Snow and Ice Research: An Assessment (1983)

Pages
141

Size
5 x 8

ISBN
0309325870

Committee on Glaciology; Polar Research Board; Commission on Physical Sciences, Mathematics, and Resources; National Research Council

Snow and Ice Research
An Assessment

Committee on Glaciology
Polar Research Board
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1983

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which established the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

Copies available in limited quantity from
Polar Research Board
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Order from
National Technical
Information Service,
Springfield, Va.
22161
Order No. PB83-231662

Snow and Ice Research
An Assessment

Committee on Glaciology

Mark F. Meier (Chairman through June 1984), U.S. Geological Survey, Tacoma, Washington
Charles R. Bentley (Chairman through June 1981), University of Wisconsin, Madison
Colin B. Bull, College of Mathematical and Physical Sciences, The Ohio State University
William J. Campbell, U.S. Geological Survey, Tacoma, Washington (term ended June 1981)
John W. Clough, Department of Geosciences, North Carolina State University (term ended June 1981)
Gordon F. N. Cox, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire
Joan Gosink, Geophysical Institute, University of Alaska
Anthony J. Gow, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire
Michael Herron, Schlumberger-Doll Research, Ridgefield, Connecticut
Edward R. LaChapelle, Department of Atmospheric Sciences, University of Washington (term ended June 1980)
Richard Moore, Space Technology Laboratory, University of Kansas, Lawrence
Ronald I. Perla, Environment Canada, Canmore, Alberta
Uwe Radok, Cooperative Institute for Research and Environmental Sciences, University of Colorado, Boulder
Ian M. Whillans, Department of Geology and Mineralogy, The Ohio State University (term ended June 1980)

Agency Liaison Representatives

Thomas J. Gross, CO_2 Research Program, U.S. Department of Energy

G. Leonard Johnson, Arctic Programs, Office of Naval Research

Ned A. Ostenso, National Oceanic and Atmospheric Administration

Edward P. Todd, Division of Polar Programs, National Science Foundation

Ex officio

David Male, Chairman, American Geophysical Union Committee on Snow and Ice

Staff

W. Timothy Hushen, Executive Secretary

Bertita E. Compton, Staff Officer

Muriel Dodd, Administrative Assistant

Polar Research Board

Charles R. Bentley (Chairman), University of Wisconsin
Vera Alexander, University of Alaska
Joseph O. Fletcher, National Oceanic and Atmospheric Administration
W. Lawrence Gates, Oregon State University
Ben C. Gerwick, Jr., University of California, Berkeley
Richard M. Goody, Harvard University
Arnold L. Gordon, Columbia University
Hans O. Jahns, EXXON Production Research Company
Philip L. Johnson, Lamar University
Arthur H. Lachenbruch, U.S. Geological Survey, Menlo Park
Louis J. Lanzerotti, Bell Laboratories
Chester M. Pierce, Harvard University
Juan G. Roederer, University of Alaska
E. Fred Roots, Department of Environment, Ottawa
Robert H. Rutford, University of Texas, Dallas
Donald B. Siniff, University of Minnesota

Ex officio
Jerry Brown (Chairman), Committee on Permafrost
Mark F. Meier (Chairman), Committee on Glaciology
James H. Zumberge, U.S. Delegate to the Scientific Committee on Antarctic Research of the International Council of Scientific Unions

Agency Liaison Representatives

Thomas J. Gross, CO_2 Research Program, U.S. Department of Energy

G. Leonard Johnson, Arctic Programs, Office of Naval Research

Ned A. Ostenso, National Oceanic and Atmospheric Administration

Edward P. Todd, Division of Polar Programs, National Science Foundation

Staff

W. Timothy Hushen, Executive Secretary

Bertita E. Compton, Staff Officer

Muriel A. Dodd, Administrative Assistant

Commission on Physical Sciences, Mathematics, and Resources

Herbert Friedman (Cochairman), National Research Council
Robert M. White (Cochairman), University Corporation for Atmospheric Research
Stanley I. Auerbach, Oak Ridge National Laboratory
Elkan R. Blout, Harvard Medical School
William Browder, Princeton University
Bernard F. Burke, Massachusetts Institute of Technology
Herman Chernoff, Massachusetts Institute of Technology
Walter R. Eckelmann, EXXON Corporation
Joseph L. Fisher, Office of the Governor, Commonwealth of Virginia
James C. Fletcher, University of Pittsburgh
William A. Fowler, California Institute of Technology
Gerhart Friedlander, Brookhaven National Laboratory
Edward A. Frieman, Science Applications, Inc.
Edward D. Goldberg, Scripps Institution of Oceanography
Konrad B. Krauskopf, Stanford University
Charles J. Mankin, Oklahoma Geological Survey
Walter H. Munk, University of California, San Diego
Norton Nelson, New York University Medical Center
Daniel A. Okun, University of North Carolina
George E. Pake, Xerox Research Center
David Pimentel, Cornell University
Charles K. Reed, National Research Council
Hatten S. Yoder, Jr., Carnegie Institution of Washington

Raphael G. Kasper, Executive Director

Foreword

This document is one of a series issued by the Polar Research Board that identifies needs and develops strategies for polar research. These studies are expected to be sufficiently searching to guide polar research over the next two decades. The setting of priorities is particularly important in times of financial stress, and it is hoped that these studies will assist the decision makers who will be doing so in government and nongovernment organizations concerned with polar regions.

Four studies in the series have now been completed: An Evaluation of Antarctic Marine Ecosystem Research; Study of the Upper Atmosphere and Near-Earth Space in Polar Regions: Scientific Status and Recommendations for Future Directions; Polar Biomedical Research: An Assessment, with an appendix, Polar Medicine--A Literature Review; and this one. Work continues on a number of other studies in the series.

Preparation of this report was made possible by the continuing support provided to the Board by the National Science Foundation, the Office of Naval Research, the National Oceanic and Atmospheric Administration, and the Department of Energy.

The Polar Research Board appreciates the time and effort of Charles R. Bentley and Mark F. Meier, past and present chairmen of the Committee on Glaciology, and of the members of the Committee in the conduct of the study and preparation of this report on their findings and recommendations.

A. Lincoln Washburn
Chairman, Polar Research Board, 1978-1981

Charles R. Bentley
Chairman, Polar Research Board, 1981-1985

Contents

1
Executive Summary

Glaciology, the study of ice in all its naturally occurring forms, is a broad subject with a variety of direct and indirect implications for society. This report is concerned only with ice on or above the surface of the earth; ice in the ground, or permafrost, is the subject of a separate report in the Polar Research Board's series, "Polar Research--A Strategy" (Committee on Permafrost, in press). Ice in biological systems and extraterrestrial ice are not included. Geographically the scope of the report extends beyond the polar regions to include any part of the earth where snow and ice occur. The Board and its Committee on Glaciology believe that a review of snow and ice research cannot exclude nonpolar aspects, particularly as the most direct impacts on society result from seasonal snow and ice cover in nonpolar areas. A statement on the general scope and problems of glaciology appears in Polar Research--A Survey (Committee on Polar Research 1970, pp. 73-74); much of the discussion there is still valid today.

PROGRESS SINCE 1970

Eight major problems in glaciology were identified in the 1970 Survey and grouped as follows:

Group A (listed in order of priority): Most timely and urgent in advancing understanding of the environment and application of this knowledge to efficient use and management of resources.

1. Sea-ice energy balance and dynamics
2. Snow-cover research and control

3. Surges of glaciers and sliding of a glacier on its bed

Group B (order not implying priority): Additional important problems.

Energy-balance studies of glaciers
Flow and diffusion through snow and frozen ground
Ice formation in running water
Physical properties of ice
Quaternary glaciology

We briefly review progress in research on these problems as background for a new consideration of priorities for research.

Sea-Ice Energy Balance and Dynamics

The principal reason for assigning top priority to this field in the 1970 Survey was the role of sea ice in the interaction between oceanic and atmospheric circulation, thus its effect on climate at high latitudes. The Arctic Ice Dynamics Joint Experiment (AIDJEX) and the analysis of satellite data brought major advances, including the formulation of a framework for a complete model of sea-ice dynamics, which provides a focus for coherent examination of physical processes in sea ice. Although satellite data became available in large quantities in the mid-1960s, only in the 1970s did systematic studies of sea ice begin. Remote sensing performed from 1970-1976 during AIDJEX demonstrated that passive microwave sensors could distinguish first-year ice from multiyear ice. LANDSAT data were useful for measuring ice deformation, documenting the quite different character of the summer and winter ice packs, and, to a limited degree, determining the relative abundance of ice of different thicknesses. Data collected by the synthetic aperture radar (SAR) on SEASAT confirmed the feasibility of using SAR to resolve fine structure in the field of ice velocity. During AIDJEX, data buoys were tracked and interrogated by satellite, and an array of buoys was established in 1979 to monitor the motion of the entire Arctic ice pack. Other programs on air/sea-ice/ocean interactions have been undertaken. Progress in research on Antarctic sea ice, however, has been relatively slow. The Committee on Glaciology believes that continued study of the energy balance and dynamics of sea ice is needed, but, because of the advances achieved by studies in the Arctic, it should no longer receive highest priority.

Snow-Cover Research and Control

Many of the recommendations made in 1970 have been implemented, and recent research has aimed increasingly toward a more fundamental understanding of snow as a material. The possibility of using electromagnetic sensors to determine the water equivalent of the snow pack stimulated interest in its electrical properties, and the importance of snow in the earth's energy budget motivated work on its optical properties. The movement of liquid water through snow has received much theoretical and field study. The mapping of snow covers by satellite has progressed, and operational snow-cover charts of the Northern Hemisphere are now released weekly. However, the extent, areal density, and relative reflectivity of the snow are not shown with sufficient accuracy. Increasing demand for water resources and the growing problem of acid precipitation make an improved understanding of snow accumulation and meltwater runoff essential.

Surging of Glaciers and Sliding of a Glacier on Its Bed

Extensive studies on Variegated Glacier fulfill many of the measurements recommended in 1970. Both Variegated and Black Rapids glaciers were found to be temperate, and the study of their motion indicates that water in and below a glacier must play a key role in triggering surges. Cyclic flow regimes have been simulated in general accord with the observed characteristics of several surging glaciers by using a simple model with a single adjustable "lubrication factor" to parameterize the water produced by friction at the base of the glacier. However, the physical validity of this model has not been established. The role of water from the glacier surface as a possible trigger of surges remains unclear, and there is not yet a single agreed-on theoretical model for the sliding of a glacier on its bed. The possibility of surges within the very large ice sheets remains; work on this question is a top priority.

Energy-Balance Studies of Glaciers

Two specific recommendations in the 1970 Survey called for continuous measurements of energy balance at selected sites and extension of the results obtained at those sites to energy balances over large areas using new developments in remote sensing. A program of the International Hydrological Decade (IHD) encouraged international efforts addressed to these objectives. Although many problems remain, the physical processes that couple glaciers to their climatic environment are better understood now than they were in 1970. In Antarctica, careful studies of the energy balance and of associated features of the boundary structure and flow have been carried out at a number of representative sites; the task now is to synthesize these in a description of the large-scale energy balance of the ice sheet. In regard to mass balance, significant regional features established since 1970 include positive balances in inland East Antarctica coupled with negative balances near the coast, suggesting a rising and steepening of the ice-sheet surface. The discovery that passive microwave radiation, which can be observed from satellites, is affected by snow properties such as temperature, density, and grain size could lead to further advances. Remote sensing may provide a way to extend mass-balance results from direct observation sites to cover large areas, even complete ice sheets.

Flow and Diffusion Through Snow and Frozen Ground

Although the movement of liquid water through snow has received much theoretical and field study, research on snow and soil as a coupled system with a complicated interaction has just begun; more research is needed (see Committee on Permafrost, in press).

Ice Formation in Running Water

Progress toward understanding the dynamics of river ice has been uneven. Emphasis has been placed more on ad hoc engineering problems than on fundamental physics. Qualitative descriptions of the evolution of a developing ice cover are available, but the underlying thermodynamic processes and dynamic forces are largely unknown. A mechanism for the multiplication of ice nucleii through "collision breeding" has been identified in streams. Recent findings suggest that the net surface heat loss in turbulent water is underestimated by most models. Theoretical and applied research has addressed the problems of maintaining open-water areas, the hydraulic resistance of river ice, and the formation, growth, and breakup of ice jams. Advances have occurred in the application of remote-sensing techniques to the observation and assessment of properties and characteristics of river ice and in understanding the production and transport of frazil ice. It is becoming apparent that frazil ice plays a key role in the development of ice covers in Arctic and Antarctic waters.

Physical Properties of Ice

Two needs emphasized in the 1970 Survey were studies of the dielectric and radiative properties of snow and ice and the rheology of large ice masses. Measurements of the electromagnetic properties of snow have been made at a few microwave frequencies, but more extensive coverage and correlation with ground-truth measurements are needed. Theoretical work on scatter and emission is incomplete and based on oversimplified models. Theoretical studies have led to better understanding of scatter and emission from sea ice than in 1970, but few studies of basic electromagnetic properties of freshwater floating ice have been reported. For glaciers, lower, more penetrative frequencies are particularly needed. Field and laboratory studies suggest that the wide range in dc conductivity between various glaciers results from the metamorphic history of the ice, but these studies have not led to a quantitative theory.

