accumulation with estimates of melting and iceberg calving indicates that the ice sheet is in balance within error limits of ±30 percent of the total snow accumulation. In other words, average thickening or thinning of the ice sheet could be as much as 10 centimeters per year, equivalent to a global sea-level change of about half a millimeter per year. Indeed, repeat measurements of a surface-elevation profile during the 1948 to 1968 period indicate thinning by about 30 centimeters per year in the ablation zone. Results from higher elevations show thickening of about 10 centimeters per year on the western side of the ice sheet, with thinning of a few centimeters per year further east. However, these results apply to only one leveled profile, and we have no way of assessing how representative they are of the entire ice sheet. There is a clear need for similar data from many parts of the ice sheet.

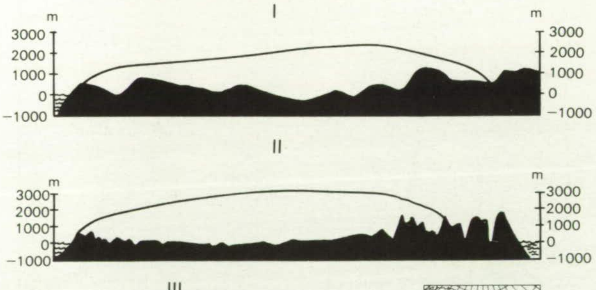

Figure 4. Three cross sections of the Greenland ice sheet showing most of the submerged bedrock to lie above sea level.

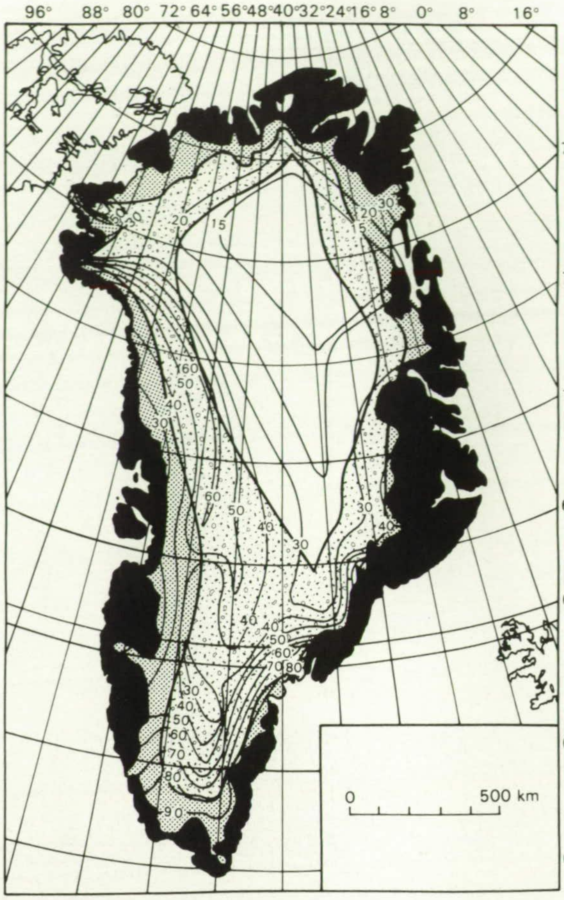

Figure 5. Annual snow accumulation over Greenland in centimeters of water equivalent. There is some surface melting over the lightly shaded area, with substantial melting in the heavily shaded regions.

ANTARCTICA

East Antarctica is a continental land mass overlain by an ice sheet with surface elevations up to 4,000 meters above sea level. Although the ice load has depressed the land by several hundred meters, most of the land, after isostatic recovery, would lie above sea level. However, large areas of the two depressed regions between 90 degrees and 180 degrees East longitude (Figure 3) would remain well below sea level. These, together with the ice in West Antarctica, form the marine portions of the Antarctica ice sheet. Theory suggests that these portions could be susceptible to comparatively rapid collapse. Ice at the coastal grounding line, where it becomes afloat, spreads seaward unrestricted by basal friction. Spreading causes the ice to thin. If the thinning rate exceeds the rate of thickening by snow accumulation and advection of thicker ice from upstream, then ice at the grounding line becomes thinner and the grounding line migrates upstream. Migration continues to a point where thickening and thinning effects are in balance. This is expected to be in an area of shallower bedrock, since the spreading rate of ice at the grounding line is predicted to increase rapidly with increasing thickness. For a marine ice sheet, bedrock in many areas becomes deeper in an upstream direction. Consequently, upstream migration of the grounding line would result in progressively larger thinning rates and consequently further migration. In theory, the process could become extremely rapid, causing large portions of the ice sheet to collapse into the sea in just a few decades.

At the end of the last ice age, part of the Laurentide ice sheet over Hudson Bay may have collapsed rapidly to cause a sea-level rise of several meters in less than 200 years. Under appropriate conditions, the present-day marine portions of the Antarctic ice sheet could collapse in a similar fashion. Marine portions of East Antarctica may be protected by coastal bedrock sills which limit ice thickness, and therefore spreading rates, attainable by ice at the grounding line. In West Antarctica, although grounding-line thickness in many areas approximates 1,000 meters, spreading rates are limited by the presence of the ice shelves. Observations to monitor behavior of the ice sheets and to enable development of realistic theoretical models are urgently required. Most of the necessary data can be obtained only from satellites.

The Role of Ice Shelves

More than half of the Antarctic coastline is bounded by ice shelves, two of which are each bigger than Texas. Along exposed parts of the coast, floating glacier tongues have coalesced to form a narrow fringe of ice shelf which may range in thickness from about 150 meters at the seaward ice front to about 400 meters at the grounding line. This value of approximately 400 meters is the thickness at which thinning due to creep of an exposed ice shelf is balanced by thickening due to snowfall and advection of thicker ice from upstream. Many of these ice shelves have run aground on shoaling seabed to form grounded ice rises (Figure 6). Upstream from these ice rises, creep-thinning rates are generally smaller

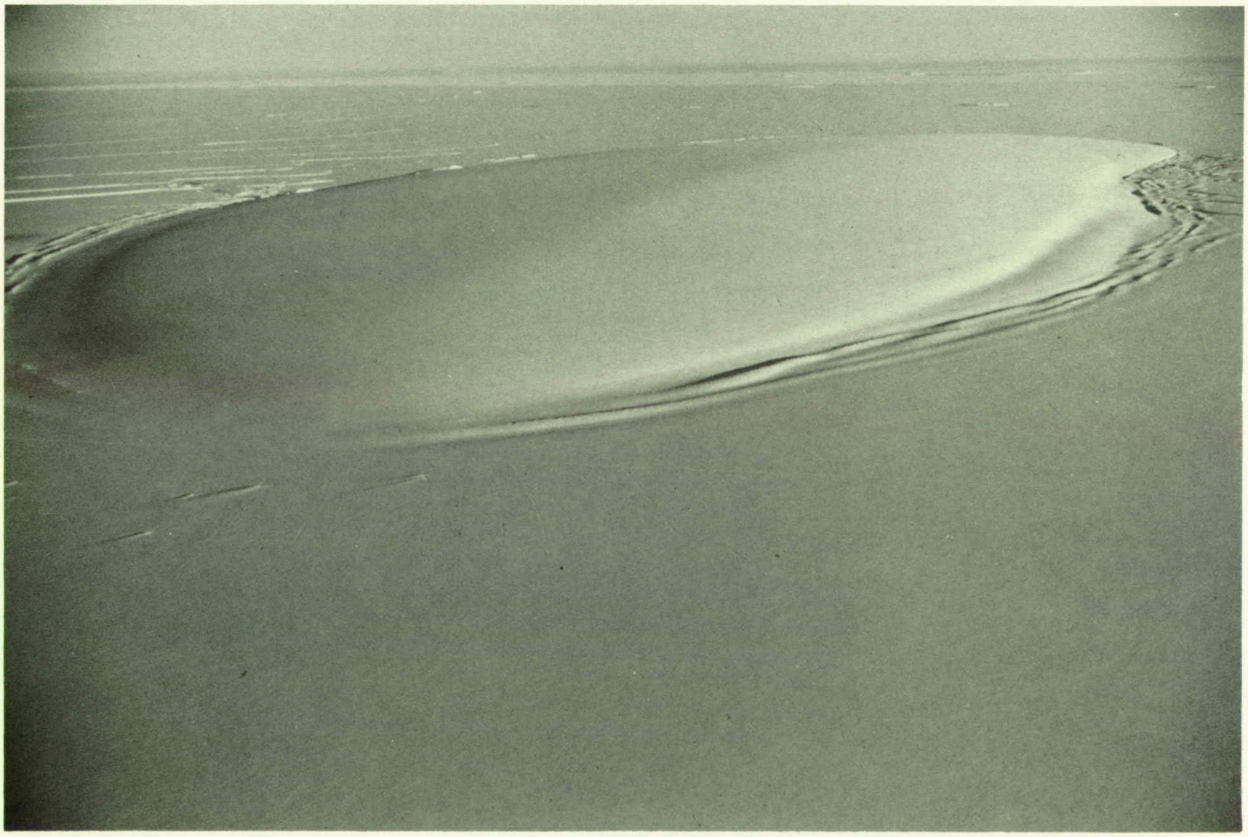

Figure 6. An ice rise—a locally grounded region within a floating ice shelf. This ice rise is 9 kilometers wide and 18 kilometers in length.

than for an unrestricted ice shelf, because an ice rise impedes seaward motion of the ice shelf. This leads to the formation of a thicker band of ice shelf extending upstream from each ice rise for a distance of tens to hundreds of kilometers, depending on the size of the ice rise.

In the major embayments of the Ross and Weddell Seas, the two largest ice shelves have formed (Figure 7). They exert a very large back pressure on ice flowing into them due to the composite effect of many ice rises and of shear between the ice shelf and its sides. This reduces spreading rates near the grounding line where the ice shelf attains thickness on the order of 1,000 meters. Weakening of the ice shelf by increased melting or accelerated calving of icebergs would lead to increased thinning rates as the back pressure decreased, and ice sheet further inland would become progressively ungrounded from the underlying bedrock. The associated rise in sea level would initially be very small, but could later increase to become a major hazard to many populous coastal regions around the world.

Although sea level would rise too slowly to be detectable during the initial stages of such a retreat, the process of ice-sheet retreat could become irreversible because of nonlinear ice flow mechanisms. Consequently, it is important to monitor the ice sheets themselves to provide warning of volume changes that could affect sea level. It is useful to note that a 1-centimeter change in sea level is equivalent to a 25-centimeter change in thickness over the entire Antarctic ice sheet. Moreover, actual ice sheet changes are more likely to occur within individual drainage basins than uniformly over the entire ice sheet. This would further increase sensitivity so that, for a sea-level change of less than 1 centimeter,

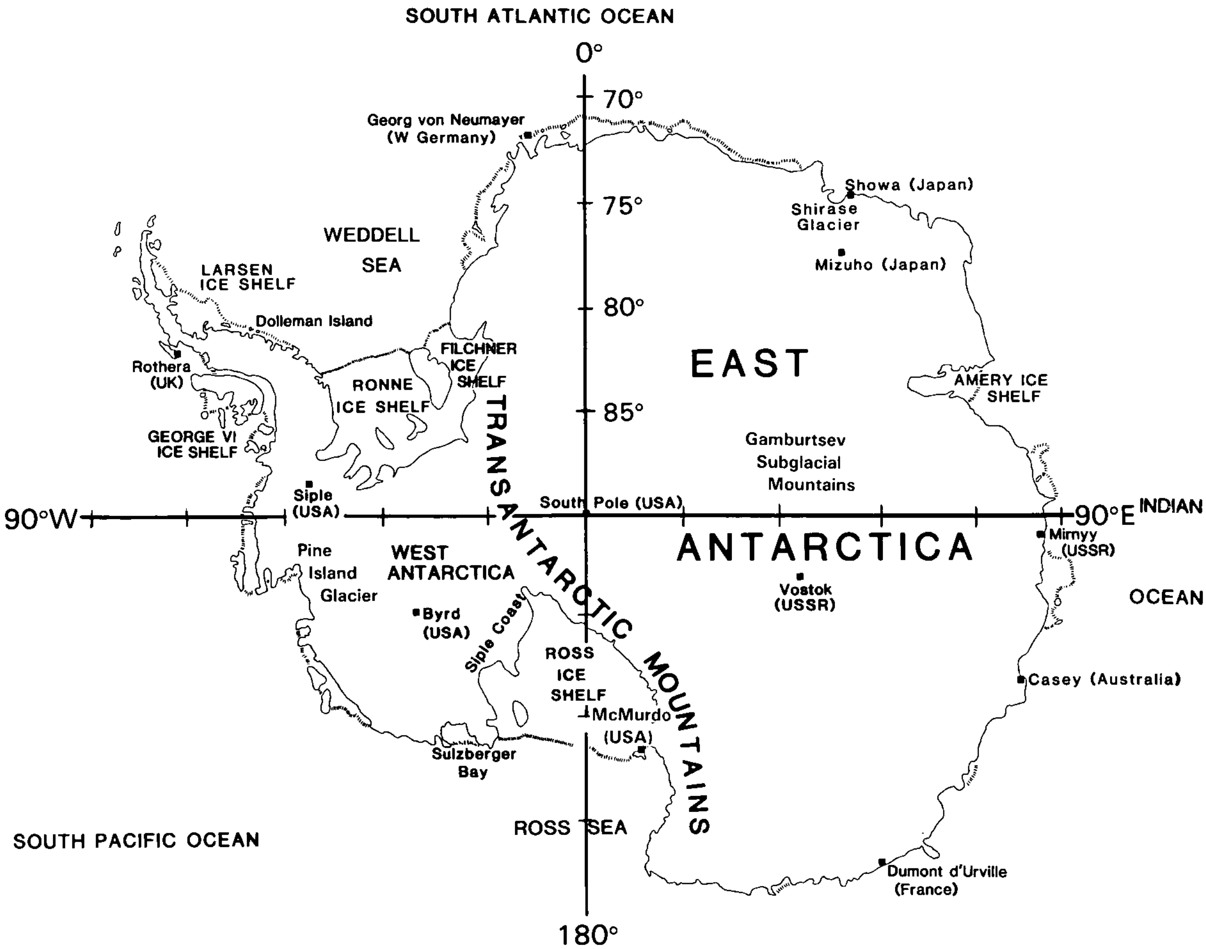

Figure 7. Antarctica, showing place names referred to in the text.

thickness within the affected drainage basin would probably change by several meters, which would be readily detectable by satellite altimetry.

Antarctic Mass Balance

There is very little summer melting over most of Antarctica, even at low elevations, and the snow line is virtually at sea level. Snowfall is compacted to ice and transported to the ocean by outward spreading of the ice sheet. Most of it flows into the ice shelves, where it is lost by calving of icebergs, or by melting at the ocean/ice interface. Average snow accumulation is equivalent to about 15 centimeters of water per year (Figure 8). This is half the equivalent value for Greenland and, away from the coast, Antarctica is the world's largest desert, with an annual precipitation of less than 10 centimeters of water.

The estimates of total Antarctic snow accumulation are probably accurate to better than ±20 percent. Errors on estimates of mass loss are far larger. There are no direct measurements of ice-shelf basal melting rates; inferences from other measurements suggest that total basal melting is equivalent to between 10 percent and 35 percent of Antarctic snow accumulation. Estimates of ice volume lost by iceberg calving are equally approximate, ranging from 30 percent to more than 100 percent of the total snow accumulation. Thus, although the consensus opinion is that Antarctic ice volume is slowly increasing, available data cannot rule out average values of thickening by up to 8 centimeters per year, or thinning by as much as 4 centimeters per year. These limiting values are equivalent to a sea-level drop of about 3 millimeters per year and a sea-level rise of 1.5 millimeters per year.

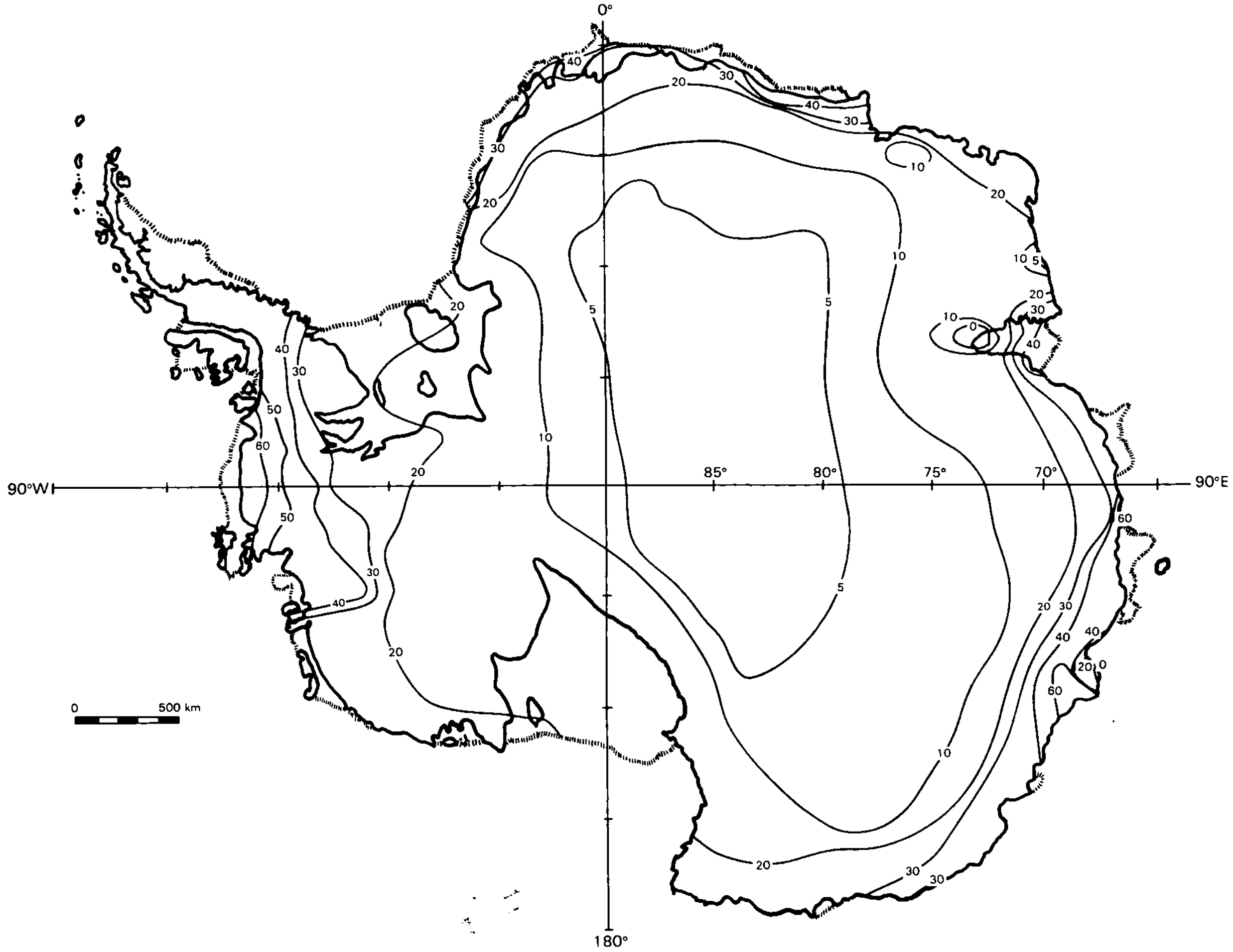

Figure 8. Annual snow accumulation over Antarctica in centimeters of water equivalent.

GLOBAL IMPACTS OF CHANGES IN THE POLAR ICE SHEETS

Major changes in volume of the polar ice sheets affect both sea level and climate. Increased melting from the surface of the ice sheets and from more numerous icebergs in Antarctic waters would alter the density structure of the ocean. This melting could have a strong impact on the circulation of deep ocean waters and on heat exchange between ocean and atmosphere. The atmosphere would also be affected by the significant decrease in ice albedo associated with enhanced surface melting.

Perhaps the strongest link between climate and the polar regions is in the potential amplification in high latitudes of future climatic warming due to increased concentration of "greenhouse" gases in the atmosphere. It is important to assess the present mass balance of the Antarctic and Greenland ice sheets in order to predict probable ice-sheet responses to the large temperature increases predicted for polar regions. In addition, systematic monitoring of ice characteristics could provide the first detection of such a change. Early responses are likely in sea-ice extent, ice-surface temperatures, and the extent of summer melt zones on the ice sheets. In the next section, we shall review the measurements needed for this research.

III. MEASUREMENTS OVER ICE

Major scientific questions that need addressing are:

- What is the mass balance of the Greenland and Antarctic ice sheets?
- What controls the size and movement patterns of the ice sheets, and are the ice sheets stable?
- What is the record of past climate as recorded in ice-core stratigraphy?

The four basic types of measurement needed to address these questions are discussed in this section.

MAPPING

Required measurements are surface elevation, ice thickness, and areal extent. These measurements are needed for two purposes: for describing ice-sheet geometry; and for intercomparison with later measurements to reveal changes in ice-sheet dimensions. Each ice sheet may be divided into inland ice, ice streams, and ice shelves. Each of these components has a distinct geometry, and each theoretically reacts differently to environmental change.

The central portion of an ice sheet is called inland ice. In the few areas that have been studied, the flow is achieved entirely or mainly by creep within the ice mass. The general surface form is convex upward, but there are surface undulations of wavelength about three times the ice thickness. These are associated with variations in the bed over which the ice is moving. Movement rates are typically just a few meters per year. This flow type predominates in Greenland, is restricted to the 100 to 200 kilometers nearest the center in West Antarctica, and possibly predominates in East Antarctica.

Ice from the central regions of Antarctica flows into ice streams or outlet glaciers separated by ridges of slow-moving ice. Ice-stream flow is mainly by bottom sliding, and velocities of 200 to 1,000 meters a year are common (Figure 9). When the ice reaches the sea, it flows into the ocean to form an ice shelf. At the grounding line separating inland ice and ice shelf, there is generally a break in surface slope. The seaward ice front, where iceberg calving occurs, is marked by an ice cliff (Figure 10). The mechanical controls on ice-shelf flow derive from the supply of ice from tributary glaciers, frictional drag against confining walls, and from grounded ice rises that impede the flow.

SURFACE CONDITIONS

Required measurements include net snow accumulation (or ice ablation), areal extent of summer melting, intensity of wind-induced surface roughness (sastrugi), and ice temperature.

Glaciers form where more snow accumulates than ablates, and the net accumulation rate is the central relevant parameter. It has been measured along surface traverses and at a few intensively-studied sites. Almost all net accumulation on the polar ice sheets occurs in a narrow coastal zone, and the interior is a virtual desert. Near the coast, accumulation is associated with low-pressure systems that orographically deposit snow. The determinants of storm frequency and intensity are not known, but they may be closely connected with sea-ice extent and concentration.

In Greenland, there is important ice ablation at lower elevations by seaward drainage of meltwater. Due to severe practical difficulties, very little is known about melt rates except by analogy with well-studied valley glaciers. In Antarctica, most of the surface melt refreezes in place.

Temperature is important to the flow of ice. Ice-sheet surface temperatures are some 10 degrees to 30 degrees lower than air temperatures about 100 meters above the surface because of outgoing long-wave radiation. Heat balance at the surface is maintained by gravity-drainage of surface air (inversion, or katabatic winds) and sinking of the air above, and by turbulent heat transfer and advection. Existing detailed temperature measurements are confined to stations that are manned and a few automatic weather stations. Broad coverage of the ice-sheet surface is required, with measurements repeated every few days.

ICE MOTION

Required measurements are absolute velocities, particularly of the major outlet glaciers, and the relative velocities of arrays of markers.

There is a net accumulation of snowfall over most of Greenland and Antarctica. Ice wastage is by seaward motion and, to a far lower extent, by basal melting at the ice/rock interface. Measurements of ice velocity near the coast give an estimate of ice drainage rates, and measurements of the relative motion of an array of markers on the ice give surface strain rates. These measurements can be used to estimate the state of local mass balance between snow accumulation and outward spreading of the ice. In

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Figure 9. An oblique air photograph of an ice stream flowing into the Ross Ice Shelf.

addition, they provide information on the mechanical response of the ice to gravity-induced driving stresses. This information is a prerequisite to formulation of realistic theoretical models describing ice motion.

INTERNAL PROPERTIES

Measurements of temperatures, ice deformation, isotopic composition, air and impurity content, and ice fabric and creep properties are needed for modeling studies and for inferring past conditions on the ice sheet. In addition, measurements of ice-sheet basal conditions (including ice-shelf basal melting) are required both for modeling studies and for investigating processes associated with the sliding of ice over bedrock.

PLANNED FIELD PROGRAMS

Although there is an increased level of activity in Greenland and Antarctica, most of the current funding of approximately half a billion dollars per year

Figure 10. The seaward front of an ice shelf on the eastern side of the Weddell Sea. The cliff is typically 20 to 30 meters high.

is devoted to *in situ* measurements in various scientific disciplines. Moreover, most of this funding is required to provide logistic support, and this expense is likely to increase as we investigate ice-sheet regions remote from the main field camps.