Recent experiments on the deformation of ice seem to support the suggestion that the minimum strain rate in a constant-stress test should correspond to the maximum stress in a constant-strain-rate test. If this correspondence can be demonstrated, a given test may provide information of value to both glaciologists and engineers. There has been progress in evaluating the temperature dependence of the creep of ice near its melting point as well as at the lower end of the polar temperature range, and in assessing the effect of impurities, but the effect of grain size is not yet clear. Research on texture, fabric, and other structural parameters is still needed. Recent studies on stress and strain rates in boreholes, made in conjunction with structural studies on core samples, have suggested substantial discrepancies between laboratory and field measurements, reflecting the results of experiments and observational as well as theoretical undertainties.

Quaternary Glaciology

Advances in this field have been dramatic. The recommendations in the 1970 Survey were, briefly, to drill for more ice cores in Antarctica and Greenland and on other glaciers and to analyze new and existing cores and the drill holes themselves as fully as possible. A number of shallow, intermediate, and deep ice cores have been recovered and analyzed for a continually expanding list of isotopic, chemical, and physical properties. Interpretation of these and other stratigraphic and thermal records in ice sheets and glaciers has provided detailed information on the environmental conditions of the recent and prehistoric past and shed light on past dimensions and dynamics of the ice sheet that are crucial to the understanding of the response of glaciers to climatic change. Measurements on ice cores have also yielded values of parameters (e.g., density, crystal orientation, electrical conductivity) necessary for the interpretation of remote-sensing information, such as radar, seismic, and electrical resistivity surveys, that can be obtained widely on large ice masses.

HIGHEST PRIORITIES FOR RESEARCH

The chapters that follow present research needs related to physical properties of ice, seasonal snow, floating ice, and glaciers; a final chapter discusses instrumentation, logistics, international cooperation, and other matters affecting the conduct of research. Here we select from the recommendations in these chapters 24 that we believe should receive highest priority. These recommendations focus on two broad themes:

- The interaction of snow and ice with past and present climate and
- The direct impact of snow and ice on society.

Climate

The interplay between low-latitude heat income and high-latitude heat loss influences the entire world climate system. This subject is a principal theme of a separate report by another committee of the Polar Research Board (Committee on the Role of the Polar Regions in Climatic Change, in press). The distribution of snow and ice strongly affects heat loss in the high and middle latitudes. The areal extent of snow in the Northern Hemisphere varies more than that of any other widely distributed material on earth. Because snow reflects about 80 percent of the sun's radiation, whereas soil and sea water absorb 80 percent or more, the extent of snow cover critically affects the earth's radiation balance, thus the global climate system.

In the Southern Hemisphere, where there is much less high-latitude land area than in the Northern Hemisphere, the great seasonal variation in the extent of sea ice affects global climate in much the same way as do snow variations in the North. The magnitude of the exchange of heat energy between the ocean and the atmosphere in the presence of ice is a crucial problem. Current information on sea ice comes largely from satelliteborne passive microwave systems and Arctic drifting stations and buoys. Observations at coastal stations in

Antarctica do not provide good regional averages because of the inhomogeneity of the ice and the large latitudinal ice extent in winter. Relatively small areas of open water have a major impact on the regional heat and mass balance. Furthermore, polynyas and leads make large contributions of "young" ice to the regional ice production. More extensive monitoring of ice thicknesses and heat fluxes in regions covered by sea ice is still needed.

Glaciers are also part of the global climate system. Although small glaciers react passively to climate, ice sheets interact with and affect it. Some models suggest that the deterioration of global climate to full glacial conditions may have followed the development of ice sheets in North America and Scandinavia. The relationships between glaciers and climate involve complex interactions on various spatial and temporal scales. Two complementary approaches to study of them are required: observation of changes of the entire climatic system, followed by formulation of deterministic or empirical rules, and construction and testing of models that incorporate the essential physics of the problem. For long time scales, observations simply lead to descriptions of existing conditions; modeling is then the only objective way to test understanding of both past and future relationships between ice and climate.

Snow and Climate

Small changes in atmospheric temperature or precipitation can trigger a large change in the global energy budget through ever-changing areal snow coverage. Because of snow-atmosphere feedbacks, the interaction between the seasonal snow cover and the global energy balance is a study of highest priority. An unresolved problem is the response of seasonal snow covers to increasing surface air temperature brought about by increasing amounts of CO_2 in the atmosphere. According to atmospheric general-circulation models, the extent of snow, especially at high latitudes, should shrink. Key questions are the following: Is such a process really taking place, or are other feedback processes leading to increased precipitation? Can snow be monitored as a climatic element? Can the CO_2

impact on snow be discriminated from unrelated perturbations?

Ground measurements alone probably will not provide sufficient data on the extent of the changing snow cover; satellite remote sensing is clearly needed. That, in turn, requires an understanding of the electromagnetic properties of snow. The principal focus of investigation at optical and infrared frequencies should be snow properties at the surface, where the heat balance is often controlled by the amount of solar radiation absorbed. Although the surface reflectivity of snow at optical or infrared frequencies must be known to relate snow to climate, satellite sensors cannot provide these data in a truly synoptic manner, because of clouds. Development of a synoptic snow-observing system operating at lower frequencies may bring important advantages, but there is an even greater lack of basic understanding of how to interpret the signals from satellite sensors at these frequencies.

Knowledge of emission characteristics is needed not only for seasonal but also for perennial snow because, with additional study, it may be possible to determine the surface mass balance of polar ice sheets from the emission characteristics and because the variable extent of snow-covered surfaces in the north polar regions probably plays a significant role in the earth's energy budget and climate.

Recommendation

Improved understanding of snow as an element of the global climate system should be sought through:

1. Development of remote-sensing methods for the large-scale, all-weather determination of the water equivalent of snow, field measurements to confirm remotely sensed results, and determination of the electromagnetic transmission and scattering properties of snow;

2. Definition of temporal and spatial variations of regional and hemispheric snow extent and albedo and their relationship to weather; and

3. The use of global snow data in the development and validation of atmospheric circulation models and in predicting the effects of a CO_2-induced increase in air temperature.

(See Chapter 4, section on "Global/Hemispheric Scale: Snow and World Climate")

In regard to part 1 of this recommendation and as emphasized in Chapter 3 on physical properties, improved understanding of dielectric properties and volume-scattering processes in dry and wet snowpacks is essential. Measurements of scattering and emission from a wide variety of snow surfaces, closely coordinated with ground-truth measurements, should be undertaken and coordinated with improvements in theory.

Interaction of Sea Ice With Oceans and Atmosphere

Variations in sea-ice extent not only alter the earth's albedo but also affect the moisture and heat exchange between the oceans and the atmosphere and thus influence the nourishment and extent of other forms of ice, from seasonal snow cover to large ice sheets. Variations in the extent of Antarctic sea ice also affect the amount of CO_2 in the atmosphere and oceans, and, through the formation of Antarctic bottom water, the temperature of the world oceans. Thus there are long-term as well as short-term effects of sea ice on climate.

Estimates of the heat energy fluxes over the pack ice are relatively few and unreliable, particularly in the Antarctic. Dynamic and thermodynamic processes at the ice edge are critical in understanding Arctic and Antarctic heat and mass budgets as well as interactions between the atmosphere, the ice, and the oceans on short (weather-related) and long (climate-related) time scales.

Recommendation

Research on sea ice should be directed to measurements of ice growth, drift, and decay and to interactions of ice with the thermohaline structure in the marginal ice zone. These studies should include a winter lead experiment on freezing processes, convection, and haline-driven circulations and atmospheric fluxes and a summer field experiment to measure ice melting rate, radiation balances, and the structure of the pycnocline.

(See Chapter 5, section on "Other Research Objectives: Ice Formation, Growth, and Decay)

Further understanding of the global climate system requires better knowledge about the vertical fluxes between air, ice, and water; horizontal heat, mass, and momentum transfer, including advection of ice in relation to air and water circulation; processes of ice growth and decay, especially in the marginal ice zone; ways to improve the use of remote sensing for routine monitoring variations of ice in time and space; and ways in which numerical models can be used to test the coupled hydrodynamic, thermodynamic, and constitutive approximations to the basic physics of the air, water, and ice systems.

Recommendations

The full potential of remote-sensing techniques for determining large-scale sea-ice conditions (extent, concentration, thickness) should be implemented to achieve maximum resolution and minimum turnaround time for data processing and distribution to users.

(See Chapter 5, section on "Research Needs--Sea Ice," subsection "Floating Ice and Climate"; and Chapter 7, section on "Instruments and Techniques," subsection "Other Remote Sensing")

An array of data buoys should be maintained in the Arctic for a minimum of five years. They should measure not only position, temperature, and pressure but also other oceanographic and atmospheric parameters wherever possible. An array of air-droppable buoys should also be deployed in the seasonal ice of the Southern Ocean to monitor pressure, temperature, and ice movement. Such data are needed to confirm and quantify the divergent nature of the Antarctic pack ice and to estimate regional rates of ice production, salt rejection, and turbulent heat exchange with the atmosphere. Data from such studies could be applied to the development, modification, and verification of numerical air/sea-ice/ocean models.

(See Chapter 5, section on "Research Needs--Sea Ice," subsection "Sea-Ice Processes"; and Chapter 7, section on "Instruments and Techniques," subsection "Other Remote Sensing")

Coupled sea-ice/ocean/atmosphere models that incorporate the essential physics of ice and ocean processes, small-scale heat and mass transfer from leads, and low-level clouds should be developed. Especially needed is a simple sea-ice model that incorporates sufficient physics to represent the essential interactive aspects of long-term climate simulations.

(See Chapter 5, section on "Research Needs--Sea Ice," subsection "Floating Ice and Climate")

Representative Glacier Basins

Mountain glaciers and small ice caps have climatic response times on the order of decades to centuries. Fluctuations have been observed over decades on some glaciers, and for some of them the climate of the surroundings is also adequately defined for at least part of that history. For a few glaciers, all the basic measurements needed to determine their response to climatic variations have been made; these "classical" glaciers are the most suitable for combined observational studies and modeling experiments.

Recommendation

Long-term measurements of the relevant aspects of the meteorological environment, together with basic glacial processes, should be continued on a few representative glaciers. The basic data sets should be put in a form that is understandable others and communicated to the World Data Center-A for Glaciology and the Permanent Service on the Fluctuations of Glaciers.

(See Chapter 6, section on "Relationships Between Glaciers and Climate," subsection "Problems of Mountain-Glacier Scale"; and Chapter 7, section on "Management of Glaciological Data," subsection "Data Management Needs")

The great mountain system bordering the North Pacific Ocean spanning Alaska, Yukon Territory, and British Columbia contains the fourth largest ice mass in the world. Storms moving out of the Gulf of Alaska produce high rates of snow accumulation in the mountains, among the highest rates of mass flux cycling through the atmosphere-ice-ocean system in the world. The winter climate of much of North America is affected by processes occurring at this ice-covered border; the copious meltwater runoff affects the productive near-shore waters of the Gulf of Alaska. Yet little is known about its mass and energy exchange processes and rates.

Recommendation

The regional glacial meteorology and mass exchange of the high mountains bordering the Gulf of Alaska should be determined.

(See Chapter 6, section on "Relationships Between Glaciers and Climate," subsection "Problems of Mountain-Range Scale")

West Antarctic Ice Sheet

The response of the West Antarctic ice sheet to climatic change is a high-priority question for research because of the possibility that a CO_2-induced atmospheric and oceanic warming could trigger its rapid shrinking. A physical theory that can treat this problem is needed but cannot be developed until basal and intraglacial processes are better understood. Until then, empirical models continue to be useful. We fully support recommendations that have been presented by the Scientific Committee on Antarctic Research (SCAR) (Group of Specialists on Antarctic Climate Research 1981) and Bentley (1982). These two studies point out that, although surface elevations of most of West Antarctica have been mapped to an accuracy of about ± 50 m, an order-of-magnitude greater accuracy is needed to detect and monitor possible climate-induced changes. These studies also emphasize the lack of knowledge about surface mass balance and its relationship to atmospheric and oceanic circulation and the extent of sea ice. They stress the need to explore the use of satellite techniques, especially passive microwave radiometry to determine the areal distribution of surface mass balance, and radar and laser altimetry to determine, and measure changes in, ice surface elevations. (Satellite measurements so far have been limited to latitudes less than 72° and have included only radar altimetry.) In addition, better knowledge of the rate of ice melting and freezing on the underside of the ice shelves receives emphasis, for that is a critical and poorly measured factor in the assessment of the mass balance of the ice sheet.

Recommendations

Every effort should be made to bring about, as soon as possible, the emplacement into a polar orbit of a satellite carrying radar and laser altimeters that are designed for effective use over ice sheets.

(See Chapter 6, section on "Energy Balance," subsection "Thickness Change and Stability of Ice Sheets"; and Chapter 7, section on "Instruments and Techniques," subsections "Remote Sensing From Satellites" and "Other Remote Sensing")

Ground-based measurement of the surface mass balance and relevant meteorological variables for one or more complete drainage basins should be completed, and the results should be extended by satellite radiometry to the whole of the West Antarctic ice sheet and incorporated into atmospheric circulation models. (Specific tasks are explained in more detail in Bentley [1982] and Group of Specialists on Antarctic Climate Research [1981].)

(See Chapter 6, section on "Relationships Between Glaciers and Climate," subsection "Problems of Ice-Sheet Scale")

Determining and understanding oceanic circulation beneath the Antarctic ice shelves and the mass and heat exchange between the water and ice should be major goals of research.

(See Chapter 6, section on "Energy Balance," subsection "Basal Mass Balance on Ice Shelves"

Determination of Past Environmental Conditions

Ice sheets and ice caps contain much information on past climates and environmental conditions. These can be inferred from the isotopic and chemical composition of the ice, the incorporated terrestrial and extraterrestrial material, the inclusions of air, and the temperature-depth profile of the ice sheet. The stratigraphic profiles of the Antarctic and Greenland ice sheets are obtained from ice cores that contain the precipitation accumulated over intervals as great as hundreds of thousands of years. The upper sections of some cores are highly resolvable, frequently permitting one season's snowfall to be distinguished from the next. These high-resolution data are available nowhere else and provide information that complements data, of lesser resolution but larger time span, obtained from the study of marine lacustrine sediments and from glacial geology. More types of analyses undoubtedly will become routine over the next decade, and new environmental parameters will be introduced.