Major glaciological programs are described in the following paragraphs.

Australia

The major objective of Australian field programs is to measure the mass flux of ice across the 2,000-meter contour in the Indian Ocean sector of Antarctica. The results are combined with measurements of the surface form of the ice sheet to assess whether or not the ice sheet is in steady state and whether there is evidence for past instability. This work complements the analysis of ice cores for paleoclimatic information that is being undertaken by Soviet and French investigators in the same sector. Programs are coordinated by the International Antarctic Glaciological Project (IAGP).

France

French programs are directed toward the analysis of ice cores drilled by both French and Soviet teams. Paleoclimatic information is already available as far back as the last interglacial stage (120,000 years ago), and plans are to continue back in time until drilling reaches the bed of the ice sheet. The work yields data on past air temperatures, snow accumulation rates and surface elevation changes, and on changes in the composition of the atmosphere. Surface strain measurements are undertaken to aid interpretation of ice core data.

Japan

Japanese glaciologists plan continuing programs to study ice dynamics within the Mizuho Plateau area of Antarctica. Shirase Glacier, which drains this area, flows faster than any other surveyed glacier in East Antarctica and provides a unique opportunity to study rapid ice motion. Mass flux across the 2,000-meter contour is being determined to extend the

Australian work underway further east. A 700-meter core, recently obtained from the Mizuho Plateau, will be analyzed for paleoclimatic and ice-dynamics studies.

United Kingdom

British glaciological programs are directed toward understanding the climatic vulnerability of ice shelves and its consequences for inland ice that feeds the ice shelves. Techniques developed on George VI Ice Shelf for determining heat and mass exchange on the inaccessible underside of ice shelves are to be extended to the much larger Ronne Ice Shelf. Both ground-based and airborne radio-echo sounding of ice thickness will continue in support of ice dynamics studies, concentrating on the inland boundary of ice shelves (the grounding line). The position of ice fronts and grounding lines in the 20 degrees West to 80 degrees West sector will be monitored using satellite imagery, Doppler satellite position fixing and tilt-meter observations. Ice core drilling for paleoclimatic studies is planned on Dolleman Island and the Ronne Ice Shelf.

United States

U.S. programs are directed toward understanding the physical characteristics of the ice sheet, ice dynamics, and the paleoclimatic record stored in the ice sheet. The stability of the West Antarctic ice sheet is considered of the utmost importance and will provide the basis for a decade of study. The morphology, dynamics, and history are the subject of current experiments on the Siple Coast later to be extended to the Pine Island Bay area, which is believed to be critical to ice-sheet stability. The ice rises and small ice shelves in the Sulzberger Bay area will be the site of a study of how a marine ice sheet begins to retreat.

Ice core drilling for paleoclimatic studies is proposed for sites in West Antarctica, for the South Pole, and for ice domes in East Antarctica. New techniques of analysis will require intact cores for studies of snow chemistry, global pollution, the eruption record of volcanoes, precipitation, air temperature, and gases trapped in the ice sheet. Drilling over the Gamburtsev Subglacial Mountains is planned to sample basal moraine and the underlying bedrock.

All of these field studies are being supported by the development of theoretical models to simulate probable ice-sheet behavior in response to climatic change. The results will be used to help plan future field programs.

USSR

Soviet ice core drilling in a low-accumulation area of East Antarctica is planned to provide a paleoclimatic record possibly extending into snow that fell 200,000 to 300,000 years ago. This will provide records of climate that will substantially overlap those obtained from ocean sediment drilling, providing a check on the consistency of both sets of data. The extent of Soviet radio-echo measurement of ice thickness is second only to that of the United States and is continuing. Both French and Soviet glaciologists are involved in the interpretation of Soviet ice cores.

West Germany

Although relative newcomers to the Antarctic, the Germans have an ambitious program to study the dynamic regime and mass balance of the Filchner-Ronne ice shelves. This involves an elaborate network of ice movement and strain measurements together with seismic sounding, radio-echo sounding, photogrammetric mapping, coring, hot-water drilling, accumulation measurements, and isotope studies.

Programs In Greenland

Currently, the major U.S. effort is to understand the dynamics of the Jacobshavn Glacier, a large outlet glacier on the west coast of the Greenland ice sheet. It has been retreating since 1850 but has stabilized in recent years. The studies focus on the mass balance of the drainage basin and on measuring the velocity field and its variation with time.

The U.S., Denmark, and Switzerland are also planning to drill a deep hole to bedrock in central Greenland for an improved climatic record.

IV. SATELLITE OBSERVATIONS

Although we will continue to need *in situ* measurements of the type described in Section III, they will never provide the broad coverage essential to a proper understanding of present ice conditions and for developing reliable predictive models. This will be achieved only by obtaining data from Earth-orbiting satellites.

Most of the measurements listed in the previous section can be obtained from satellite sensors. The complement of sensors needed to accomplish this includes radar and laser altimeters, Synthetic Aperture Radars (SARs), calibrated radars called scatterometers, and visible, infrared and microwave radiometers.

A summary of the measurements described in the previous section is given in Table 2, with an indication of desired accuracy and a listing of satellite sensors that can be used to obtain the measurements. Apart from the laser instruments, all of the sensors included in Table 2 have flown aboard satellites with orbits passing over ice sheets. There are firm plans for repeat missions during the next decade; however, these missions are primarily for the investigation of ocean and land surfaces and, in most cases, no provision is made for processing and analysis of data acquired over the polar ice sheets. Figure 11 lists existing and planned satellites that will provide useful data over ice. We strongly recommend that these data be processed to a form suitable for research purposes and archived in appropriate data centers for easy access by the research community.

Visible, infrared, and microwave sensors give

Table 2
Ice-Sheet Measurements From Space

Parameter	Required Minimum Accuracy	Satellite Sensor	Frequency
Surface elevation	5 m	Radar altimeter or Laser altimeter	5 years
Elevation change	0.5 m		
Ice fronts and surface features and changes in their positions	1 - 2 km	Landsat/SPOT Synthetic Aperture Radar (SAR)	1 year
	0.1 - 1 km	Altimeter (for mapping grounding lines and seaward ice cliffs)	
Surface velocity	± 10%	Laser ranger; Landsat/SPOT; SAR	1 year
Surface strain rates	± 10%	Laser ranger	1 year
Surface temperature	± 1 °C	Infrared radiometer	Monthly averages
Extent of summer melt zones	10% of area	Microwave radiometers; SAR; scatterometer	1 year
Snow accumulation	± 10%	Microwave radiometers; scatterometer	5 years

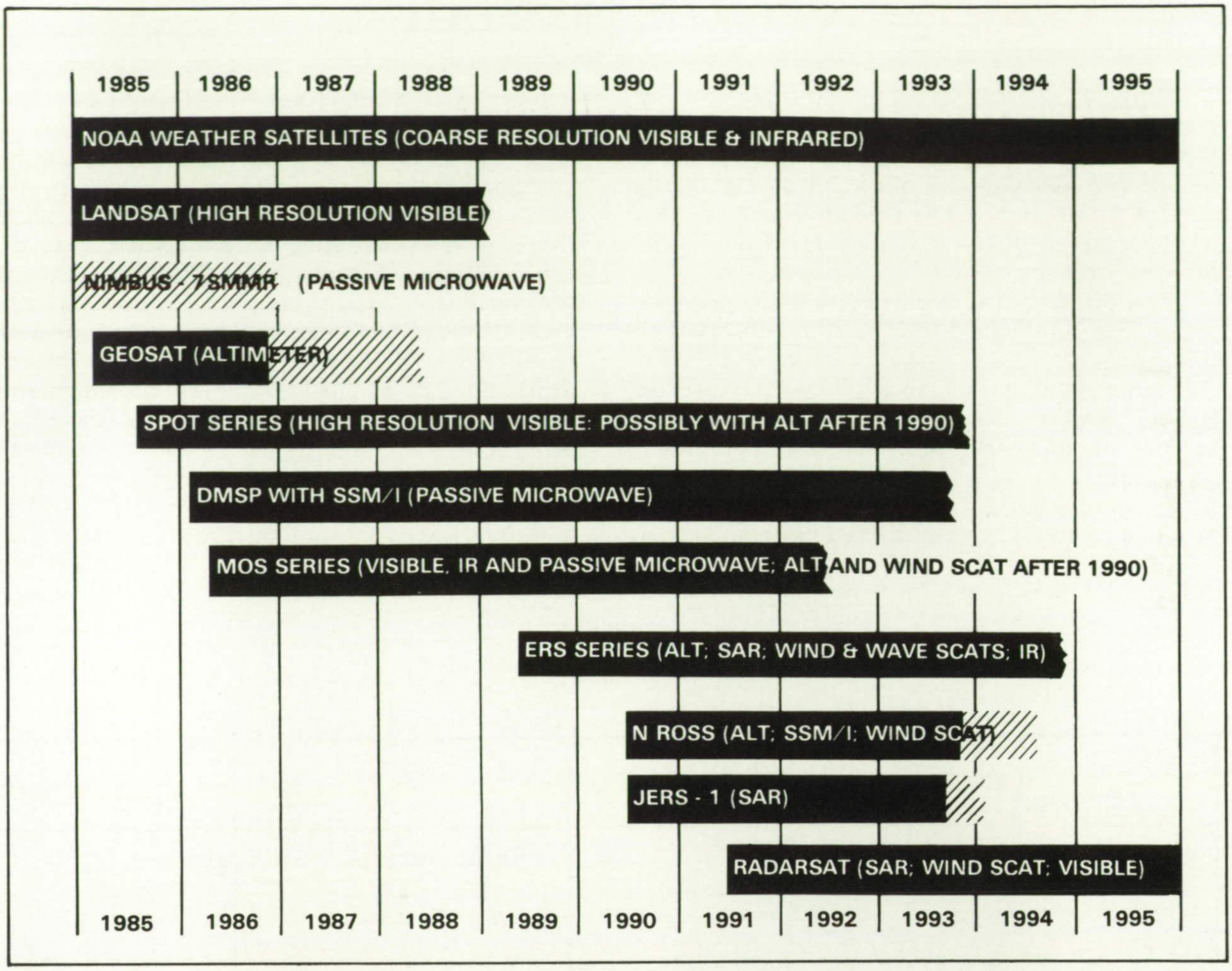


Figure 11. Spacecraft missions planned during the next decade which will acquire data over the polar ice sheets with potential research applications. Satellites generally continue operating beyond their planned lifetime —indicated here in black. In addition to these missions, a series of Shuttle Imaging Radar (SIR) flights will provide extensive SAR coverage of both Greenland and Antarctica.

useful information on the polar ice cover. Of these, only microwave measurements can be made in all weather, day and night, to provide the global, synoptic cover required for most research applications. In the following sections, we provide a brief review of each sensor, with a description of the data required over ice.

RADAR ALTIMETERS

Radar altimeters are proven instruments for conducting glaciological research from space. They were carried aboard two NASA satellites: Geos-3 (April 1975 to December 1978), which covered the area between 65 degrees North and 65 degrees South; and Seasat (July to October 1978), which extended the coverage to ±72 degrees. These data are currently being used to improve significantly the surface-elevation maps of most of the Greenland ice sheet and northern parts of the Antarctic ice sheet. While these altimeters were designed to measure ranges to the relatively flat ocean surface, the undulating surface of the ice sheets sometimes caused the tracking circuit, which anticipated the arrival of the return pulse, to miss the return pulse altogether. Nevertheless, almost a million useful measurements were made over Greenland and Antarctica during the 3-month lifetime of Seasat. To have collected these many data with conventional ground surveys over such large areas of both polar ice sheets would have occupied many people for several decades. Thus, it is unreasonable to expect ground-based field parties

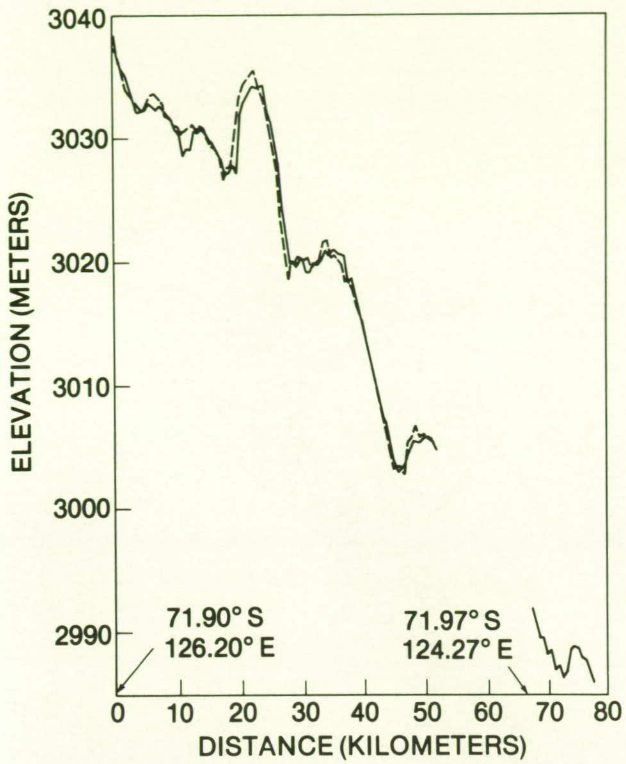


Figure 12. Two surface-elevation profiles (solid and broken lines) across part of the Antarctic ice sheet, derived from altimetry data from "repeat" Seasat orbits separated horizontally by approximately 40 meters.

ever to provide a complete survey of ice-sheet elevation; the only feasible means is with satellite altimetry. An indication of the data consistency attainable by the Seasat altimeter is provided by Figure 12, which shows two sets of Seasat measurements along repeat tracks over Antarctica. Measurement consistency over smoother portions of the ice sheet was ±25 centimeters. Errors increased over sloping or undulating surfaces, and data consistency estimated by comparing measurements at orbit crossing points averaged ±2.7 meters over the entire ice sheet.