Deep ice cores so far obtained from Greenland and Antarctica contain ice probably no older than about 120,000 years--back to the most recent previous interglacial epoch. Deep, continuous, high-quality ice cores with basal ages of several hundred thousand years or more will help to answer questions about the causes of glacial ages, the relative severity of the major glacial stages, and the past and future response of ice sheets to climatic change. Ice cores to meet these demands can best be obtained from Central Greenland and East Antarctica.

Recommendation

A long-term program of shallow-, intermediate-, and especially deep-core drilling in Central Greenland and in Antarctica should be implemented, including the development of techniques that will produce continuous, high-quality ice cores suitable for scientific analysis.

(See Chapter 6, section on "Quaternary Glaciology," subsection "Long-Term Environmental and Climatic Records"; and Chapter 7, section on "Instruments and Techniques," subsections "Drilling and Coring," "Core Analysis," and "Borehole Equipment")

About 120,000 years ago the West Antarctic ice sheet may have largely disappeared, flooding coastal areas now occupied by a large fraction of the world's population. Variables reflecting former ice sheet elevations, extent of sea ice, and paleoclimate can be measured on a core to the bedrock of the West Antarctic ice sheet and on intermediate-depth cores collected on and between the ice streams that drain West Antarctic ice.

Recommendation

A continuous ice core to the bedrock should be obtained from a site that will permit determination of the presence or absence of the West Antarctic ice sheet during past interglacials and will provide paleoclimatic data. These data can be supplemented by data from other cores and geophysical surveys within the Ross Embayment.

(See Chapter 6, section on "Quaternary Glaciology," subsection "History of West Antarctica"; and Chapter 7, section on "Instruments and Techniques," subsections "Drilling and Coring," "Core Analysis," and "Borehole Equipment," and section on

"Logistics," subsection "Support for Antarctic Ground Programs")

An ice-core signal reflects the combined contributions of global, hemispheric, regional, and local conditions. To address the problem of sorting out these contributions, signals in polar ice cores must be compared with signals in cores from subpolar regions, with historical weather records, and with other proxy climate data. Ultimately, all the core records for a drainage basin must be reconciled with a modeled history of the ice and the climate.

Recommendation

The climatic and environmental information contained in ice cores should be compared with local or regional meteorological information, historical records of climatic and environmental changes, including past solar activity and volcanism, and long-term data from tree rings, lake and ocean sediment cores, and glacial deposits. To aid in this comparison, intermediate-depth ice cores should be obtained from a number of polar and nonpolar latitude bands and from diverse meteorological and glaciological environments.

(See Chapter 6, section on "Quaternary Glaciology," subsection "Identification of Climatic Information from Ice Cores"; and Chapter 7, section on "Instrumentation and Techniques," subsections "Drilling and Coring," "Core Analysis," and "Borehole Equipment")

Dynamics of Rapid Glacier Changes

It is not sufficient to understand how climatic variations affect the boundary conditions on glaciers; it is also necessary to understand how these complicated dynamic systems respond to those variations. Glacial motion occurs by a combination of internal deformation and basal sliding, but the rates of neither process can be predicted with confidence. The internal deformation is affected by variations of structure and temperature with depth; field observations and laboratory experimentation do not yet suffice to establish a definite quantitative flow law. To understand the sliding process, it will be necessary to make many detailed observations of the structure of the basal zone and the physical processes acting there. Ultimately, any prediction of future changes in glaciers must involve numerical modeling.

In regard to rheological properties of ice, further field and laboratory studies of the response of ice to a stress are needed. This work should be focused on providing a basis for predicting the response. Measurements are needed not only on polycrystalline ice but also on single crystals, so that existing theories can be tested.

Recommendation

Laboratory measurements on the deformation of polycrystalline and monocrystalline ice samples of widely varying physical and chemical characteristics should be conducted over a broad range of stresses and strains.

(See Chapter 3, section on "Mechanical Properties," subsection "Ice")

In regard to processes at the glacial bed, there is still no general agreement about the principal controlling factors in the sliding process; even qualitative physical understanding is lacking. Several methods of study are available and should be combined. Most important are measurements in boreholes to determine basal water pressure, interface morphology, and slip rate. Borehole measurements should be coupled with measurements of surface movement, both horizontal and vertical, on short time scales. Remote sensing could provide an effective way to measure sliding changes, and observations of the characteristics of discharged water could yield additional information about the basal hydraulic system. Surge-type glaciers in particular should be studied because they display a full range of sliding speeds on a fixed-bed geometry over the course of a surge cycle. Some outlet glaciers in Greenland and Antarctica flow continuously at surge speeds, and these need to be studied to determine how such speeds can be maintained. Studies of both types of fast-sliding glaciers should add fundamental insight into the problem of glacier sliding.

Recommendations

The several types of measurement related to processes at the glacier bed should be made on both normal and surge-type glaciers, and they should be conducted simultaneously on any particular glacier. A similar measurement program should be instituted on a continuously fast-sliding glacier, such as the Jakobshavn Glacier.

(See Chapter 6, section on "Glacier Surging and Sliding," subsection "Processes at the Glacier Bed")

The ongoing field studies and remote sensing of surging glaciers should be continued through and beyond the surges now occurring and expected in the 1980s. Support should also be provided for interpretation of the data.

(See Chapter 6, section on "Glacier Surging and Sliding," subsection "Processes at the Glacier Bed")

Direct Impact of Snow and Ice on Society

Important as the interaction between snow and ice and climate is, particularly on the longer time scale, many other interactions have a more immediate and direct effect on society. Such diverse problems as the development of oil and gas resources in Arctic regions, the flooding of rivers due to ice jam formation, avalanches, and snowmelt forecasting all require intensified research into the physics of ice and snow.

Interaction of Floating Ice Covers With Natural Barriers and Man-Made Structures

Processes in floating ice that deserve more attention include the formation and dynamics of broken ice covers, pressure ridges, rubble piles, and ice jams and the ride-up and pile-up of ice on structures.

The interaction of sea ice with man-made structures includes both consolidated bodies, such as sheet ice, large floes, multiyear pressure ridges, and "floebergs," and unconsolidated aggregates or fragments of ice of various sizes, such as first-year pressure ridges, rubble fields, and fragmented ice covers. The heights, sizes, and extents of these ice forms have been studied using laser and sonar profilometry. Better characterizations are required of the ice environment, the mechanical properties of the ice cover, and the failure modes of ice against different types of structures to facilitate exploration, production, and transportation of oil and gas on the continental shelves of the Arctic. Information on the distribution of thickness and motion of sea ice is essential also for ice navigation of large ocean-going vessels and for placement of underwater pipelines and cables. Much of our understanding of the large-scale mechanical properties of the ice cover and of ice-structure interaction will be derived from model tests in ice basins. (The action of ice on a variety of different structures, including gravel islands and cones, is discussed in greater detail in a report by the Panel on Sea Ice Mechanics of the Marine Board [1981]).

Recommendations

The mechanisms and forces associated with the formation of pressure ridges and rubble piles and with ice ride-up and pile-up should be studied. The degree of consolidation of ridges and rubble piles with time should be investigated.

(See Chapter 5, section on "Research Needs--Sea Ice," subsection "Sea-Ice Processes")

Systematic small-scale laboratory tests should be performed to determine the mechanical properties of sea ice and to develop suitable constitutive laws. Emphasis should be placed on understanding the physical processes controlling the mechanical properties of ice. A limited number of large-scale ice-strength tests are also needed to determine appropriate scaling factors for the small-scale strength data.

(See Chapter 5, section on "Research Needs--Sea Ice," subsection "Ice Loads on Structures")

Because much of our understanding of the large-scale mechanical properties of the ice cover and ice-structure interaction will be derived from model tests in ice basins, efforts to develop a properly scaled model of the ice cover should be continued.

(See Chapter 5, section on "Research Needs--Sea Ice," subsection "Ice Loads on Structures")

In regard to freshwater ice, the formation, growth, and breakup of ice jams is the subject of primary interest. Field measurements of the controlling parameters are virtually nonexistent, and analysis has concentrated on theoretical and laboratory modeling of ice jams. There is evidence that the breakup of river ice may be linked strongly to hydraulic transients such as the rate of rise and the total rise of river stage as well as the thickness and strength of the ice.

Recommendation

Field studies and observational programs should be conducted to document the locations, stability, and mechanics of ice jams and the resulting changes in river stage. Investigations of both frazil-ice jams, commonly formed during freeze-up, and of large-scale ice jams, formed during breakup, should be undertaken. Quantitative theoretical models should be developed of breakup progression, the dynamics of moving ice fronts, processes of pressure- and sheer-ridge formation, large floe development, and the hydrodynamics of two-phase frazil-ice-laden flow.

(See Chapter 5, section on "Research Needs--River and Lake Ice")

Frazil Ice

Frazil ice consists of individual discs that are formed in open-water reaches of rivers and in leads and polynyas in sea-ice covers. It is a product of the nucleation of ice crystals in turbulent water, and the bulk physical properties of aggregated frazil ice differ appreciably from those of ice formed in a quiescent body of water. Large productions of frazil ice can halt navigation on rivers and even block their flow, plug freshwater or seawater intakes, and cause the formation of anomalously thick river ice. Research on the formation, growth, and behavior of frazil ice is essential to improved understanding of the growth and characteristics of floating ice covers in general and of Antarctic sea ice in particular. Virtually no data are available on the mechanical properties of frazil ice during its morphological changes. Furthermore, the role of frazil ice in the redistribution of fine sediment in both seawater and fresh water should be studied.

Recommendation

A major emphasis in research on floating ice should be the formation, growth, and behavior of frazil ice, especially under field conditions, including:

1. The nucleation mechanisms of frazil-ice formation;
2. The growth rates of individual frazil-ice crystals in supercooled water;
3. The mechanical properties of frazil ice during the different stages of its growth and formation; and

4. Crystallographic studies of frazil-ice cores to discern sediment entrapment, expulsion, and transport processes.

(See Chapter 3, section on "Mechanical Properties," subsection "Frazil Ice")

Fundamental questions about mass and heat transport at the interface between turbulent fresh water and air are another high-priority area for research. Although most analyses of the thermal regime of rivers make use of standard procedures for assessing the surface heat exchange, recent findings suggest that the net surface loss in turbulent water is underestimated by most models, probably because of the effects of frazil ice crystals.

Recommendation

Research on freshwater ice should focus on heat and mass exchange mechanisms at the turbulent water surface, secondary nucleation during freeze-up, and melting rates and radiation balances during breakup. These studies should include the thermal regime of the water during freeze-up and breakup and the characteristics of the frazil ice, especially adhesion, during its formation, evolution, and flocculation. Field investigations should be emphasized.

(See Chapter 5, section on "Other Research Objectives: Ice Formation, Growth, and Decay)

Mechanical Properties of Snow

Because of the wide variety of types of snow and the rapid transformations that occur between them, much work on the basic mechanical parameters is still needed. Because the mechanical and thermodynamic properties of an ice crystal in a snowpack are so sensitive to water content and the effect of water on mechanical properties is largely unknown, study of the relationship of water and temperature to snow properties should be a particular goal of research.

Recommendation

The dependence of the strength and creep of snow on properties such as grain size, shape, bond diameter, density, and, in particular, liquid-water content should be measured.

(See Chapter 3, section on "Mechanical Properties," subsection "Snow")

Forecasting the Regional Deposition and Melting of Snow

Snow occurs in many different forms that change rapidly in response to changes in local climatic conditions. Although each climatic province will have a wide variety of snow types, and each of these will change during the season, the predominant snow type will differ significantly from one province to another. The distinction between the snow types in different provinces is important to hydrological modeling or forecasting because the characteristics of snowmelt runoff depend on the properties of the snowpack. Orographic precipitation models now available for several areas of the western mountains offer promise for the mesoscale prediction of variations of snow cover.

A key factor in runoff is that snow and soil behave as a coupled two-layered system with a complicated interaction. Another factor about which little is known is the areal energy exchange between a snow surface and an advected warm air mass.

Acid precipitation, which has caused widespread public concern, is magnified in the snow cover, for soluble impurities are leached principally by the first fraction of meltwater. The processes responsible for this sudden release of acid runoff must be investigated because of the problems caused by the sudden lowering of pH in streams and lakes.

Recommendation

The physical bases for forecasting snowmelt runoff, soil-water reserve, and basin storage should be developed. Research may require different approaches and emphases in each snow province and should include:

1. Meteorological and topographical controls on the deposition of snow at the mesoscale, with attention to the altitude distribution of snow in the mountains and snow albedo at less than global scale;
2. Liquid and vapor transfer across the snow-soil interface; and
3. Impurities in the snowpack, their discharge into runoff, and management of the problem. Acid impurities should receive special attention.

(See Chapter 4, section on "Regional and Drainage Basin Scale: Snow as a Water Resource")

Icebergs

Icebergs are derived from glaciers by calving. They float in the oceans, may be associated with sea ice, and may present floating hazards to vessels and structures. Two quite different types of icebergs exist: huge tabular icebergs derived from ice shelves in the Antarctic and from northern Ellesmere Island, and blocky icebergs of a few meters to about a kilometer in size that are derived from outlet glaciers in Greenland, Alaska, and many other areas. The blocky icebergs from Greenland outlet glaciers tend to move counterclockwise around Baffin Bay, then to drift south in the Labrador Current, where they may approach offshore oil and gas installations or drift further south and east into the North Atlantic steamer lanes. Icebergs in other northern waters, such as the Valdez Arm, Alaska, may also present hazards.

Problems for research include: (a) detection and measurement, especially of underwater shape; (b) prediction of drift trajectories, which depend on wind, water currents, Coriolis force, and the ever-changing shape of the iceberg due to melting, rotation, or breakup; (c) towing characteristics; and (d) mechanical properties, which are important in the prediction of breakup and of the consequences of impact on structures, such as drilling platforms or pipelines on the seabed.

Recommendation

Research should be continued on the remote detection of icebergs and the mapping of their shapes using acoustic, radar, or other types of instruments as well as on the use of these data for the modeling of natural iceberg drift and for their drift under towing forces. Research is needed on ablation rates of icebergs and on ways that ablation affects the hydrodynamic and mechanical stability of icebergs.

(See Chapter 5, section on "Research on Icebergs")

2
Scope and Organization

Glaciology, the study of ice in all its naturally occurring forms, is a broad subject with a variety of direct and indirect implications for society. This report is concerned only with ice on or above the surface of the earth; ice in the ground, including permafrost, is the subject of a separate report in the Polar Research Board's series, "Polar Research--A Strategy" (Committee on Permafrost, in press). Ice in biological systems and extraterrestrial ice are not included, although some of the research topics mentioned here, especially those in Chapter 3 on physical properties, are relevant to an understanding of these other occurrences of ice. The high-pressure forms of ice (those other than Ice Ih) are also excluded from discussion.

Geographically the scope of the report extends beyond the polar regions to include any part of the earth where snow and ice occur. The Board and its Committee on Glaciology believe that a review of snow and ice research cannot exclude nonpolar aspects, particularly as the most direct impacts on society result from seasonal snow and ice cover in nonpolar areas. A statement on the general scope and problems of glaciology appears in Polar Research - A Survey (Committee on Polar Research 1970, pp. 73-74); much of the discussion there is still valid today.

Engineering and resources development problems and opportunities involving snow and ice are not emphasized here; these are treated in other reports, such as Understanding the Arctic Seafloor for Engineering Purposes (Committee on Arctic Seafloor Engineering, Marine Board 1982) and Engineering at the Ends of the Earth (Panel on Polar Ocean Engineering, Marine Board

1979). However, many of the important scientific questions discussed here are relevant to engineering and resources development problems, and such relevance was considered in the assignment of priorities.

The remainder of this report begins with a chapter on the physical properties of ice, which addresses basic questions that apply to several subdisciplines of glaciology (Chapter 3). Seasonal snow is the subject of the next chapter (Chapter 4), followed by one on floating ice, which includes sea ice and freshwater ice (Chapter 5). A chapter on glaciers includes ice caps and ice sheets under the broad definition of glacier (Chapter 6). Ice shelves, which float, are also discussed in this chapter, but icebergs, which break off from glaciers or ice shelves, are considered in Chapter 5 on floating ice. In each of these chapters, the status of the field and progress since Polar Research - A Survey (Committee on Polar Research 1970) are treated first, followed by a discussion of the salient research needs, viewed from a 1983 perspective. The final chapter deals with needs related to support of basic science, such as instrumentation, logistics, international cooperation, data management, and organizational arrangements (Chapter 7).

The Committee on Glaciology wanted to call particular attention to those research needs that were clearly of greatest importance. It also decided that its recommendations had to be focused and specific, rather than broad and general, so that priority for attention could be assessed. As a result, this reports contains a large number of quite specific recommendations for research attention.

The Committee attempted to evaluate the relative priority of each of the research questions and needs. This priority assessment was based mainly on intrinsic scientific value (to what extent would progress in the field be advanced and how widely would the results be applicable). In addition, the Committee considered the likelihood of achieving significant results in the next decade with the support likely to be available. Relevance of the research to engineering, resources management, and environmental and societal issues were also considered but given slightly less weight. As a result, the recommendations were assigned ratings of Priority, High Priority, or Highest Priority. Only Highest-Priority or High-Priority recommendations appear in the Executive Summary.

The Committee on Glaciology and the Polar Research Board recognize that this arrangement of priorities is subjective, based on the judgment of a relatively limited number of individuals (members of the Committee and the Board as well as workshop participants, outside experts, and reviewers). It further reflects a judgment at one point in the continuous evolution of science. There was consensus on the few Highest-Priority recommendations, but the separation between Highest Priority and High Priority and between High Priority and Priority was in some instances difficult to define.

3
Research on Physical Properties of Ice

Knowledge of the basic physical properties of ice is fundamental to the solution of many problems involving snow, ice on lakes, rivers, and oceans, and grounded ice in glaciers and ice sheets. In attempting to resolve some of these problems, measurements of the pertinent physical properties should be made in both field and laboratory and at scales ranging from the molecular to the macroscopic. Individual chapters of this report treat in greater detail the importance of physical properties in the various subdisciplines of glaciology. Here we emphasize that the physical properties are a common factor linking those various subdisciplines.

Research on the physical properties of ice was one of the five "important problem areas" noted in the 1970 Survey (Committee on Polar Research 1970). The recommendations were broad: "dielectric and radiative properties of snow, ice and frozen ground need further study" and "the rheology of large ice masses needs further study."

To glaciologists, physical property measurements include a variety of studies to improve understanding of ways in which snow and ice behave in different natural settings. With recent increased interest in the engineering aspects of glaciology, the need for more comprehensive knowledge of the basic physical properties of ice and snow has become more urgent than was anticipated a decade ago. This need must be met before adequate design criteria can be established or predictive models developed.

The discussion that follows deals with four categories of physical properties: electromagnetic, mechanical, thermal, and those related to diffusion.

ELECTROMAGNETIC PROPERTIES

Because of the different nature of the problems involved in determining electromagnetic properties of snow, sea ice, freshwater ice, and glaciers, we discuss each of these separately. The principal concerns are three:

(1) The complex dielectric constant, a fundamental quantity giving the speed of wave propagation and the energy absorption coefficient;
(2) The emissivity, which determines the radiational energy ("brightness temperature") at a given physical temperature; and
(3) The (back) scattering coefficient, which determines the energy returned on illumination by an active source.

The common factor that underlies all electromagnetic properties is the interpretation of remotely sensed data; therefore, the 1970 Survey emphasized the frequency range from 1 to 100 GHz (wave lengths of 0.3-30 cm), included measurements of bulk as well as of surface properties, and pointed out the need to obtain correlative ground-truth data.

Remote sensing of snow-covered terrain and ice sheets has increased greatly over the last decade, but in many cases data are still being acquired at a rate far exceeding that of the physical property measurements (ground-truth data) needed to interpret the imagery. This situation occurs even though the 1970 Survey stated that the large mass of remotely sensed data then in existence could not be used effectively because of the lack of ground-truth data. The glaciological community should be aware of this need and should take a more aggressive approach to obtaining coordinated ground-truth and remotely sensed observations on snow and ice bodies of all kinds.

Snow

Although some measurements of the electromagnetic properties of snow have been made at a few microwave frequencies before and since the 1970 Survey, knowledge of these properties over the complete useful range of frequencies, temperatures, and structures remains scant. Scattering coefficients of seasonal snow were measured at various frequencies between 1.2 GHz and 95 GHz during the 1970s, but many of these included insufficient ground-truth measurements to allow correlation between the scattering coefficient and other properties of the snow. Extensive sets of electrical measurements combined with surface data, made between 1 and 18 GHz and at 35 GHz, showed correlation with free-water content.

Numerous measurements of emissivity have been made at spot frequencies between 5 GHz and 95 GHz. Controlled measurements with ground truth show correlations similar to those for the scattering coefficient. Correlations between satellite observations and shallow snow depths in plains areas have been reported.

Recently, numerous theoretical papers on microwave scatter and emission from snow have appeared, but the theories are incomplete and are based on simplified models for the structure of the snow mass and its surface. Furthermore, there is a lack of high-quality experimental measurements under varying conditions against which the theoretical concepts can be tested.

The effect of water content and thickness of the snowpack on its dielectric properties has practical significance, for the use of electromagnetic sensors to determine these characteristics could result in a major improvement in runoff forecasts, and consequently in the management of water resources. Knowledge of emission characteristics is important not only for seasonal snow but also for polar snow; it should be possible, with additional study, to determine surface mass balance on the polar ice sheets from the emission characteristics (see also Chapter 6). In addition, because snow surfaces reflect a major fraction of incoming solar radiation, quantitative knowledge of the factors affecting reflectivity, absorption, and scattering would contribute to improved understanding of the earth's energy budget.

Surface-based and helicopter-based active scattering and passive emission measurements, with ground-truth determinations of such quantities as temperature, density, moisture content, grain size, transmissivity, and reflectivity of the surface layers, are needed over as wide a range of environmental parameters as possible, particularly at frequencies on, or planned for, spacecraft and aircraft instruments. For seasonal snow, measurements on flat areas are important for determining fundamental relations, but measurements on slopes and in tree-covered areas are also needed. Fine-resolution probing measurements of snowpacks should be made not only to understand the scattering and emission measurements but also to ascertain the ability of a radar-sounding instrument to determine snow depth and, possibly, bottom or internal conditions relating to forecasting of avalanches and runoff. On the polar ice sheets, there is particular need for ground-truth measurements as an aid to interpreting the passive microwave data that already exist. Development of the theory of microwave scattering and emission should continue in close coordination with field measurements. More-effective field measurement methods and instruments should also be developed.

Recommendations

HIGHEST PRIORITY. Measurements should be made of scattering and emission from a wide variety of snow surfaces and should be closely coordinated with ground-truth measurements and improvements in theory.

PRIORITY. The use of a radar system to measure the total thickness and internal conditions of snow cover should be explored.

Sea Ice

Measurements of the electromagnetic properties of sea ice have generally been made over relatively limited range of frequencies. Scattering coefficients have been measured at several seasons of the year over the frequency range of 8-18 GHz and more recently during fall, spring, and early summer seasons between 4 and 8 GHz. In addition, measurements have been made at 1.5 GHz during the late winter and early spring in the Beaufort Sea. Numerous measurements were made at 13.3 GHz in the Canadian Arctic with an airborne scatterometer, but the operating range of the ground-truth parties was limited.

Many measurements of emissivity have been made from aircraft and spacecraft at a variety of frequencies since the 1970 Survey, but almost none with concomitant ground-truth measurements. Several expeditions have flown radiometers over surface parties, but even then, because of the restricted movement of the surface parties, most of the data were collected without ground truth. The use of the Nimbus-spacecraft ESMR (electronically scanning microwave radiometer) has demonstrated clearly that the extent of the polar sea ice can be mapped at 19 GHz with imaging radiometers, but the interpretations made of the differences in emissivity of the different classes of ice again lack adequate confirmation from surface measurements.

Because of the difficulty of measurement, almost no information on electromagnetic properties is available on the microwave-length scale needed for insertion into theories of volume scattering that have been developed in recent years. However, the current status of the theories is such that a much better understanding of sea-ice scatter and emission is possible today than in 1970.

Better use of remote-sensing systems to determine salinity, brine content, temperature, age, and thickness of floating ice requires further study of the effect of these characteristics on electromagnetic properties. Understanding the electromagnetic effects of grain boundaries as well as bulk electrical properties is essential for such determinations. Seasonal and geographic differences should receive special attention. The variability in the scattering signature of particular classes of ice requires further study in localized areas as well as in major regions. Further study of the correlation of the scattering coefficient with ice thickness is particularly important. More observations are needed at frequencies between 1 and 10 GHz, as several suggested spaceborne ice radars would operate in this region.

Because, to date, nearly all measurements with microwave radiometers over sea ice have been made from aircraft and spacecraft, with attendant difficulties in correlating the results with surface measurements, a top priority should be surface- or helicopter-based measurements, with concomitant ground-truth observations.

Knowledge of scattering and of emission characteristics is needed not only to interpret data obtained from remote sensing but also to establish the basic capabilities and limitations of remote-sensing techniques and to ascertain the optimal system parameters to be used in radiometer and radar systems.

Recommendations

HIGH PRIORITY. The scattering coefficient of sea ice should be determined under a wide variety of conditions, with careful attention to ground-truth measurements. Analyses should be undertaken to explore the possibility that a multiparameter radar might allow interpretations not possible with any single-parameter radar.

HIGH PRIORITY. Surface-based and helicopter-based emission measurements should be undertaken in close coordination with ground-truth studies. The effect of snow cover on the ice should receive particular attention, as studies have shown its importance in determining the scattering signature.

PRIORITY. Active and passive microwave signatures of sea ice should be monitored continuously to determine seasonal and daily changes.

PRIORITY. Active and passive microwave measurements should be made on sea ice grown in the laboratory under known conditions so that the individual effects of the many parameters involved can be determined.

PRIORITY. Theories should be modified to take into account the small-scale variability of the dielectric constant within the ice at different depths and times in the growth cycle. At the same time, improved techniques for the measurement of that small-scale variability should be developed.

Freshwater Floating Ice

Freshwater ice is much simpler than sea ice in terms of electromagnetic properties. It contains air bubbles but does not have the complex structure related to brine inclusions that characterizes sea ice and makes it so difficult to model electromagnetically. The attenuation in freshwater ice is relatively low so that electromagnetic waves penetrate it readily.