It is important to note the physical significance of these measured radar-altimeter elevations. The radar beam produces a broad footprint on the surface with a radius of about 12 kilometers, similar in size to the spacing between surface undulations. The leading edge of the return pulse is formed by reflections from the undulation summits closest to the satellite, not necessarily directly beneath the satellite or along the subsatellite path. Therefore, the resulting apparent surface derived from the measured ranges represents a smoothed envelope biased slightly above the actual surface (Figure 13). This bias depends on local regional slope, undulation amplitude, and altimeter characteristics. To some extent, bias errors due to the regional slope can be corrected, but complete correction requires a dense network of satellite tracks. Nevertheless, the smoothed envelope obtained in this way is well suited to most glaciological requirements. Intercomparison of surfaces obtained from two altimetry missions a decade or so apart would provide clear indication of significant regional changes in ice topography since the local biases would be approximately the same for each survey. It is important to note that altimeter design characteristics must be similar for both surveys. To cover the Antarctic ice sheet completely with closely spaced orbits would require approximately 6 months of continuous operations and some 10 million measured ranges.

In addition to their utility in measuring surface elevations, the details of the shape of the return pulse can be used to map the margins of the ice sheet, the seaward limit of sea ice, and the occurrence of icebergs. The return pulse shape of a sea-ice reflection is generally specular (rising to a sharp peak), while that from either ocean or ice sheet is diffuse (rising to a plateau value). When the satellite passes over an ocean/sea-ice or sea-ice/ice-sheet boundary, the footprint covers both sea ice and either ocean or ice sheet creating a hybrid return-pulse shape. The details of the evolution of the pulse shape from specular to diffuse can be followed for individual satellite passes to mark the ocean/sea-ice or sea-ice/ice-sheet boundary. With this method, position accuracy of the ocean/sea-ice boundary is probably a few kilometers due to the often diffuse nature of the marginal ice zone. For the general case of a sea-ice/ice-sheet boundary, the accuracy is better than ±1 kilometer, and a few kilometer segment of the ice cliff adjacent to the subsatellite track can be mapped. Currently, the entire Seasat data set is being used to map most of the Antarctic coastline north of 72 degrees South to an accuracy of ±(0.1 to 1 kilometer)—a major improvement over existing surveys. Comparison with results from conventional surveys and future altimetry missions will reveal changes in the position of coastal ice cliffs due to ice movement and/or iceberg calving. Systematic measurements over several years would probably distinguish the effects of iceberg calving, which is intermittent, and ice movement, which is continuous.

Icebergs that fall within the beam footprint will affect the return-pulse shape, even if the satellite does not pass directly overhead. The Seasat data set contains many such examples, which provide a powerful technique for monitoring iceberg population in Antarctic waters, and indirectly obtaining an estimate of ice discharge from the continent.

Slight changes to the Seasat altimeter design could yield major improvement in performance over ice. Some of these changes have been implemented on the U.S. Navy's Geosat, launched in March 1985. This satellite will cover the same latitude band as Seasat

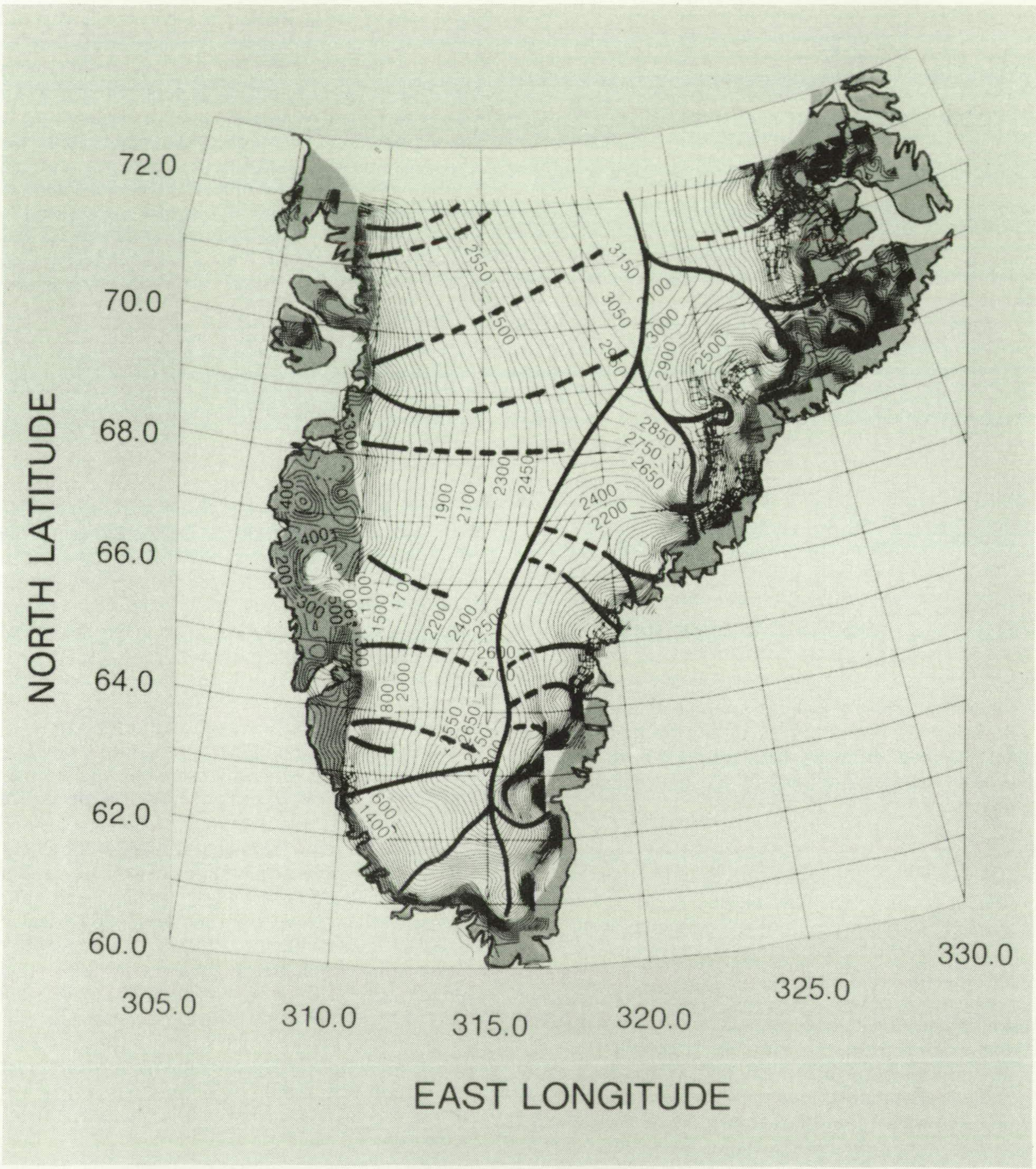


Figure 13. Greenland showing surface elevation contours derived from the 3-month Seasat altimetry data set. The bold lines delineate drainage basins.

(72 degrees North to 72 degrees South), and over-ice data from Geosat will provide an important comparison with the Seasat data set. Nevertheless, much of the surface topography of Antarctica will not be mapped until the launches of the European Space Agency's (ESA's) ERS-1 in 1989 and the U.S. Navy/NASA/NOAA joint mission NROSS in 1990. Both of these missions will carry altimeters in a latitude band between 82 degrees North and 82 degrees South. In order to achieve the full potential

of over-ice data from these missions, accurate knowledge of satellite orbit will be essential. Desired minimum accuracies are ±10 meters in horizontal satellite coordinates and ±0.5 meter in the radial coordinate.

LASER ALTIMETERS

In laser altimetry, a nadir-pointing, pulsed laser beam, a few tens of meters in diameter at the Earth's surface, is used to measure surface elevation at intervals of a few hundred meters along the subsatellite path. Potential range accuracy is better than ±10 centimeters. Because of the small footprints, detailed surface profiles of sloping and undulating terrain are obtained without the location ambiguities and biases inherent to radar altimetry. Repetition of such precise measurements of ice-surface elevation provides a sensitive means of determining changes in ice volume. Although sequential surveys by radar altimeters should reveal major thickening or thinning trends within large regions of the ice sheet, only laser altimetry will provide detailed information on elevation changes within such a region. Moreover, the significantly increased accuracy of a laser, combined with reduced ambiguity of data interpretation, will permit early detection of elevation changes of just a few tens of centimeters.

In addition to very accurate overall elevation surveys, ice-front elevations above sea level, ice-shelf surface profiles, and wavelength spectra of surface undulations can be uniquely obtained by laser altimeters. Ice-front elevations and profiles of the ice shelf from the ocean to the grounding line are especially needed both to map the grounding-line position and to investigate the rate of melting or freezing at the underside of the ice shelves, which is a process of critical importance to understanding the vulnerability of the ice shelves to climatic warming. Spreading of the reflected laser pulse by variations of surface height within the laser beam provides an indication of the surface roughness due to pressure ridges on sea ice and sastrugi on ice sheets. These data are needed for modeling sea-ice motion and for studying katabatic winds.

For several decades, lasers have been used to make extremely precise distance measurements for a variety of scientific, commercial, and military applications. A laser altimeter on the Apollo-lunar orbiter measured the height of the orbiter above the Moon's surface. In addition, airborne lasers have measured surface-height profiles of Arctic sea ice along thousands of kilometers of flight track. NASA designed a laser altimeter system capable of high-resolution ice mapping from space in the early 1980s. Developmental versions of this altimeter could be tested aboard the space shuttle in the near future, and a complete system is under consideration for flight aboard NASA's EOS during the mid-1990s. We strongly support these developments, and we particularly encourage the inclusion of a laser altimeter aboard a Shuttle Imaging Radar (SIR) mission. Over-ice data interpretation would be simplified and enhanced by the complementary measurements.

LASER RANGERS

In space-borne laser ranging, a laser beam is pointed in specified directions to illuminate individual corner-cube reflectors located on the surface. From the precise range measurements to different reflectors, the distances between all reflectors can be accurately determined. Successive range measurements at approximately 1-year intervals would provide accurate estimates of absolute ice velocities and the relative velocities (strain rates) of all the reflectors. The absolute accuracy of the position of any given target would probably be limited to about 1 meter, but estimates of relative positions in an ice-strain network would be accurate to a few centimeters. The position of the satellite in orbit can be determined accurately from a series of measurements to reflectors at selected control sites on the surface. Although the pointable laser ranger is more complex than a fixed nadir-pointing altimeter, the additional scientific return from measurement of ice velocities and strain rates by the laser ranger is considerable.

The laser ranging technique is already being used with transportable ground-based systems to measure small motions along surface faults in the southwestern United States. A similar instrument on a satellite passing over the polar ice sheets would be capable of measuring velocities and strain rates anywhere on the ice wherever target reflectors could be installed. A space-based surveying technique would represent a great advance in both logistics and scale over the ground-based methods currently used by glaciologists. Conventional techniques require each site to be occupied for each measurement of position. With a space-borne laser ranger, each site need be visited only once for target installation, and a position would be obtained every time the satellite passed within range in clear weather. The laser ranger is also more flexible due to its independence from the line-of-sight restrictions that affect ground-based surveys. Strain-rate measurements over very long baselines would be possible without the need for additional intermediate stations.