Perhaps because of this greater simplicity, microwave studies of freshwater ice have been fewer than those of snow and sea ice, and few data on basic electromagnetic properties have been reported in recent years. Some measurements have been made of the radar backscattering coefficient of shallow Arctic lakes at frequencies of 1.5 GHz and 8-18 GHz. The scattering was quite low and strongly influenced by the snow cover. Microwave radiometers have not been used to any extent over freshwater ice, presumably because of their poor areal resolution, and little information about the passive microwave response of such ice is available. Some imaging radar flights and some scatterometer flights at 13.3 GHz have been made over the St. Lawrence River, and a few backscatter measurements with a helicopterborne radar spectrometer have been reported recently.

Although remote sensing of lake and river ice can probably be done reasonable well with present systems, additional research would be useful.

Recommendation

PRIORITY. A set of imaging-radar and scatterometer measurements should be collected in winter in an area with ground-truth information and under various conditions of ice growth and temperature. The resolution required to monitor lake and river ice should be determined experimentally.

Glaciers

Studies since 1970 have confirmed that across a broad frequency range (about 1 MHz to 10^4 GHz) the real part of the dielectric constant is nearly constant and is isotropic within at least 0.5 percent. However, differences of 1 or 2 percent between metamorphic ice and ice frozen from a melt have been reported, and field measurements of electromagnetic polarization phenomena suggest anisotropy of a few tenths of a percent. A number of measurements of the absorption coefficient have yielded wide differences that are not understood. Field and laboratory studies have increasingly suggested that the well-known wide range in dc conductivity between various glaciers is the result of the metamorphic history of the ice, but these studies have not led to a quantitative theory. That minute quantities of impurities also have significant effects on the conductivity has been well demonstrated, but measurements have not yet clarified those effects.

The principal need--for better knowledge of electromagnetic properties of glaciers at frequencies above 1 GHz--is associated with the expectation of determining snow accumulation rates from microwave measurements. Although the electrical properties of ice at frequencies below 1 GHz were not mentioned in the 1970 Survey, they are important in connection with two types of geophysical applications: radar soundings of ice thickness and internal properties and resistivity studies. For the first, a knowledge of the dielectric permittivity between 1 and 1,000 MHz is needed; for the second, knowledge of the electrical conductivity and its variation with temperature and impurity content at or near dc is required.

The value of the dielectric permittivity of solid ice is fairly well determined by both laboratory and field measurements, especially at frequencies above 10 MHz. Precise measurements in the 1-10 MHz range are needed to calibrate low-frequency (monopulse) radar systems. Field measurements using the radar wide-angle technique require attention to possible internal instrumental errors resulting. Carefully controlled experiments to ensure good agreement between field and laboratory results are needed.

Field measurements suggest a significant anisotropy in the dielectric constant of a single crystal of ice, so far too slight to be measured in the laboratory. Because the determination of bulk anisotropy in glaciers is important for glacier dynamics, a better knowledge of the single-crystal anisotropy in the dielectric constant should lead to a valuable geophysical exploration tool.

Field measurements on firn yield results that are consistent with theoretical mixing relations, but there are few laboratory measurements. In regard to dielectric properties of wet ice, there are few laboratory or field measurements, although radar might provide a way to measure the water content. The mixing relations used for ice-air combinations might be applicable to mixtures involving inclusions of water in ice; they should be tested against direct measurements on temperate glaciers and wet snow fields.

Recommendations

PRIORITY. Field measurements of the dielectric constant in the frequency range from 1 to 1,000 MHz should be carried out using several different techniques and with equipment that is carefully calibrated. Whenever possible, measurements should be conducted in boreholes.

PRIORITY. A definitive determination of the anisotropy in the dielectric constant of the ice crystal should be made. To do so may require that laboratory and/or field measurement techniques be refined.

PRIORITY. Laboratory measurements should be conducted on the permittivity of snow, firn, and ice-water mixtures.

Although the large differences between the conductivities and activation energies of polar glaciers, temperate glaciers, and laboratory ice and the variability within each type of ice are well known, the cause is uncertain: Are the differences attributable to impurities in the ice, the glacial metamorphic process, or some other factor? Furthermore, there are few measurements on snow and firn. Determination of conductivities and activation energies on firn and ice are necessary for effective interpretation of resistivity soundings on glaciers and ice sheets.

Recommendation

PRIORITY. Field and laboratory measurements of the dc conductivity of snow, firn, and ice as a function of impurity content, metamorphic history, and temperature should be conducted.

MECHANICAL PROPERTIES

Ice

Rheological properties involve the rate of deformation in response to an applied stress. It is generally accepted that on application of a constant stress, solid ice will deform, at first rapidly and then at a decelerating rate, until a minimum creep rate is reached. Thereafter, recrystallization leads to an increase in creep rate. It seems likely that eventually a constant strain rate will be attained, although the experimental techniques needed to test this hypothesis have not been developed. Conversely, on application of a constant strain rate, the stress rises to a maximum value and then decreases, possibly to an eventual constant value at very large strains.

It has been suggested that the ratio of stress to minimum strain rate (from a constant stress experiment) should correspond to the ratio of maximum stress to strain rate (constant strain rate experiment); a similar correspondence between other stress/strain ratios may be established. Such information could be of use to glaciologists, whose main concern is with strain rate at constant stress, and engineers, who are more concerned with the maximum stress (or peak strength) for a given strain rate. A recent review of the state of the art of ice rheology has been published (Hooke et al. 1980).

Some progress has been made in evaluating the temperature dependence of the creep of ice near its melting point and in assessing the effect of impurities. However, conflicting results have been obtained on the effect of grain size on creep of ice, and a better understanding of the role of texture, fabric, and other structural parameters of creep is needed. This need is especially great in regard to structural changes that occur during the primary, secondary, and tertiary stages of creep of ice. A similar situation exists with respect to in situ measurements of stress and strain rate in boreholes, made in conjunction with structural studies on core samples. In particular, recent studies have suggested substantial discrepancies between laboratory and field measurements due perhaps to scale effects, incorrect estimates of in situ stresses in the field, or inadequacy of constitutive equations based on a von Mises (or Tresca) yield criterion.

The basic studies need to be extended to determine how properties vary with ice structure and impurity content. Data are needed on the variation in the values of minimum strain rate and maximum stress with fabric, texture, impurity and brine content, confining pressure, and temperature (particularly close to the melting point). Of particular importance are studies to establish the point of minimum strain at low stresses, systematic tests that go to large strains and give data on constant strain rate and constant stress, and high-quality strength tests at high rates, using apparatus that is capable of tracking complete stress-strain curves. Also of special concern is the critical comparison of laboratory and field measurements. In addition to the common types of tests using compression and tension, studies of ice deformation in bending and shear should be conducted. Test conditions extending to very low temperatures and/or very high pressures will be especially useful to the study of the icy planets and satellites of the solar system.

Measurements are needed not only on polycrystalline ice but also on single crystals, so that theories of dislocation multiplication can be tested using crystals of known dislocation density. Investigations of nonbasal slip systems, including measurements of the activation energy, would provide an indication of the deformation mechanisms involved in creep.

Recommendation

HIGHEST PRIORITY. Laboratory measurements on the deformation of polycrystalline and monocrystalline ice samples of widely varying physical and chemical characteristics should be conducted over a broad range of stresses and strains.

Frazil Ice

The importance of frazil ice, which consists of individual ice discs or aggregated floes and pans, is discussed in Chapter 5. Frazil (frazil ice) is the product of nucleation of ice crystals in a turbulent water column, and the bulk physical properties of aggregated frazil are known to differ appreciably from those of ice formed in quiescent water. Large productions of frazil can halt navigation on rivers, even block their flow, plug freshwater or seawater intakes, and cause the formation of anomalously thick river ice.

The frazil ice content of sea ice affects heat exchange through the ice cover. Recent studies show that Weddell Sea pack ice in Antarctica, for example, is composed of up to 50 percent frazil ice and that Arctic multiyear ice contains much more frazil ice than previously expected. Recently, the role of frazil ice in the redistribution of fine sediment in both the seawater and freshwater has been recognized. Thus understanding of the formation, growth, and behavior of frazil ice is essential to understanding the growth and characteristics of floating ice covers. But such understanding is not far advanced. The precise mechanisms by which frazil ice is formed are not known; basic questions about the growth rate of individual frazil crystals in supercooled water, especially the effects of variations in turbulence and salinity, have yet to be answered. Virtually no data are available on the mechanical properties of frazil ice during its morphological changes. These properties evolve during the different stages in the growth and formation of frazil ice from frazil-laden flow, when a viscous or Newtonian model might be appropriate, to frazil-ice pans or floes, in which a viscoelastic model may be more suitable, to bonded frazil-ice lattice structures, for which a viscoplastic model may be required, and, finally, to warmed or decaying frazil-ice covers. This information is critical for studies of ice jams, conveyance capacities of rivers, navigation in Arctic waters, hydroelectric development, and other problems. Both experimental studies and theoretical modeling are needed.

Recommendation

HIGHEST PRIORITY. A major emphasis in research on floating ice should be the formation, growth, and behavior of frazil ice, especially under field conditions, including:

1. The nucleation mechanisms of frazil-ice formation;
2. The growth rates of individual frazil-ice crystals in supercooled water;
3. The mechanical properties of frazil ice during the different stages of its growth and formation; and
4. Crystallographic analysis of frazil-ice cores to discern sediment entrapment, expulsion, and transport processes.

Snow

The basic mechanical behavior of snow has defied systematic analysis because of the wide variety of types of snow and the rapid transformations of snow from one type to another. Accordingly, much work on the basic mechanical parameters (e.g., strength, deviatoric properties, and compressibility) is still needed, with emphasis on such research problems as the propagation of shock waves and the relationships between observed behavior and grain size. The effect of water content is particularly important because of the almost complete absence of any information on the strength of wet snow. Investigations of the creep of snow are also needed to improve understanding of avalanche release and snow pressure buildup on structures. Advances in the solution of these problems will require both laboratory and theoretical work.

Past research has generally utilized continuum theories to characterize the mechanical properties of snow. Concepts of viscoelasticity or viscoplasticity were used to determine empirically the deformational properties of snow without regard to the microstructural properties (grain size, bond diameter, bond density, etc.). As a result, most of this work has not been successful in characterizing mechanical properties as a function of density or type of snow. New research should be directed toward formulating continuum theories that incorporate the microstructure. In this way, more accurate determinations of the mechanical properties of snow can be combined with constitutive equations that may be used in engineering problems.

Recommendations

HIGHEST PRIORITY. The dependence of the strength and creep of snow on properties such as grain size, shape, bond diameter, density, and, in particular, liquid-water content should be measured in the field and in the laboratory, and the results used to develop and test continuum and microstructural creep models.

PRIORITY. Continuum mechanical theories of the properties of snow that incorporate grain structure theories should be formulated.

Other Problems

Icing of such diverse structures as space shuttles, propeller blades, wires, power lines, and piles is a continuing problem that substantially increases construction and maintenance costs. Adhesion of ice to surfaces may involve both physical (surface roughness) effects and molecular effects. Better understanding of this process may aid in devising solutions.

Recommendation

PRIORITY. The physics of ice adhesion should be further developed, and techniques for reducing or preventing icing on a variety of structures should be systematically tested.

Fracture toughness is a physical parameter that determines the condition for catastrophic crack propagation in a solid. Available experimental measurements of the value of the fracture toughness of ice vary over an order of magnitude. Furthermore, different experiments have shown opposite signs for the variation of the fracture toughness with temperature.

Recommendation

PRIORITY. Detailed studies of the processes that occur on grain boundaries, including the effect of temperature on the thickness of the boundary layer of a grain, should be conducted.

Sonic velocity measurements in boreholes and on ice cores provide a rapid measure of quantities that are functions of the mechanical properties of the ice. The crystalline fabric is particularly important, but textural variations and bubble content may also play a significant part that is not yet understood. Because the internal physical characteristics of glaciers affect their dynamic behavior (see Chapter 6), a better basis for the interpretation of sonic velocities is needed.

Recommendation

PRIORITY. Sonic velocity measurements should be made on polycrystalline ice samples of known fabric and texture. To avoid boundary effects, samples should have diameters at least 10 times the mean grain diameter.

THERMAL PROPERTIES

The thermal properties of isothermal ice, including the conductivity, heat capacity, and coefficient of expansion are reasonably well known. However, there is a temperature gradient in natural floating ice that affects the bulk thermal expansion, thus the forces exerted on structures. Thermal contraction, leading to cracks in floating ice, is also altered by a temperature gradient. A better understanding of these processes and other phenomena related to thermal properties would have many practical applications.

Recommendation

PRIORITY. Studies should be made of the effect of a temperature gradient on the stresses exerted on structures due to thermal expansion and on the formation of cracks in ice during thermal contraction. The effect of temperature and density on thermal diffusivity should also be measured.

DIFFUSION AND FORMATION OF CLATHRATE HYDRATES

Two aspects of diffusion in ice deserve attention. One is the effect of pressure on self-diffusion, as this effect will establish the activation volume for ice, which can be compared with experimental data suggesting that the hydrostatic pressure has a negligible effect on creep. The second is the diffusion of gases into ice, particularly as all air bubbles in ice sheets disappear below a certain, variable depth (Byrd Station, Antarctica: 1,100 m; Vostok, Antarctica: 1,300 m; Dye 3, Greenland: 1,600 m). It has been suggested that a gas hydrate or clathrate is formed, and recent study of the Dye 3 ice cores appears to confirm this suggestion. Of particular paleoclimatic significance are the diffusion of CO_2 in ice and the effect on the relationship between the CO_2 concentrations in the ancient atmospheres and in the bubbles in the ice.

In snow, a better understanding of the diffusion of water vapor and the formation of depth hoar is needed. This process leads to zones of structural weakness resulting in high pressures on structures on snow-covered slopes and, if failure occurs, in avalanching.

Recommendations

HIGH PRIORITY. Studies should be conducted on the diffusion of gases in ice, with particular emphasis on the diffusion rates for different gases and on determining whether these gases enter the ice lattice as clathrate hydrates.

PRIORITY. Measurements of the effect of pressure on self-diffusion should be made to provide a good determination of the activation volume for ice.

PRIORITY. To understand the formation of depth hoar, measurements of the diffusion of water in snow and of the physics of crystal growth from the vapor phase should be undertaken.

PRIORITY. Accurate descriptions of snowpack processes should be developed, including:

1. Crystal growth, sintering, and metamorphism in wet and dry snow layers;
2. Development of improved techniques for measuring the liquid water content of snow; and
3. Incorporation of microstructure into theoretical modeling of snow mechanics.

4
Research on Seasonal Snow

Although research on perennial snow and seasonal snow have much in common, such as studies of the wind transport of snow, processes of snow metamorphism, and electromagnetic characteristics important for remote sensing, perennial snow can best be considered together with the glaciers, of which it forms an essential and integral part (see Chapter 6).

Seasonal snow is significant on both local and global scales. It affects local winter transportation, impeding traffic and visibility or fostering the use of alternatives to modes of transportation employed in warmer seasons. It also affects structures, damaging buildings by pressure or decreasing winter heat loss (through fortuitous or planned engineering). In addition, it affects local hydrology through the destruction caused by snowmelt flooding. Furthermore, knowledge of snowpack mass is used to optimize the operation of water reservoirs for hydroelectric power or irrigation. Because the germination of food crops depends on the early availability of soil moisture, seasonal snow has an impact on agriculture. As a threat to life and property through avalanches or as a medium for travel by ski or snowmobile, it affects recreation. Finally, it constitutes a seasonal interface between sea ice and the atmosphere.

The global importance of seasonal snow may be less obvious than the local effects but is equally great. Its high reflectivity, together with its rapid changes over large areas, make it vital to the earth's surface-radiation balance, and thus to global climate.

The hazards snow poses are among its principal impacts on society. The most obvious of these hazards are avalanches. As winter activity in the "back country" in the United States increases, the potential for injury and death from avalanches also increases. In the 1950s, the average number of deaths was 4 per winter; by the mid-1970s the number was 18. Such statistics demonstrate the need for data collection as a basis for an expanded avalanche-forecast network and the need to educate the public about the hazards of avalanches.

Less obvious hazards related to snow include its effect on highways and airport runways, roof deterioration and collapse, and snowmelt floods. Improved knowledge of snow characteristics is necessary to diminish these hazards. For example, forecasting of snowmelt floods could be made more efficient, timely, and precise if the relationship between processes of energy balance at the snow surface and larger-scale atmospheric conditions were well established. This need cannot be met until the complex processes of energy exchange at the snow surface are better understood.

Snowmelt floods usually peak slowly, providing time for both activating flood-control measures and warning those in jeopardy. Such is not the case in the disastrous snowmelt floods and mudflows that volcanoes can trigger; for example, those resulting from Mt. St. Helens eruptions and those from Ruapehu Volcano in New Zealand, in which 150 people were killed in 1953. The impacts of snow on society depend on scale, as do the problems and goals of snow research. The smallest scale involves laboratory investigations of the physical and chemical processes at the level of individual grains. These phenomena are important because snow is a finely divided material at or close to its melting point; therefore, all its properties change rapidly with minor changes in weather. On a scale of 1-100 m, the details of snow transport, stratigraphy, and distribution should be investigated in situ, as these characteristics affect water-flow patterns, estimates of the accumulation or melt of snow on the ground, and avalanche potential. On larger scales, the areal coverage and conditions of the surface of the snow cover need to be known promptly so that the relationship of snow to weather and climate can be determined; therefore, remote sensing is required, with support from additional field and laboratory investigations.

The 1970 Survey identified needed research on snow, and many of its recommendations were implemented. The report mentioned a "flavor of empiricism" characterizing snow research at that time; in 1976, the Working Group on Snow and Ice Hydrology of the U.S. National Committee for the International Hydrological Decade (1976) also emphasized the lack of fundamental understanding. Recent research has been directed toward achieving a more fundamental knowledge of snow as a material. The possibility of using electromagnetic sensors to determine its water equivalent has sparked interest in electrical properties, and the importance of snow in the earth's energy budget has provided motivation for work on its optical properties. The movement of liquid water through snow has received much theoretical and field study.

During recent decades, satellite mapping of snow cover has progressed. Operational snow-cover charts of the Northern Hemisphere are released once a week by the National Oceanic and Atmospheric Administration (NOAA) and by the Air Force Global Weather Central. Although the charts have improved in the last few years, they still have flaws. The extent, areal density, and relative reflectivity of snow are shown with little spatial or temporal accuracy. Substantial improvement is needed.

In spite of progress in some areas of snow research since 1970, much work remains, partly because of growing recognition of the importance of snow cover. For example, increasing demand for water resources requires better understanding of snow accumulation and meltwater runoff. The crucial role of areal snow cover in the earth's albedo is another major concern.

In the sections that follow, organized according to the scale of the problems, we outline major research needs related to snow.

GLOBAL/HEMISPHERIC SCALE: SNOW AND WORLD CLIMATE

The interplay between low-latitude heat income and high-latitude heat loss drives the world climate systems. Heat loss in high and middle latitudes is strongly influenced by the distribution of snow (see Committee on the Role of the Polar Regions in Climatic Change, in press; Climate Research Committee, Climate and Atmospheric Sciences Board, in press). The areal extent of snow varies more rapidly than that of any other widely distributed material on earth. In the Northern Hemisphere, the monthly mean area covered by snow on land ranges from 11 to 60 x 10^6 km^2, or from

7 to 40 percent of the land area. Snow reflects about 80 percent of the sun's radiation, whereas soil and sea water absorb 80 percent or more, so the amount of land (and sea ice) covered by snow is critically important to the earth's radiation balance, thus to the global climate system. In the Southern Hemisphere, there is less land area and a great seasonal variation in the extent of sea ice, thus sea ice has a similar effect on global climate. Although sea ice has been emphasized in analyses of the effect of snow and ice on global climate, the equally important effect of seasonal snow cover on land is only now being recognized, and knowledge of it is less advanced.

Small changes in atmospheric temperature or precipitation can trigger a large change in the global energy budget through the continually changing areal snow cover. Because of the snow-atmosphere feedbacks, the interaction between the seasonal snow cover and the global energy balance should receive highest priority in research. One of the key parameters is the surface radiation balance. Changes in radiation balance are extreme when the snow cover is first established and when it disappears. The balance varies with latitude and with the thickness and persistence of snow cover. For example, in latitudes above 65°, the rapid vernal increase in solar radiation coincides with the rapid melting of shallow snowpacks to produce extreme changes in the surface radiation balance over periods of about 10 days.

The direct effect of snow on the earth's radiation balance is sometimes modified by fog or low clouds formed over the cold snow surface. This self-regulating process needs to be better understood so that it can be incorporated in climatic models.

Snow cools and dries the atmosphere above it. High-pressure cells form in the snowbelts, leading to blocking ridges and to anticyclonic outbreaks exporting the cold dry air to middle latitudes. Although not yet sufficiently studied, the role of snow in winter climate dynamics appears to be critical.

The response of seasonal snow covers to increasing atmospheric CO_2 is a current urgent concern. Atmospheric general-circulation models suggest that the extent of snow, especially at high latitudes, should shrink because of increasing surface air temperature resulting from increased atmospheric CO_2. If such a process is occurring, we need to know about it, to devise means of monitoring it, and to determine whether the impact of CO_2 on snow can be discriminated from unrelated perturbations affecting the atmosphere at high latutudes.

To assess the effect of seasonal snow on climate, and thereby to improve medium- and long-range weather forecasts, we need accurate data on the extent, density, thickness, and optical properties of snow cover. Although such data are easy to gather at some locations, data collection is insufficient. Only certain meteorological stations report the presence and thickness of snow on the ground on a daily basis; fewer give the water equivalent, and none gives data on the surface characteristics and texture of snow. Information on snow cover is not included in weather maps, nor, with few exceptions, in the international exchange system of the World Meteorological Organization (WMO). The number of stations reporting snow thickness on a daily basis should be expanded; data on other snow parameters should also be reported; and an efficient worldwide distribution of data on snow cover should be maintained.

Some atmospheric general-circulation models require data on snow (or reflectivity); other models calculate the extent of the changing snow cover and require data on snow for calibration or validation. Ground measurements alone are unlikely to provide sufficient data for model development or validation. Satellite remote sensing is clearly needed, which, in turn, requires an understanding of the electromagnetic properties of snow.

Since 1970, a better understanding of the optical properties of snow, including reflectance, has been achieved, but there are two major needs: high-quality experimental measurements against which to test theoretical concepts and sufficient spectral reflectance data combined with simultaneous measurement of the physical properties of snow. For example, liquid-water content has a significant effect on the grain configuration in wet snow, so the optical properties should be affected, but few investigations of the optical properties as a function of liquid content have been made.

The most important question related to optical properties is their values at the snow surface, where the heat balance is often controlled by the amount of solar radiation absorbed. The reflectance of snow is largely a surface phenomenon, and the surface is likely to have a different grain configuration from the bulk of the snow cover because of the strong radiation environment on the surface. The large grain clusters observed in wet snow, for example, are likely to melt along grain boundaries and break into smaller units; therefore, the grain size, grain shape, and arrangement of the liquid at the surface require careful investigation.

Although the surface reflectance of snow at optical or infrared frequencies must be known to relate snow to climate, satellite sensors can never provide these data in a truly synoptic way: both kinds of radiation are stopped by clouds, and optical reflectance cannot be observed at night. A synoptic snow-observing system must operate at lower frequencies. Satellites now in orbit carry a variety of microwave sensors of potential value for synoptic measurements of snow cover, yet the ability to monitor snow extent rapidly over large areas is lacking. Nor is is possible to monitor snow thickness, density, or liquid-water content, which are even more important, because basic understanding is insufficient to interpret the signals from advanced sensors.

Because microwave frequencies penetrate the thickness of typical snowpacks and can penetrate cloud layers, microwave remote sensing might possibly be used to gather synoptic information about the water equivalent and liquid-water content of snow cover over large areas. Radar systems have not been tested so far for spaceborne measurements of snow cover, because suitable systems have not yet been flown in space, but passive (thermal emission) microwave sensing does respond to snow properties. However, this response is complicated and not yet fully understood. Before such a system can be effectively employed, the complex dielectric constant of snow must be known for various snow types and liquid-water contents. The complicated shapes of the liquid and ice inclusions in snow make this a difficult problem, as does the hypothesized liquid-like surface layer with a dielectric constant between that of ice and water. In addition, the process of volume scattering of radiation within a snow mass must be understood, as volume scattering has a dominant impact on the release of microwave thermal emission.

Recommendation

HIGHEST PRIORITY. Improved understanding of snow as an element in the global climate system should be sought through:

1. Development of remote-sensing methods for the large-scale, all-weather determination of the water equivalent of snow, field measurements to confirm remotely sensed results, and determination of the electromagnetic transmission and scattering properties of snow (see Chapter 3);

2. Definition of the temporal and spatial variations of regional and hemispheric snow extent and albedo and their relationship to weather; and

3. The use of global snow data in the development and validation of atmospheric circulation models and in predicting the effects of a CO_2-induced increase in air temperature.

REGIONAL AND DRAINAGE-BASIN SCALE: SNOW AS A WATER RESOURCE

Competing uses for snowmelt runoff emphasize the need for better forecasting, which in turn requires better techniques for large-scale inventories of snow. Measuring the areal extent, water equivalent, and liquid-water content of the snow cover by satellite is a possibility, but currently only areal extent under cloudless sky can be measured. There are many problems with the discrimination of cloud cover and snow. To use passive microwave systems for measurements through clouds and for detecting more than just areal extent requires not only improved understanding of the dielectric and scattering properties of snow (as described in the previous section) but also, for hydrological applications, high-resolution microwave images, which are unlikely to be possible in the next decade.

An exciting possibility is the determination of the areal extent of snow cover with high resolution on an operational basis by using a sensor of 1.55-μ wavelength to distinguish snow from cloud. Such a satellite system would permit routine observation of snow extent at drainage-basin scale, assuming that the whole scene was not cloud covered; the resulting data would be of immediate use to forecasters and essential to achieving a better understanding of climatic changes. In preparation for such a system, a substantial data base should be developed on the variability of areal extent and snow thickness. Although some work has been done on the local variability of the snow cover, the effects of altitude, aspect, and vegetation should be studied as well as the effects of these surface elements on the remote sensing of the snow cover.

Snow occurs in many different forms that change rapidly in response to changes in local climatic conditions. Although each climatic province will have a wide variety of snow types, and each of these will change during the season, the predominant snow type will differ significantly from one province to another. The distinction between snow types of provinces is important to hydrological modeling or forecasting because the characteristics of snowmelt runoff depend on the properties of the snowpack. The prevailing snow types within each province should be characterized in terms of properties such as grain type and size, hardness, density, layering, and depth. The prevailing conditions that determine those properties, such as snow residence time, humidity, temperature gradient, basal and surface temperature, wind conditions, and climatic variability, should be determined to show the relationship of prevailing conditions to snow characteristics.

We offer a few examples to illustrate the concept of snow provinces: the maritime mountain snow of the Sierras and Cascade Ranges--dense, thick, wet, and persisting; the interior mountain snow of the Rocky Mountains--light and powdery, cold, strongly affected by avalanches and winds; the continental interior snow of the high plains--thin, patchy, and concentrated by wind into gullies and drifts and around vegetation. Alaska contains two sharply defined climatic boundaries that place three major climatic zones in proximity, and each zone has its own characteristic snow cover: tundra snow, north of the Brooks Range; taiga snow, in the continental interior between the Brooks Range and the Coastal Ranges; and maritime snow, on the coastal mountains.