A capability for long baseline strain surveys is particularly desirable on the polar ice sheets in order to average out localized variations. Currently, strain networks are limited to a few tens of kilometers, but a space-based system would provide strain rates over several hundred kilometers as required to study the large-scale deformation of ice.

VISIBLE IMAGERS

Visible imagers include Landsat, SPOT (a French mission due for launch in 1985, carrying a high-resolution visible imager), and the NOAA weather satellites. A visible imager may also fly aboard Canada's Radarsat to be launched in 1990. Landsat imagery, available since 1972, has a spatial resolution of a few tens of meters. It has a swath width of 185 kilometers, and data are not collected continuously along each orbit. Visible and infrared images from weather satellites have lower resolution (1 to 4 kilometers) but a swath width of 3,000 kilometers, and they are obtained continuously. Total coverage of useful data can be acquired only in cloud-free conditions and, for the visible, in sunlit conditions.

Satellite imagery currently provides the easiest way of measuring the rate of ice discharge across the long coastline of Antarctica (Figure 14). Errors of measurement are greater than they are in ground surveys, but this is more than offset by the much larger number of observations that can be made from images. Sequential images can also be used to detect:

- Changes in crevasse patterns indicative of of changes in ice activity
- Ice velocity, by measuring displacement with time of conspicuous features
- Changes in the size and number of ice rises, which indicate changes in how firmly an ice shelf is anchored to the seabed
- Changes in the areal extent of surface ablation
- Changes in the position of grounding lines and calving fronts of ice shelves
- Changes in the number and distribution of icebergs

Although 13 years have elapsed since the launch of Landsat-1, most of the images of the continental ice sheets date from the 1972 to 1974 period. The images were acquired as a result of the foresight and initiative of one man, the late W. R. MacDonald, of the U.S. Geological Survey. To this day, the far side of the Moon is better mapped than many parts of Antarctica. Consequently, there is an urgent need for systematic coverage by Landsat or SPOT of at least the coastal regions of Antarctica and Greenland repeated at intervals of 1 to 5 years. Such information will provide an essential complement to altimetry data. It will assist in the interpretation of surface features and provide for planimetric interpolation between altimeter ground tracks.

The spatial resolution needed for studying ice sheets is the approximately 30-meter nadir resolution of the Return Beam Vidicon imagers carried on Landsats-1, -2, and -3; of the Thematic Mapper carried on Landsats-4 and -5; and of the High Resolution Visible linear array to be carried on the SPOT series. We need 30-meter resolution to complete the first-generation medium-scale mapping of the ice sheets and to monitor changes, most of which are much larger than 30 meters. The calving of a single iceberg, for example, can change the position of an ice front by many kilometers in a single day.

SYNTHETIC APERTURE RADAR

A SAR provides all-weather high-resolution imagery of radar backscatter that can be used for mapping and for interpretation of surface and near-surface characteristics. Over ice sheets, a number of features are clearly delineated due to the radar's sensitivity to even subtle differences in surface roughness, local relief, grain size, and moisture content. The most obvious application of SAR images to ice sheet research is as an all-weather mapping tool. While visible imagery potentially can provide similar information, persistently cloudy conditions have prevented many of these same features from being revealed. A SAR is a high-resolution sensor that is weather-independent; observational parameters can be varied in order to extract additional information on surface characteristics of the ice sheet.

A SAR achieves its high spatial resolution by selection of radar frequency and antenna size, and utilization of the Doppler shift in reflected radiation frequency that occurs as it illuminates a swath some tens of kilometers wide, off to the side of the moving platform. A very high data rate results (about 100 million bits per second), which imposes constraints on data storage aboard the satellite and necessitates direct transmission of raw data to receiving stations. A complex processing sequence is then required to yield a digital image of the illuminated ground swath in which intensity is proportional to radar backscatter. Fairly steep topography, when imaged at low radar incidence angles (15 to 30 degrees), introduces distortion to the image which can, however, be removed by appropriate correction procedures. Precise orbit determination is required to provide the accurate Earth location of a given resolution cell. A SAR was flown aboard Seasat; it imaged a 100-kilometer-wide swath, with spatial resolution of 25 to 40 meters. Subsequent correction of image distortion and careful registration using the precise Seasat

Figure 14. Icebergs calving from a West Antarctic ice shelf. The largest iceberg is 32 kilometers in length. This enhanced Landsat image was obtained in January 1973 and shows ice rises, crevassed areas, and flow features. Periodic imaging of the same area would reveal changes in any of these features. [Provided by B. Lucchitta, U.S.G.S.]

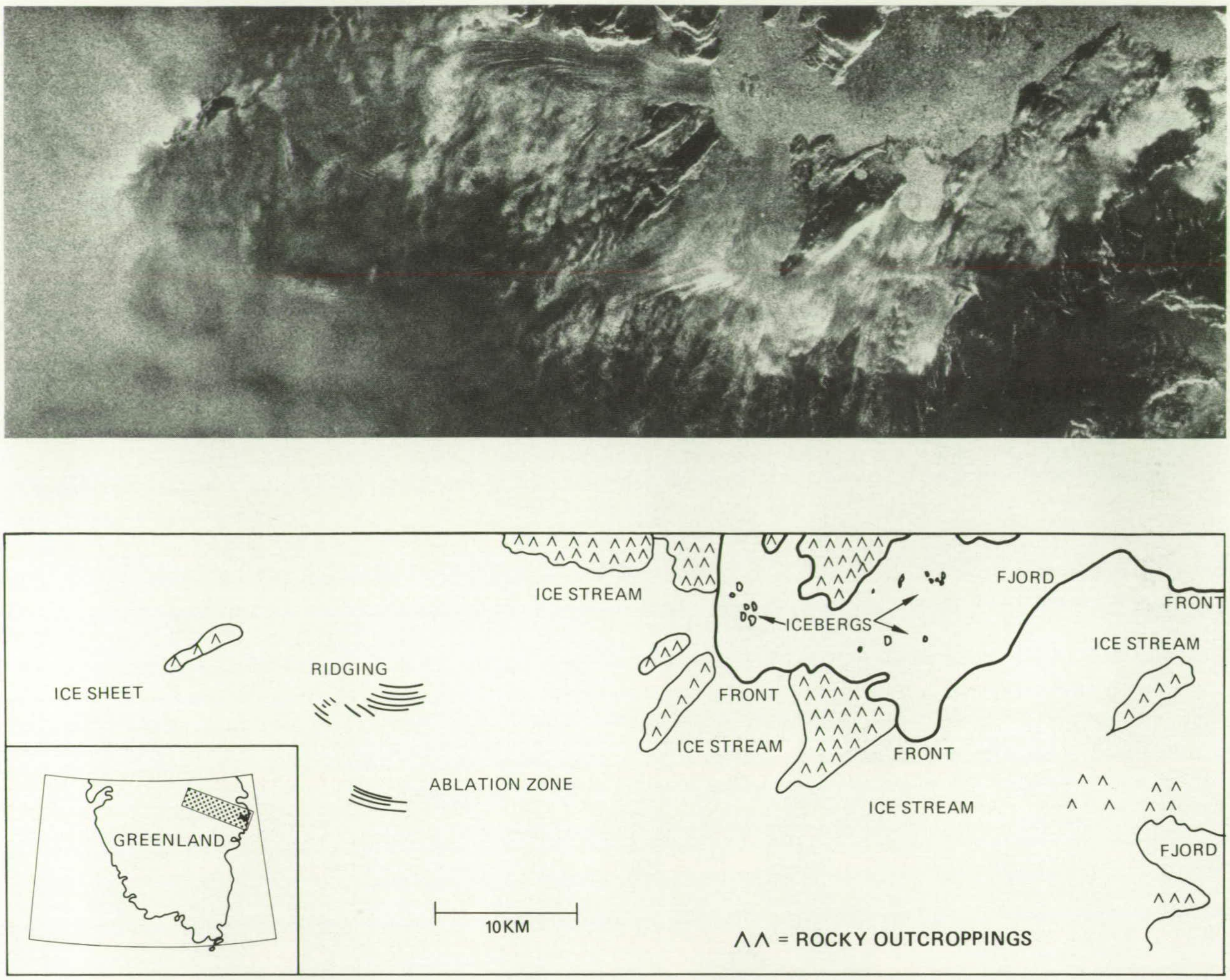


Figure 15. A SAR image of an area on the southwest coast of Greenland. This is an optically-processed image; significantly improved resolution can be obtained in digitally-processed imagery.

orbits has provided absolute Earth location with an accuracy of ± 100 meters.

Satellite SAR imagery over ice sheets has numerous applications. The coastal edges of ice sheets could be accurately mapped and monitored for change in position. Ice motion could be determined by tracking identifiable features such as crevasses in sequential imagery over a given region. Features such as flow streamlines on outlet glaciers and ice streams, ice rises on ice shelves, crevasse fields, flowbands, and melt zones could be mapped and routinely monitored to detect changes (Figure 15). Such information would complement altimetry data, both for mapping purposes and for interpretation of observed changes in ice-surface elevation. In addition, periodic monitoring of the size, distribution, and rate of calving of icebergs at the ice-sheet margins would provide an indication of the rate of ice discharge.

Upcoming space shuttle missions will provide opportunities to acquire SAR data to map large areas of the ice sheets of both Greenland and Antarctica. The reflight of Shuttle Imaging Radar-B (SIR-B) is scheduled for early 1987, and the Shuttle Imaging Radar-C (SIR-C) will be flown in 1989 and possibly again in 1990. The SIR-B reflight will probably be in a nearly true polar orbit, and we strongly support plans to acquire SAR data whenever possible over Antarctica. This 10-day mission could provide more detailed Antarctic information on ice features than has been acquired during 25 years of surface and airborne investigations.

The next satellite SAR will be aboard ESA's Remote Sensing Satellite (ERS-1), due to be launched in 1989. NASA plans to establish a SAR ground receiving station in Alaska, which together with the ESA and Canadian receiving stations at Kiruna, Sweden, and near Ottawa, Canada, will provide almost total coverage of Greenland from ERS-1 (Figure 16). Germany plans to establish a station in Antarctica to receive ERS-1 SAR data. Other SARs will be carried aboard a Japanese spacecraft and the Canadian Radarsat, both planned to be launched in 1990. Radarsat will carry onboard tape recorders providing another opportunity to acquire SAR data over Antarctica.

The prime application of SAR imagery to ice-sheet research will be to supply detailed information from areas of particular interest. Within those areas, observations for mapping and ice motion could be obtained by annual sampling. ERS-1 and Radarsat are designed to operate for at least 3 years, and we strongly endorse the acquisition of data over as much of the ice-sheet area as possible, preferably at yearly intervals. Space shuttle missions will be of 7- to 10-day duration, and while the narrow swath width (about 40 kilometers) will limit the areal coverage, the SAR imagery will be valuable both for mapping in these remote regions and for research on the interpretation of SAR data over ice.

MICROWAVE RADIOMETRY

Passive microwave data indicate the onset of snow melt for seasonal snow cover and the regions where summer melting occurs on the ice sheets and ice shelves. Monitoring of the extent and duration of summer melting will be important if CO_2-induced climatic warming occurs in the decades ahead. In addition, it may be possible to deduce snow-accumulation rates over the polar ice sheets.

Passive microwave radiation is the natural emission of electromagnetic radiation with wavelengths of millimeters to centimeters. All matter radiates electromagnetic energy as a consequence of molecular interaction, and different materials emit different amounts. The strong dependence of the microwave emissivity of various materials on structure, composition, and temperature provides the physical basis for remotely sensing characteristics of the Earth's surface.

The first satellite sensor to provide global passive-microwave data was the Electrically Scanning Microwave Radiometer (ESMR), launched by NASA aboard Nimbus-5 in December 1972. The ESMR measured horizontally polarized radiation at 1.5 centimeters with a spatial resolution of about 30 kilometers, and useful swath width of 1,400 kilometers. Total coverage of the polar regions was obtained every day until 1983. The next major advance was provided by the Scanning Multichannel Microwave Radiometer (SMMR) launched in 1978 aboard Seasat and Nimbus-7. SMMR acquires data in both vertical and horizontal polarization at five frequencies with spatial resolution ranging from 30 to 150 kilometers, over a swath width of 780 kilometers. Seasat operated for only 3 months, but the SMMR aboard Nimbus-7 still provides excellent data. Starting in 1986, a series of U.S. Defense Meteorological Satellite Program (DMSP) spacecraft will carry the Special Sensor Microwave/Imager (SSM/I), a scanning microwave radiometer that will collect data similar to those from SMMR over a 1,300-kilometer swath.

The microwave emissivity of a snow surface is sensitive to the grain-size distribution with depth, which is determined mainly by snow-accumulation rates and snow temperature. Preliminary ice-sheet accumulation maps have been derived based on an empirical relationship between observed emissivity and the few measured accumulation rates, but additional research is needed to refine this relationship and to take fuller account of snow temperatures. In Figure 17, the microwave emissivities are low (0.65 to 0.75) in the low-accumulation area of the East Antarctic ice sheet, and high (0.8 to 0.9) in the high-accumulation region of West Antarctica. The strong accumulation gradient over the West Antarctic ice divide is seen as a strong microwave gradient. An independent determination of the physical temperature, possibly from satellite thermal-infrared measurements would greatly assist the mapping of accumulation rates from the microwave measurements, as well as being of direct interest to studies of ice-sheet climate.

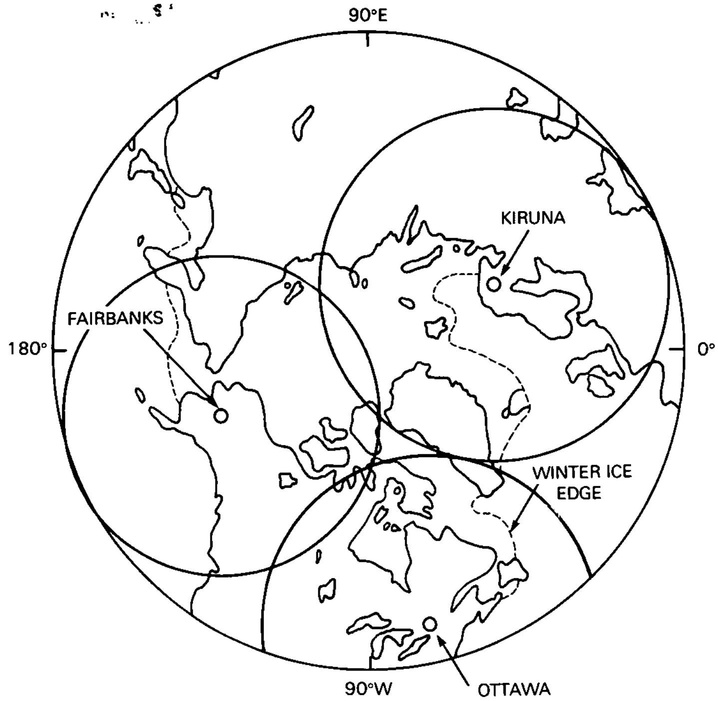
The microwave emissivity of snow increases markedly with wetness, and the change in emissivity due to onset of surface melting is large and easy to detect. For example, in regions of significant summer melting, such as the Larsen Ice Shelf in Antarctica (Figure 7) and the percolation zone of southwest Greenland, marked increases in emissivity are observed, as shown in Figure 18.

INFRARED RADIOMETERS

Measurements of surface temperatures in the polar regions are important for climate studies, for heat flux calculations, and in modeling both the dynamic and the radiative properties of the polar ice cover. They are also needed to supplement microwave data in order to improve detection of ice surface characteristics. Conventional measurements of surface temperature are routinely available from only a few locations, particularly in Antarctica.

Although satellite microwave and infrared sensors have been utilized to obtain surface temperatures

APPROXIMATE STATION MASKS
ERS-1 SAR



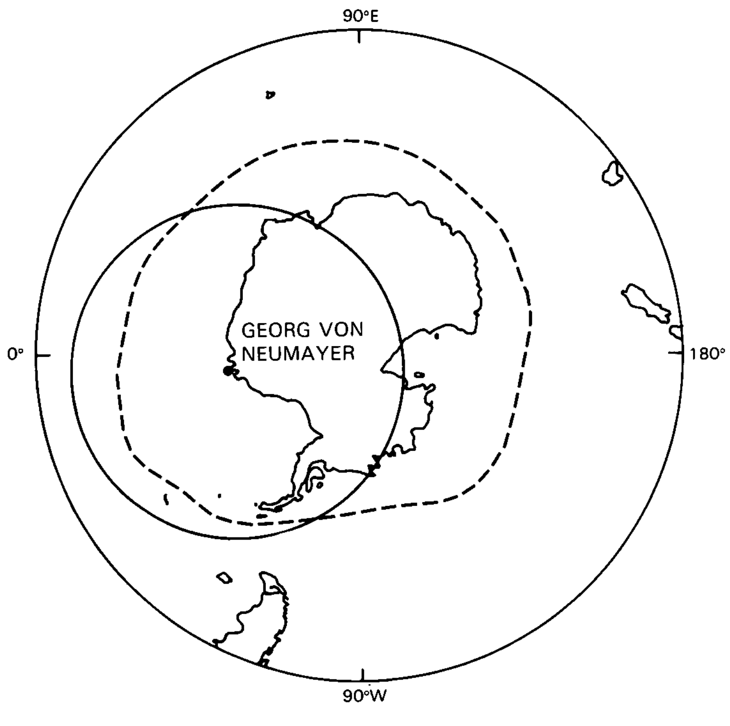


Figure 16. Data-acquisition masks of receiving stations proposed for acquisition of ERS-1 SAR data in the polar regions. The Antarctic station will be transportable, and may be relocated during the lifetime of ERS-1.

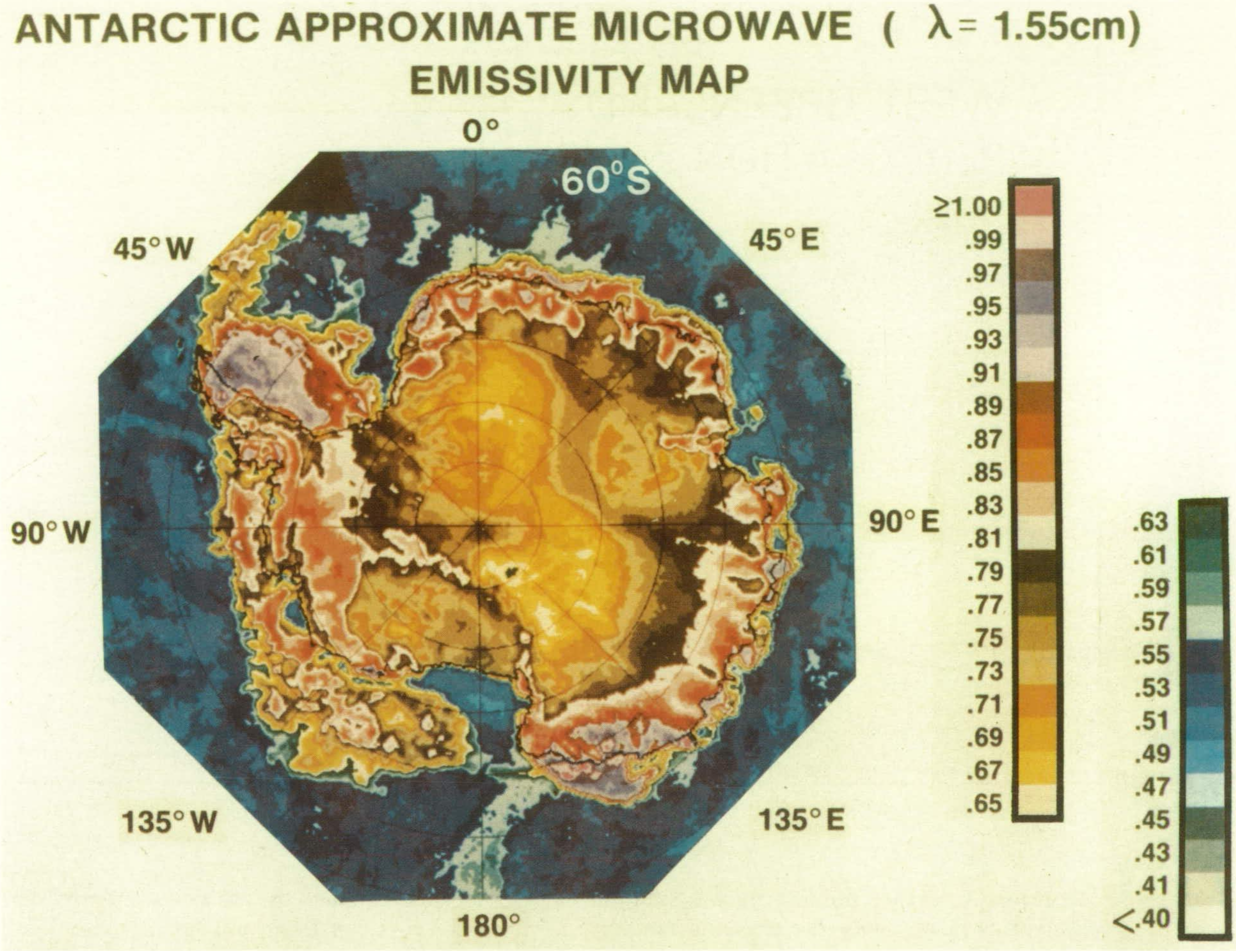


Figure 17. Approximate microwave emissivity of the Antarctic ice sheet is derived from satellite passive microwave and infrared data. Emissivity is low in regions of low snow accumulation, and the change from low to high emissivity across ice crest in West Antarctica indicates increasing accumulation nearer the ocean.

with an accuracy of about ±1 degree C, especially over the ocean, there have been limited applications in the polar regions. A simple retrieval technique using the 11.5-μm channel from the Temperature-Humidity Infrared Radiometer (THIR) aboard Nimbus-7 has been developed recently. A statistical technique is applied to filter out data from cloud-covered areas and obtain estimates of ice-surface temperature. Figure 19 shows average temperatures for March 1979 obtained by this technique. Alongside are the corresponding climatic records mapped in a similar way. The temperatures are generally consistent, with isotherms and extreme temperatures located at nearly the same places, especially over Antarctica. This method could be further improved using data from the NOAA Advanced Very High Resolution Radiometer (AVHRR) sensors or the Along Track Scanning Radiometer (ATSR) which will fly aboard ERS-1. Moreover, inclusion of the 1.6-μm channel on AVHRR in the late 1980s will permit discrimination of ice from clouds, significantly improving the reliability of derived surface temperatures.

SCATTEROMETER

The scatterometer, like the SAR, measures radar backscatter from the viewed surface. However, spatial resolution is coarse (some 25 kilometers), backscatter measurements are made at a range of incidence angles within a 1,400-kilometer swath, and the instrument is well calibrated to provide absolute values of the backscatter. A scatterometer flew on Seasat for the purpose of deriving sea-surface wind vectors. Data were also acquired over sea ice and ice sheets. Figure 20 shows backscatter measurements at

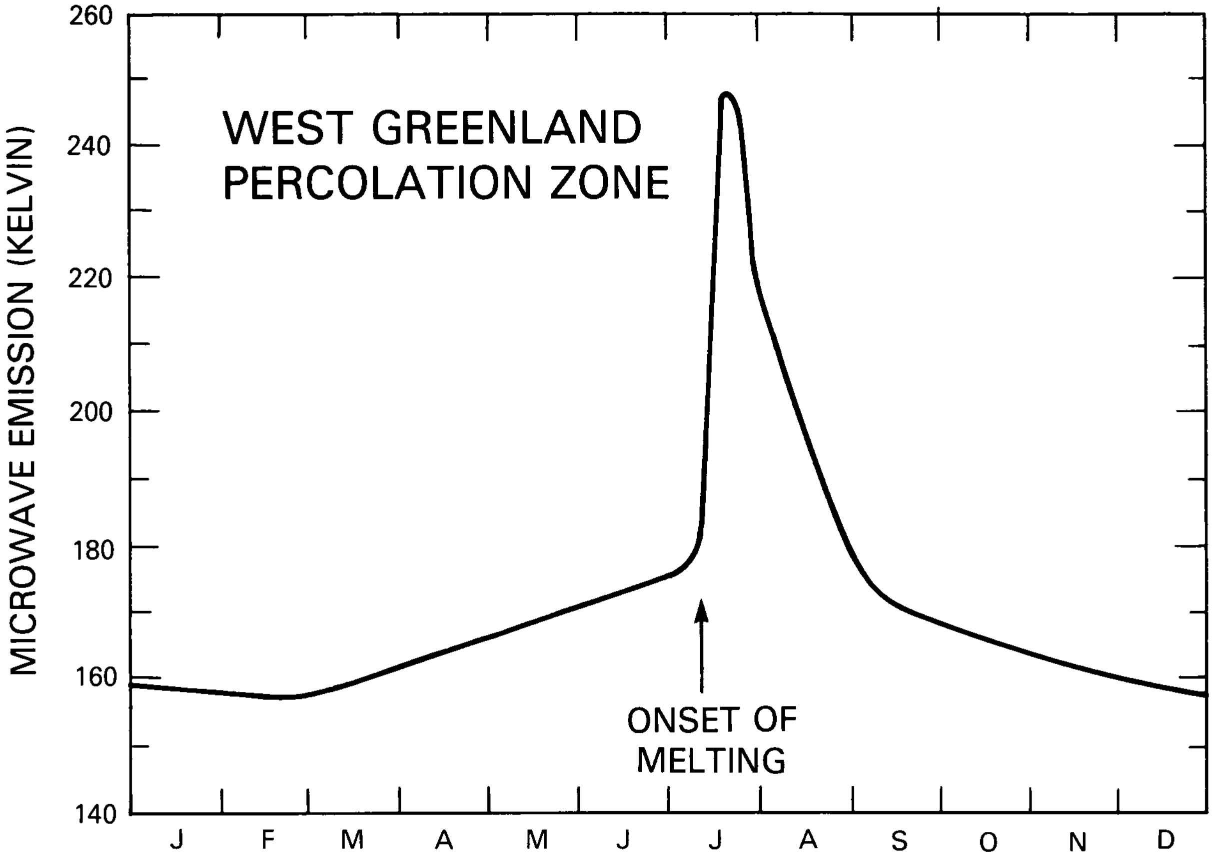


Figure 18. Regions of surface melting during summer can be mapped because the microwave emission from snow varies slowly with the seasonal temperature until wetness causes an abrupt increase.

horizontal polarization from the Seasat scatterometer for Greenland.