A high priority for research is a systematic summary of the physical properties of snowpacks in the major snow provinces. The physical properties of the snow, and the processes active in it, should be defined in terms of such variables as the time span during which snow exists, snow thickness, latitude, temperature gradients, and wind action.

Snow has long been recognized as a water resource; its importance increases with increasing demand for snowmelt runoff. Improved runoff forecasting faces many difficulties. The problem of assessing the amount of snow on the ground has been mentioned; but there are many other problems, because many phenomena affect snowmelt runoff, including processes of water flow, details of snow stratigraphy, and variations in the distribution and properties of snow with different elevations. One major factor is that snow-soil horizons behave as coupled two-layer systems with a complicated interaction. The snow is an effective insulator that reduces frost penetration in soil; the soil cannot accept much water during the melt season if it is frozen. Studies of snow and soil as a coupled system have just begun. In addition, little is known about the areal energy exchange with an advected warm air mass, although much work has been done on the detailed energy exchange at the snow surface.

The movement of airborne impurities over great distances is a cause of "acid precipitation," an environmental problem that is resulting in international concern and controversy. The problem is magnified in the snow cover because the soluble impurities are largely leached by the first fraction of meltwater. The processes responsible for this sudden release of acid runoff should be investigated in light of problems caused by the sudden lowering of pH in streams and lakes.

Orographic precipitation models now available for several areas of the western mountains should make possible mesoscale prediction of variations of snow cover. Such models should be developed for all western mountain areas. Accurate prediction of snow cover in mountainous areas would have far-reaching implications not only for water yield but also for winter safety, transportation, mining activities, and winter sports. Better near-surface wind-flow models for mountainous areas would be useful in determining local snow-cover conditions.

The use of present hydrological forecasting models offers many benefits. The seasonal forecasts of meltwater supply and daily forecasts of snowmelt floods provide needed information for geographic regions. However, current methods of forecasting must be based on more comprehensive physical data before full use of the increasing supply of information on the characteristics and extent of the snow cover will be possible. The development of better models should occur simultaneously with the development of better remote-sensing techniques and associated field work.

Recommendation

HIGHEST PRIORITY. The physical bases for forecasting snowmelt runoff, soil-water reserve, and basin storage should be developed. Research may require different approaches and emphases in each snow province and should include:

1. Meteorological and topographical controls on the deposition of snow at the mesoscale, with attention to the altitude distribution of snow in the mountains and snow albedo at less than global scale;
2. Liquid and vapor transfer across the snow-soil interface; and
3. Impurities in the snowpack, their discharge into runoff, and management of the problem. Acid impurities should receive special attention.

LOCAL TO MESOSCALE

The seasonal snow accumulation tends to vary among provinces annually, thus presenting problems ranging from drought to roof failures. Years of excessive snowfall result in transportation delays, large snowmelt floods, power-line failure, collapse of buildings, and property loss from avalanches. Years of little snowfall result in groundwater depletion, diminished surface-water supply, lack of soil-frost protection for agriculture, and massive losses in the winter recreational industry. Although little can be done to change the total amount of precipitation, much can be done to manage the snowfall.

Windblown Snow

An outstanding example of snow management is the control of drifting snow around highways, airstrips, buildings, and wind turbines by effective design of facilities and snow fencing techniques. These methods have been effective in keeping snow out of selected areas, especially highways across Wyoming and Colorado. However, the complex physical processes involved in the transportation and deposition of snow have not been sufficiently studied; for example, physical methods of predicting snow deposition profiles are completely inadequate in all but the simplest ground terrains, such as an infinite flat surface. Theoretical methods for predicting snow deposition should be developed. New techniques will be needed: multiphase theory (or mixture theory) might be used to characterize the transport of snow through the atmosphere to the surface of the snowpack. New theories of particle adhesion and turbulent boundary layers might also be used to determine the rate of transport to the surface, the rate of loss by sublimation in transport, and the rate of deposition. Where the terrain is complicated (over highways, around buildings, and in mountainous terrain), computer-based numerical methods may be needed.

In addition to developing theoretical models of snow transport and deposition, more field data on the flux of windborne snow will be required. Advances in monitoring equipment have occurred since 1970, and particle size can be measured now. However, more effort should be directed to acquiring the necessary data for good theoretical models of wind transport.

Although blowing snow on the Arctic Slope of Alaska affects all operations there for three fourths of the year, little is known about this snow. Some models and measuring techniques developed in Wyoming have been applied on the Arctic Slope; for example, use of the Wyoming Fence to shield precipitation gauges showed that U.S. Weather Service records for snowfall on the Arctic Slope were erroneously low by a factor of three.

Determinations of the total amount of snow transported by the two primary wind directions have also improved.

The Arctic Slope of Alaska is a good site for research, for the petroleum industry needs the data and the basic relationships estblished there could be applied elsewhere. Furthermore, Arctic research should be coordinated with that in progress in Wyoming and Colorado under the U.S. Forest Service and the findings from the two regions compared. Obvious next steps would be comparison with studies of blowing snow in Greenland and in the Antarctic.

A better understanding of blowing snow mechanisms is also needed in connection with proposed engineering projects involving large snow drifts (on the order of 10^6 Mg). These large drifts could supplement irrigation resources, complement artificial snow equipment in ski areas, and provide building materials for roads and airstrips and pads for drill rigs.

Recommendations

PRIORITY. Improved techniques for forecasting and managing blowing snow should be developed, including:

1. Improved instrumentation for monitoring precipitation during strong wind transport and in adverse environments and

2. Improved models of the flux, sublimation, and deposition of blowing snow in a variety of topographical and climatological configurations.

PRIORITY. The following research should be undertaken on blowing snow on the Arctic Slope of Alaska:

1. Determine the total precipitation and the amount that falls as snow;

2. Determine the amount of snow remaining on the tundra after some has blown away and concentrated in draft traps;

3. Determine the flux of windblown snow from each of the primary winds that move snow (a task that includes determining what fraction of this flux is lost by sublimation during

transport and what fraction is stored as drifted snow);

4. Determine correction factors for application to long-term records of winter snow and summer rain.

Avalanches

As development and winter sports increase in the western United States and Canada, so, too, do the hazards posed by avalanches. Avalanches are a threat to participants in winter sports, to mountain transportation systems, and to mountain homes and industries. Small avalanches account for most of the accidents to individuals; larger and less frequent avalanches do the greatest damage to property and present the greatest threat of catastrophic loss. Slush flows are a significant hazard in the higher parts of the Brooks Range in northern Alaska. Weather, snow cover, and terrain features are important for the prediction of the smaller and more frequent avalanches. Long-term records of avalanche size and occurrence are needed to evaluate the potential for the less frequent, larger avalanche.

Current techniques for predicting the occurrence and extent of avalanches are based largely on empirical relationships. Forecasting has been primarily a subjective process carried out by experienced persons for local areas. Recently, these techniques have been expanded and modified to permit avalanche warnings on a regional basis; however, improved models are needed to integrate weather, snow, terrain features, and past avalanche occurrences into determinations of relative avalanche hazard. Such an evaluation procedure depends highly on accurate mountain weather forecasts (precipitation, wind, and snow transport), current data on changes in snow strength, and better information on snow failure.

The failure criteria for snow on steep slopes and the dynamics of avalanche motion are extremely complex phenomena for which we have only empirical approximations. As both are critical for the accurate prediction of the occurrence and the extent of avalanches, better theoretical understanding is much needed. The snow cover on steep natural terrain is subject to the vagaries of the weather during and following deposition and to the nonuniform stresses created by uneven deposition and irregular terrain features. These conditions result in stress concentrations that are thought to be the sites of initial failure. Sometimes such local failures do not propagate; at other times they propagate rapidly and invade areas of snow too stable for failure initiation.

Means of determining the degree of stability of snow and the location of stress concentration points in avalanche- starting zones would be of great practical value. Once in motion, avalanches can move as sliding blocks with little relative motion, or they can move in highly turbulent motion like that of a heavy gas. A better theoretical understanding of avalanche dynamics would lead to more realistic modeling of avalanche motion and better estimates of runout distances and impact forces. Both are important for accurate avalanche zoning and control.

Recommendations

PRIORITY: A better understanding of avalanche dynamics is needed, including the mechanisms of release, flow, and impact. Especially needed as a basis for theoretical and modeling studies are field measurements of avalanche speed, runout distance, mass distribution, and impact forces.

PRIORITY: Improved techniques for avalanche forcasting and control should be developed, especially in regard to incorporating snowpack and meteorological parameters in forecast models, and innovative and more efficient techniques of avalanche control are needed.

SMALL SCALE: BASIC PROCESSES

To understand such problems as microwave emission, snowpack melting, and avalanche release requires knowledge of snow processes at smaller scales, down to basic crystal structure. Processes in snow tend to be more complex than those in most other engineering or solid-earth materials, for snow is thermodynamically active over comparatively short intervals of time.

Because natural snow is near its melting point, its phases change constantly. Both its continuum properties (density, temperature, stress distributions) and microscale properties (crystal morphology, crystal bonding) change in response to small variations in the environment.

Individual snowflakes nucleate in the atmosphere and fall to earth, where they immediately begin a temperature- and pressure-dependent metamorphosis. Normally, the original crystal morphology cannot be recognized after the snow has spent a few hours or days on the ground. Crystals begin joining to each other through sintering, a process that involves molecular transport of water to concavities between individual grains. Although this process has been studied in considerable detail for other materials, it is not well understood within the snowpack, yet to a large extent it determines snowpack strength; hence, it directly influences avalanche release, travel over snow, snow removal, and related problems. Also, larger crystals grow at the expense of smaller crystals as the ice skeleton evolves toward minimum surface area (lowest surface-free energy); temperature-controlled vapor-pressure gradients move molecules through the pore spaces from warmer to colder regions. Recent findings show that heat conduction through the solid ice itself is also important. A comprehensive explanation of snow crystal metamorphism on the ground has yet to be developed--a remarkable gap in knowledge considering the abundance of snow over much of the globe.

The study of snow processes becomes most complicated when liquid water is present. Even today, there is no satisfactory method of measuring the amount of water in a given snow sample. Different methods for determining the proportion of the three phases (ice, water, and air) unfortunately lead to significantly different results. Accuracy and reliability of these measurements are not well defined. Interpretation of larger-scale measures of the snowpack (e.g., using microwave radiometry) will eventually require some standard of calibration at the smaller scale.

The basic mechanical behavior of snow has defied systematic analysis because of the wide variety of snow types and the rapid transformations between them. Accordingly, much work on the basic mechanical parameters (e.g., strength, deviatoric properties, and compressibility) is still needed, with emphasis on relating observed behavior to grain scale parameters. Advances will require sophisticated laboratory and theoretical work.

Past research on the mechanical properties generally made use of continuum theories to characterize snow. Concepts of viscoelasticity or viscoplasticity were employed to determine empirically the deformational properties of snow without regard to the microstructural properties. As a result, much of this previous work was not successful in characterizing mechanical properties as a function of density or type of snow, especially for snow of density less than about 400 kg/m^3. There is need for continuum theories that incorporate the microstructural composition of the material, thus making possible a more accurate determination of the mechanical properties of snow. With the incorporation of such data in continuum theory, the resulting constitutive equations would be applicable to engineering problems.

Recommendation

PRIORITY. Accurate physical descriptions and numerical models of snowpack processes should be developed, including crystal growth, sintering, and metamorphism in wet and dry snow layers. Techniques for measuring the liquid water content of snow should be improved, and microstructure should be incorporated into snow mechanics.

5
Research on Floating Ice

This chapter deals with the scientific investigation of problems related to sea, river, and lake ice and icebergs; floating ice shelves and floating glaciers are discussed in Chapter 6. Only recently has the broad range of problems associated with floating ice begun to receive attention in national research planning. Since publication of the 1970 Survey, increased fundamental and applied research on sea ice was stimulated, first, through the Arctic Ice Dynamics Joint Experiment (AIDJEX) and, second, through the realization that sea ice is a critical factor in global climate variability and in the extraction and safe transportation of oil and gas resources in polar regions. Resource exploration and development have also led to greater awareness of problems of river and lake ice. In addition, a series of cold winters in the northern areas of the United States has drawn attention to such problems.

Studies of floating ice in relation to climatic variability and offshore petroleum production are currently high among national polar research priorities; numerous other fundamental and applied problems require attention. Some examples of the principal problems for research are:

- Ice and climate interactions
- Ice hazards to structures and transportation
- Ice forecasting
- Dispersion and containment of pollutant spills
- Position of the ice margin and its relation to atmosphere, ocean, and marine ecosystems
- Frazil-ice entrainment and deposition
- Motion and deformation of sea ice

Prediction of ice jams and their alleviation in rivers
Mechanics of shear and pressure-ridge formation
Detection of icebergs and prediction of iceberg trajectories

The diversity and complexity of floating-ice problems require multifaceted research efforts.

Previous reviews (Panel on Glaciology 1967; Committee on Polar Research 1970) noted that sea-ice energy balance and dynamics were the major problems in glaciology and deserved highest-priority attention. A principal reason for assigning high priority to this field was the pivotal role of sea ice in the interaction between oceanic and atmospheric circulation, and thus on climate at high latitudes. Sea ice is still viewed as a vital component of the world climate system (Committee on the Role of the Polar Regions in Climatic Change, in press).