At the 14-GHz frequency (~2 centimeters wavelength) of the Seasat scatterometer, penetration of the transmitted pulse is far less than for the L-band or 1.25-GHz SAR frequency. Thus, the scatterometer measurements contain information primarily on surface roughness and snow characteristics within a few meters of the surface. In Figure 20 the slopes and the southern portion of Greenland are far stronger backscatterers than is the high cold central area. The regions of strong backscatter are assumed to be associated with areas of appreciable surface melting. However, there is a strong need for additional research on the interpretation of scatterometer data over ice.

DATA COLLECTION PLATFORMS

Spacecraft are also used as relays for data transmitted from surface-based instrument packages. Categorized as data buoys, these instruments can measure a broad range of variables. In the polar regions, Automatic Weather Stations (AWSs) were the first to make use of this technology, and they continue to make important contributions to our understanding of meteorology in the polar regions where ground stations are sparse. Wind speed and direction, air temperatures at various levels, and barometric pressure are transmitted by the AWS to overflying NOAA satellites which store the data for later transmission as the satellite passes within range of a receiving station.

Glaciologists have made very little use of data buoys. The harsh environment and the relatively large costs of instrument development have deterred the use of this technique. Recently, however, NASA engineers have expressed an interest in developing sophisticated data buoys complete with a controlled environment to use the Antarctic as a test bed for new spacecraft technologies. The advantage of data buoys is that the data are collected year-round, permitting the scientist to examine seasonal variations at locations far from manned stations. The measurements that could be obtained usefully with such a system are position, temperature profiles in the near surface snow, the amount of snowfall, seismic ac-

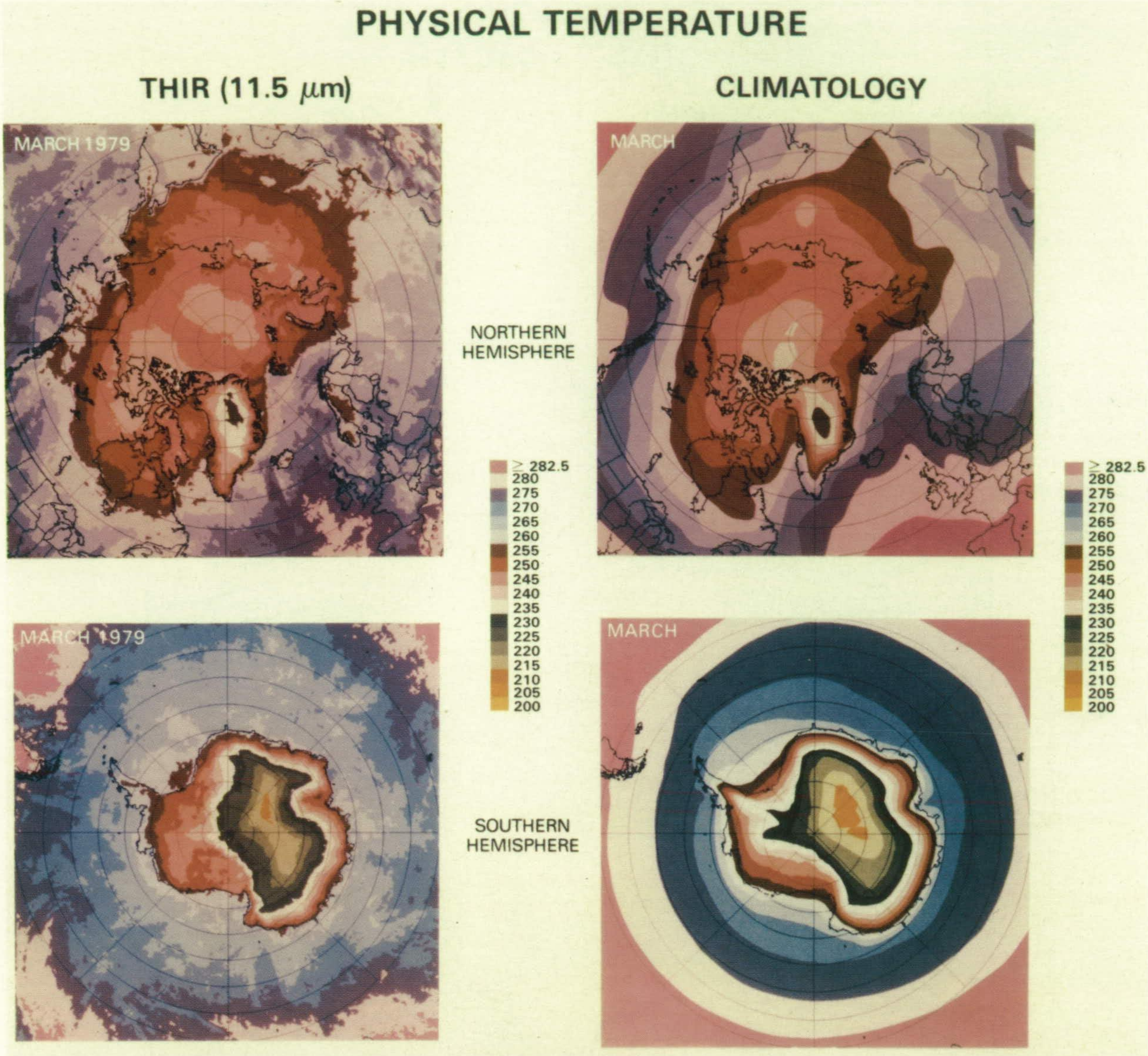


Figure 19. Average temperatures over the polar regions during March 1979, derived from satellite thermal infrared data and from climatic records.

tivity, and all of the standard weather parameters. In addition, conditions in a deep bore hole could be routinely monitored to reveal, for instance, the rate of tilting of a bore hole on the grounded ice sheet, or temperature changes near the bottom of a floating ice shelf, and ocean conditions beneath. Position could be measured using the TRANSIT or Global Position System (GPS) satellites to detect any temporal variation in velocity. This would be an extremely valuable measurement on ice streams, where such variations would suggest nonsteady water flow at the base of the ice.

The temperature profile in the near-surface firn is one of the important physical characteristics affecting the microwave emissivity of the surface layers. These data, in combination with data on snowfall and grain size, are needed to improve models of microwave emissions from snowpacks. These models could then be applied elsewhere to calculate accumulation rates from passive microwave data. Passive seismic monitors can detect the shocks associated with single crevasse formations. The integrated signal is a measure of ice activity and how it varies in time.

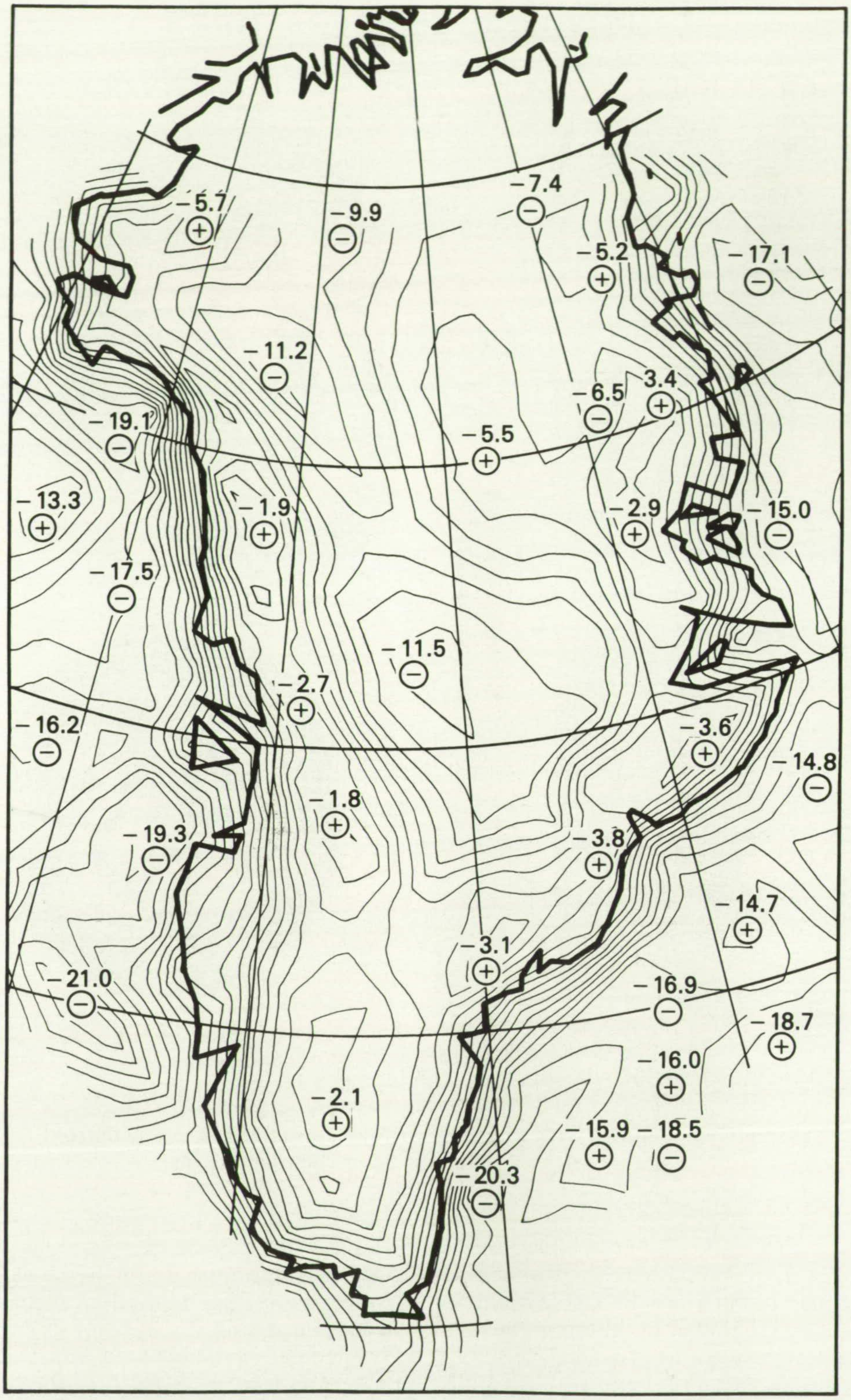


Figure 20. Contours of radar backscatter (in dB) over Greenland derived by averaging 30 days of Seasat scatterometer data obtained during September and October, 1978. The regions of strong scattering along the coast (marked with +) appear to be centered over areas of significant summer melting leading to the formation of subsurface ice lenses which scatter the incoming radar signal.

V. A TEN-YEAR RESEARCH STRATEGY

Until recently, polar research has by necessity consisted of piecemeal intensive projects directed at problems of specific interest to individual investigators, and limited in scope to localized areas and short time periods. These projects have provided us with a great deal of information relevant to these localized areas at the time of study, but we still lack an overall description of the ice sheets and their present behavior. This seriously limits our ability to assess the significance of results from the many individual research projects and to place them in context. Satellite remote sensing offers the means of obtaining the overview that we lack.

During the next 10 years, several spacecraft will carry appropriate sensors over the polar ice sheets. The purpose of the research strategy that we propose is to determine the topography and document broad patterns of behavior of the ice sheets. Within the constraints imposed by the planned schedule of satellite launches, we believe that by 1990 satellite data will provide us with sufficient insight to formulate detailed plans for *in situ* measurements that will address problems identified using the satellite measurements. Meanwhile, we endorse the currently planned field programs described in Section III. These address important problems, and they will take several years to complete.

Beyond the 1980s, we look to satellite remote sensing to provide the observations needed to monitor ice behavior, and to provide both coarse and fine resolution information on surface characteristics in areas of specific interest.

The major questions in polar glaciology are:

- What is the mass balance of the Antarctic and Greenland ice sheets, both overall and for the major drainage basins?
- What controls present-day ice dynamics, especially in the ice streams and ice shelves into which they flow?
- How are the paleoclimatic records contained in ice stratigraphy to be interpreted?

Satellite remote sensing is the only way to obtain an unambiguous answer to the first of these questions, and is indispensable to addressing the other two, for which drilling and other conventional surface studies are needed to complement the satellite data.

MASS BALANCE

The mass balance is the most important unknown quantity. It represents the first step in understanding ice-sheet behavior, and its systematic measurement will lead to a major realignment of glaciological research. It may be different for each of the major ice drainage basins. Conventional techniques have been used to calculate mass balance in selected, limited areas, but there are large error estimates. A consistent pattern has not emerged and even the sign of the global ice balance is not known. Two methods are proposed for measuring the mass balance. The first is repeated mapping by satellite altimeters of the surface elevation of ice sheets to detect rising or lowering ice elevations, and the second is the observation of changes in surface features, such as the seaward ice front, glacier streamlines, crevasse patterns, ice rises, and grounding lines.

Results for Seasat and Geos-3 have shown that ice-sheet topography can be mapped using satellite radar altimeters, but we need long-term data to assess the sensitivity of this technique to possible thickening or thinning of the ice. Data from the U.S. Navy's Geosat would be ideally suited to this purpose. Although coverage will be limited to latitudes between 72 degrees North and 72 degrees South, there will be extremely dense coverage of the ice sheets within this latitude band during the anticipated 3-year mission. This dense coverage will permit development and testing of analysis techniques for optimal use of data from satellites providing less dense coverage. Moreover, comparison with Seasat data should indicate whether data from separate altimetry missions can be compared reliably. We strongly recommend that all Geosat data over ice be released for these research applications. The data set should include measurements from the sea-ice or ocean surface within approximately 30 kilometers of the ice-sheet boundaries to permit mapping of these boundaries.

More complete coverage (to 82 degrees North and 82 degrees South latitude) will be provided by altimeters aboard ERS-1 and NROSS, which will be launched after the planned lifetime of Geosat. In addition to enlarging geographic coverage, these missions will permit simultaneous comparison of two different altimeters over ice, and they will extend to 15 years the time series of altimetry data between 72 degrees North and 72 degrees South latitude. For all altimetry missions, it will be necessary to reprocess over-ice data to correct for the effects of the nonhorizontal and possibly specular surface. In addition, satellite positions should be determined as accurately as possible, preferably to a few tens of centimeters vertically, and a few meters horizontally.

Although major changes in ice thickness over large areas should be detectable from sequential radar-altimetry surveys, laser altimeters will be required to map details of these changes and to detect more subtle thickening or thinning trends. Consequently, we strongly support development of the satellite laser altimeter proposed for inclusion aboard the EOS.

The second approach proposed for assessing ice-sheet mass balance is detection of changes in surface features. This can be implemented by comparing visible or radar images of ice fronts, ice rises, crevasse patterns, and grounding lines obtained at different times. Consequently, a time series of high-resolution satellite images is needed to complement altimetry surveys, and to interpret conditions between altimeter orbit tracks. In addition, the imagery will be useful in assessing the cause of observed changes in ice-sheet elevations.

We urgently recommend a systematic mapping of at least the coastal regions of Greenland and Antarctica by both SAR and Landsat-quality visible imagers. The imaged regions should extend at least 100 kilometers inland from the coast to include the entire ablation region in Greenland, all major outlet glaciers, and the Antarctic ice shelves. The initial survey will permit identification of regions of particular interest, which should then be resurveyed, preferably every year.

Acquisition of the necessary visible imagery should be given high priority in the Landsat and/or SPOT programs. To complement these data, full use should be made of ice-sheet SAR imagery from SIR missions, ERS-1, and Radarsat. In particular, reflight during 1987 of the SIR-B mission in true polar orbit will present a first opportunity for mapping large areas of Antarctica, and we strongly endorse this application of SIR-B′ data. Planned data acquisition from ERS-1 should permit SAR mapping of most of Greenland, and parts of Antarctica may be imaged if a proposed German portable receiving station is implemented. However, Radarsat offers the first opportunity for periodic mapping of almost the entire Antarctic ice sheet with SAR imagery. The 5-year planned lifetime for Radarsat will permit compilation of time-series imagery over regions of particular interest.

ICE DYNAMICS

Once the mass balance is known, the key issue is to explain the causes of the observed changes. This, in turn, requires determination of the forces that drive motion and those that restrain it, and an understanding of the controls on snow accumulation, ablation, and temperature.

The following sections show how satellite programs would contribute. They would play a direct role in measuring the geometry and driving stresses, an important role in assessing the restraining stresses, and a necessary role in understanding the temperature and accumulation rate on the ice sheet surface. Temperature is important because it affects the stiffness of the ice. Snow accumulation is the mass influx to the ice sheets and its distribution affects ice flow patterns. A final topic is calving dynamics, widely held to be important, but very little is known about calving because of limited data. Satellite-borne programs will provide the large-scale information essential to the development of a comprehensive theory on calving dynamics. On all of these topics, satellites will provide continent-wide data, free from site-specific biases characteristic of conventional measurements obtained by many different investigators using many different techniques.

Driving Stress

Glaciers flow due to gravity, and the gravitational driving stress (force per unit planimetric area) is obtained from the product of ice thickness and surface slope. The surface slope is usually very small (10^{-2}) and is currently difficult to estimate, but it could readily be derived from satellite altimetry. Maps of the magnitude and direction of surface slopes delineate drainage basins, and they help to identify areas which may be critical to ice sheet stability. The compilation of maps of surface slope and driving stress (using existing and planned measurements of ice thickness) should be given high priority in the altimetry program.

Restraining Forces

Ice motion is restrained by forces which oppose the driving stress. On grounded ice, these derive mainly from shear between the ice and bedrock, and the "basal shear stress" is approximately equal to the driving stress. Thus, maps of the driving stress give proxy information on basal-ice conditions. For instance, where the ice is frozen to bedrock, basal shear stress is significantly larger than where the basal ice is melting, and resulting meltwater can lubricate a sliding motion. Consequently, accurate measurements of surface topography delineate different basal-ice regions within a catchment basin. In particular, the rapidly moving ice stream that drains the catchment basin can be identified solely from its characteristic low surface slope.

The extreme case of zero basal shear stress is embodied in the ice shelves around Antarctica. Here, restraints to motion are provided by shear between the ice shelf and its margins, and by the presence of grounded ice rises or "pinning points" within the ice shelf. The presence of these features and changes in their dimensions over time should be monitored by high-resolution satellite imagery (SAR or visible).

The calving front of an ice shelf also represents a restraint to motion due to seawater pressure acting on the submerged ice. However, its main importance is as a proxy indicator of forces acting upstream. For instance, a rapid advance of a section of the calving front would indicate a probable reduction in restraining forces further upstream (possibly due to ice-shelf thinning and ungrounding of an ice rise) permitting an increase in ice-movement rates. Or a steady advance of the entire calving front could indicate ocean conditions conducive to ice-shelf growth, which ultimately would increase total restraining forces. These two examples have many possible causes and effects, which highlight the need for the total coverage provided by satellite data. Such data are essential to identify actual causes and effects.

Observations should be made each year to map calving fronts of all ice shelves, and to provide estimates of iceberg populations in the Southern Ocean. Again, the useful sensors are SARs, high-resolution visible imagers, and radar altimeters.

Temperature and Surface Melting

Surface temperatures should be measured over the entire ice-sheet area for two reasons. First, the creep hardness of ice is sensitive to temperature, and ice-sheet modeling studies require a mapping of surface temperatures as a fundamental boundary condition. Second, systematic changes in surface temperatures over the ice sheets may be an early indication of global climate change. Consequently, we strongly recommend additional research aimed at developing and validating techniques for deriving ice-surface temperatures from satellite infrared measurements. A climatic change would also affect the distribution of melt ponds on ice sheets (observable by SAR and visible imagery) and the extent of surface melting (observable by passive microwave). Ice discharge rates from the Greenland ice sheet may be sensitive to small changes in the amount of summer melt. These melt zones should be carefully monitored with time.

Accumulation Rate

Glaciers exist where snow accumulation exceeds ablation, and their dimensions are sensitive to the rate of accumulation. Of special interest is the pattern of accumulation in Antarctica. Most of the accumulation occurs in a narrow band near the coast. The controls on accumulation rate in Antarctica should be studied using data from manned and remote weather stations, measurements of snow-accumulation rates, and observations of the extent of sea ice and its concentration. Microwave remote sensing has the potential to measure accumulation rates and is already routinely used to monitor sea ice.

PALEOCLIMATIC RECONSTRUCTION

A major portion of glaciologic research is directed toward obtaining and interpreting deep ice cores. These cores record in their stratigraphy past temperatures, snow accumulation rates, dust content, volcanic ash, atmospheric air composition, and other parameters. A proper interpretation must make allowance for the ice flow pattern, the geographical distribution of accumulation rate and temperature, and possible changes in the ice sheet with time. These aspects require satellite-obtained data as noted in the previous sections.

VI. CONCLUSION

The inescapable lesson learned from 80 years of polar exploration and research is that the ice sheets are too vast, field seasons too short, and logistic costs too great for ground-based field studies ever to provide us with a proper perspective on the behavior of ice sheets as complete units. After World War II, the age of polar exploration was replaced by a succession of scientific field programs from an ever-increasing number of nations. However, even large multinational programs, such as the IAGP, have had to limit the geographical scope of their research. After 25 years of field research costing billions of dollars, many of the most fundamental data on surface elevation, accumulation rate, surface temperature, and calving rates are known poorly or only in very limited areas. Moreover, we find ourselves in this situation despite extensive use of aircraft both for logistic support and for remote sensing. Consequently, the only means to effect a major advance in ice-sheet research is to make full use of remote-sensing data from polar orbiting satellites.

To develop this technology is not to turn our backs on field research, but rather to provide the data necessary to answer the questions of mass balance for the ice sheets as a whole, define individual drainage basins, and determine those basins which are most active. These data will benefit all existing field programs and help direct efforts to those regions that are most appropriate to research objectives for future field programs.

With the radar altimetry data from Geos-3 and Seasat, a small but successful beginning has been made utilizing satellite remote sensing in glaciology. The need for greatly expanding the application of satellite remote sensing to ice-sheet research must be recognized. Relevant data include:

- Imagery, at visible wavelengths from Landsat and SPOT, in the infrared from weather satellites, and at microwave frequencies from scanning radiometers from SARs, and data from scatterometers

- Measurements of ice-surface elevation using radar and laser altimeters

- Accurate measurements of target positions on the ice using satellite laser rangers

- Measurements of atmospheric, oceanic, and ice characteristics by data-collection platforms, relayed to investigators via polar-orbiting satellites

Our principal recommendations are listed below.

- Full acquisition and processing of all over-ice radar altimetry data from Geosat, ERS-1, NROSS and all other proposed altimetry missions.

- Modification of altimetry "tracking" software to improve data acquisition over ice, and full transmission of 20-per-second data (compared to Seasat's 10-per-second data rate).

- Accurate orbit determination (to tens of centimeters vertically and a few meters horizontally) for all altimetry missions.

- Use of a "standard" (Seasat) design for future radar altimeters, to permit intercomparison of data from different missions.

- Development of a satellite laser altimeter with early testing aboard the Shuttle.

- Significantly increased coverage of the polar ice sheets by Landsat-quality imagery for mapping and for detection of changes with time.

- Increased research effort toward improved interpretation of passive-microwave, SAR, infrared and scatterometer data over ice sheets.

- Intensive effort to map the Greenland and Antarctic ice sheets using SAR data from SIR missions, ERS-1 and Radarsat. This will require accurate orbit determination, and we strongly recommend inclusion of a GPS receiver aboard SIR missions and Radarsat.

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16. Abstract

This report assesses potential research applications of satellite data over the terrestrial ice sheets of Greenland and Antarctica and recommends actions required to ensure acquisition of relevant data and appropriate processing to a form suitable for research purposes. Relevant data include high-resolution visible and SAR imagery, infrared, passive-microwave and scatterometer measurements, and surface topography information from laser and radar altimeters.

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