Although some of the recommendations on the energy balance and dynamics of sea ice have already been implemented, the reasons for research on sea ice have become broader and more urgent. For instance, active exploration and anticipated development and transport of oil, gas, and other resources from the Arctic Ocean basin present a new range of sea-ice research needs (Panel on Polar Ocean Engineering, Marine Board 1979; Committee on the Arctic Oil and Gas Reserves 1981; Committee on Arctic Seafloor Engineering, Marine Board 1982). The extraordinary marine biological productivity associated with seasonal sea ice in the Southern Ocean (Committee to Evaluate Antarctic Marine Ecosystem Research 1981) and in Arctic areas such as the Bering Sea is also attracting international attention and major research efforts.

Since publication of the 1970 Survey (Committee on Polar Research 1970), a number of national and international organizations have examined programs and needs in research on sea ice. In particular, sea ice/climate interrelations have been discussed in, for example, Joint PRB GARP/CAS/OSB Polar Experiment (POLEX) Panel (1974, 1976); WMO-International Council of Scientific Unions (ICSU) (1975, 1978); WMO (1977, 1982); United Nations Educational, Scientific, and Cultural Organization (UNESCO) (1978); Arctic Ocean Energy Balance Working Group, Scientific Committee on Oceanic Research (1979); Andersen et al. (1980); Baker et al. (1980); Group of Specialists on Antarctic Climate Research, Scientific Committee on Antarctic Research (1981); and U.S. Army Cold Regions Research and Engineering Laboratory (1981).

Not only have many recommendations been made, but the current state of research is being reexamined by several groups in the National Research Council and other organizations. For example, a major regional study, Air-Sea-Ice Interaction Programs for the 1980s, is being designed as a contribution to the World Climate Research Program. Two substantial field programs are being planned as part of this larger effort: the Marginal Ice Zone Experiment (MIZEX) and the Greenland Sea Experiment. These programs will be multinational. Program documents have been reviewed by the Ocean Sciences and Policy Board of the National Research Council.

The Committee on Glaciology and the Polar Research Board generally endorse the recommendations made in these reports; however, we also note that most reports emphasize the role of sea ice in the global climate system. There are much broader reasons for research on floating ice.

This report emphasizes the scientific aspects of floating ice. Solution of these scientific problems will assist progress in engineering, resources development, and management of the environment. Also, relevance to these practical concerns has been considered in the assignment of scientific priorities. The reader is directed to a number of reports for a fuller explanation of these engineering or developmental aspects (Panel on Sea Ice Mechanics, Marine Board 1981; Committee on the Arctic Oil and Gas Reserves 1981; Committee on Arctic Seafloor Engineering, Marine Board 1982).

PROGRESS IN RESEARCH ON SEA ICE

Properties of sea ice, particularly the structural, chemical, electrical, mechanical, and thermal characteristics, have been studied extensively in the last few years. The properties of sea ice show large variations, with changes in brine volume, air content of the ice, and the degree of crystal alignment in the horizontal plane (the importance of the latter has been recognized only recently). Few studies in which these property-controlling variables were independently measured have been completed. Mathematical models of the viscoelastic and plastic properties of sea ice have been devised (Panel on Sea Ice Mechanics, Marine Board 1981), but the effects of natural variability, rate of strain, and formation history of the ice are so wide-ranging that model verification is limited. Knowledge of the electrical properties of sea ice is also incomplete. A better understanding would be useful in both developing better systems for remotely sensing properties of sea ice and improving the interpretation of field data. Of those classes of properties discussed here, the thermal properties of sea ice are perhaps best understood.

Satellite data became available in large quantities in the mid-1960s, but only during the 1970s did sea-ice research enter the space era with systematic studies. Satellites have now replaced drifting ice stations as the dominant observation platforms.

Remote-sensing missions performed as part of AIDJEX (1970-1976) demonstrated that passive microwave sensors had the potential for distinguishing first-year ice from multiyear ice. LANDSAT data were used to measure ice deformation. In 1978, the synthetic aperture radar (SAR) on SEASAT acquired some data on sea ice that have been used successfully for measuring ice displacements with a significantly denser sampling in space than was previously possible, thus confirming the anticipated potential of SAR to resolve the fine structure in the ice-velocity field. The usefulness of satellite microwave measurements for monitoring the extent of the sea-ice packs in both hemispheres has been demonstrated. Satellite-tracked and -interrogated data buoys now monitor the motion of the entire ice pack and atmospheric pressure fields over the Arctic Basin. Since the AIDJEX-manned camps were abandoned in 1976, there has been virtually no attempt to do research on sea ice from manned drifting stations. The recent Fram I, Fram II, and LOREX stations were established for purposes other than research on sea ice.

Understanding of the essential physics of the dynamics and thermodynamics of sea ice has increased since the 1970 Survey. The most intensive effort has been the AIDJEX, which focused on the development of models for the simulation of sea-ice dynamics. Perhaps the most important contribution of this and other recent research has been the formulation of a framework for a complete model of sea-ice dynamics, one that provides a focus for the examination of physical processes in sea ice.

Understanding of the role of sea ice in climate has increased. Heat and mass balance measurements, carried out at manned drifting stations in the Arctic, have provided information on the various radiation components, turbulent heat exchange, albedos, air and water temperatures, snow cover, ice growth, and ice salinity and structure. However, these data do not necessarily represent regional averages. In the Antarctic, such studies are fewer, and they are generally restricted to regions near coastal stations where there is only shore-fast ice. Thus our picture of large-scale interactions between the ice, the ocean, and the atmosphere, as deduced from such data, is not likely to be accurate because of the inhomogeneity of the ice and the strong coupling between the dynamics and thermodynamics of different ice types. Wind and water stresses give rise to strains within the ice that produce open water and deformed ice. Winter leads are areas of intense ice production, turbulent heat loss, and salt input to the oceanic mixed layer; summer leads have a low albedo and admit large quantities of shortwave radiation to the upper ocean, which strongly influences the summer decay of the ice pack. Thus, relatively small areas of open water can have a major impact on the regional heat and mass balance. Although exchange rates decrease rapidly with increasing ice thickness, young (< 1 m) ice still loses heat much more rapidly than perennial ice. Calculations indicate that contributions made by young ice to the regional ice production and turbulent heat exchange are comparable to those made by open leads. Clearly, variations in ice thickness, not just the average value, are important thermodynamically.

Much activity has been devoted to modeling. Model simulation of dynamics and thermodynamics of sea ice on space scales of 100 km and time scales of one day, such as those of AIDJEX, merit particular attention. Mechanistic models feature varying ice rheology concepts, ice thickness, and grid configurations. The spatially varying heat-balance simulations have included simple thermodynamic models, models that also include a constitutive law relating ice deformation and thickness to ice stresses, and global simulations that couple a full atmospheric circulation model to an oceanic circulation model.

Features of sea ice that occur in nature and might interact with natural or artificial structures can be divided into two broad categories: consolidated ice features, for which information on the various constitutive laws describing the deformation of a continuum is needed, and unconsolidated aggregates or fragments of ice of various sizes, for which the bulk properties of the aggregate are required.

Only recently, as a consequence of studies related to offshore resource exploration, have quantitative observations begun on the behavior of the highly deformed ice near the coast of the Beaufort Sea. The limited data available suggest, not surprisingly, that this behavior is commonly quite different from that of the ice further out to sea. In some locations, there is little motion during much of the winter, and the motions that occur do so as a series of irregular "jerky" events. At other locations, the pack moves steadily past the coast and shows large, eddy-like motions.

Ice scour, ice pile-ups, and ice ride-ups are major coastal processes caused by sea ice. The keel of grounded pressure ridges produces ice scour of ocean-bottom sediments. Such groundings plough deep gouges that can reach a depth of several meters. When ice pile-ups occur, the ice also grounds, and sail heights may be pushed up to an impressive 30 m or more. Major pile-ups also occur on beaches; at times ice can completely override low islands. Clearly, pile-ups can present serious threats to coastal communities and structures.

Recent coastal observations have revealed extensive frazil ice incorporated into the sea-ice cover in the Beaufort, Chukchi, and Bering seas in the Arctic, and especially in the Weddell Sea of the Antarctic, where up to 70 percent of the sea ice has the structure of frazil. This form of ice, similar to that formed in turbulent rivers, is characterized by a different structure, and presumably different properties, from "normal" sea ice. Why it is more common in the Southern Ocean than in the Arctic is not known. In addition, studies have shown that large amounts of fine-grained sediment may be entrained into a frazil-ice cover. These facts have implications for the heat balance of the ice cover, for the thermodynamics of ice growth, for the strength of the cover, for sediment transport analyses, and, because of light attenuation, for the biological regime in and below the ice. Frazil ice may also plug seawater intakes used for water flooding and for the maintenance of pressure in petroleum reservoirs, so the conditions for its formation and disappearance need to be understood.

Large areas within the seasonal sea-ice zone of the Southern Ocean are frequently free of sea ice during the winter. These polynyas are of two basic types: the more common coastal polynyas and the open-ocean polynya. The coastal polynyas may be primarily latent heat features, in which ice is removed by the wind as rapidly as it forms. The open-ocean polynya is more likely to be a sensible heat polynya, maintained by oceanic heat and transfer mechanisms.

Within the polynyas, the lack of the insulating effect of sea ice allows for massive heat, water, and gas exchanges with the atmosphere.

RESEARCH NEEDS--SEA ICE

Sea-Ice Processes

Information about the thickness and distribution of sea ice in both hemispheres is essential for ice-climate studies, ice navigation of large ocean-going vessels, design of offshore gravel islands and cones, and placement of underwater pipelines and cables. The role of ice-ridge formation, ablation, frazil-ice growth, and mechanical erosion in the annual mass balance is largely unknown.

Recommendations

HIGH PRIORITY. The mechanisms and forces associated with the formation of pressure ridges and rubble piles and with ice ride-up and pile-up should be studied. The degree of consolidation of ridges and rubble piles with time should be investigated.

HIGH PRIORITY. An array of data buoys should be maintained in the Arctic for a minimum of five years. They should measure not only position, temperature, and pressure but also other oceanographic and atmospheric parameters wherever possible. An array of air-droppable buoys should also be deployed in the seasonal ice of the Southern Ocean to monitor pressure, temperature, and ice movement. Such data are needed to confirm and quantify the divergent nature of the Antarctic pack ice and to estimate regional rates of ice production, salt rejection, and turbulent heat exchange with the atmosphere. Data from studies could be applied to the development, modification, and verification of numerical air/sea-ice/ocean models.

PRIORITY. The data needed for model development and verification in the very active and complex part of the sea-ice cover near its edge (the marginal ice zone) should be sought. These data should include measurements of ice drift, growth, and decay, ice pulverization by waves and transport by wind, and variations in atmospheric and oceanic fluxes near the ice edge.

PRIORITY. The role of frazil ice in the growth of sea ice and its effect on the exchange of heat between atmosphere and ocean should be evaluated, especially in the Southern Ocean.

PRIORITY. The oceanic and atmospheric processes leading to the generation and maintenance of polynyas should be resolved, and the role of polynyas in relation to climatic and ecological systems should be studied.

Ice Loads on Structures

Better understanding of ice loads and the interaction between ice and man-made structures is urgently needed to facilitate exploration, production, and transportation of oil and gas on the continental shelves of the Arctic. Better characterizations are required of the ice environment, the mechanical properties of the ice cover, and the failure modes of ice against different types of offshore structures.

Recommendations

HIGH PRIORITY. Systematic small-scale laboratory tests should be performed to determine the mechanical properties of sea ice and to develop suitable constitutive laws. Emphasis should be placed on understanding the physical processes controlling the mechanical properties of ice. A limited number of large-scale ice-strength tests are also needed to determine appropriate scaling factors for the small-scale strength data.

HIGH PRIORITY. Because much of our understanding of the large-scale mechanical properties of the ice cover and ice-structure interaction will be derived from model tests in ice basins, efforts to develop a properly scaled model of the ice cover should be continued.

PRIORITY. The fate and effects of oil spills and pollutants are crucial aspects of offshore petroleum development; therefore, research should be undertaken on the movement of pollutants in and under the ice, the detection of oil under ice, the dispersion of oil in waters with floating ice, and the prediction of trajectories of oil-spill movements.

PRIORITY. Regional, long-term statistics should be compiled on the geometry and occurrence of first-year pressure ridges and rubble fields, shore ice pile-ups and ride-ups, multiyear pressure ridges, and ice island fragments. (More detailed recommendations appear in the report of the Marine Board's Panel on Sea Ice Mechanics [1981]).

Floating Ice and Climate

Further understanding of the global climate system requires better knowledge of the vertical fluxes between air, ice, and water; the horizontal heat and momentum fluxes, including ice advection and various mechanisms of water circulation; processes of ice growth and decay, especially in the marginal ice zone; ways in which remote-sensing techniques can be better used to monitor ice variations in time and space; and ways in which numerical models can be used to test the coupled hydrodynamic, thermodynamic, and constitutive approximations to the basic physics of the air, water, and ice systems. These research needs are also discussed in The Polar Regions and Climatic Change (Committee on the Role of the Polar Regions in Climatic Change, in press) and in a new report issued by the World Meteorological Organization (1982).

Recommendations

HIGH PRIORITY. The full potential of remote-sensing techniques for determining large-scale sea-ice conditions (extent, concentration, thickness) should be implemented to achieve maximum resolution and minimum turnaround time for data processing and distribution to users.

HIGH PRIORITY. Coupled sea-ice/ocean/atmosphere models that incorporate the essential physics of ice and ocean processes, small-scale heat and mass transfer from leads, and low-level clouds should be developed. Especially needed is a simple sea-ice model that incorporates sufficient physics to represent the essential interactive aspects of long-term climate simulations.

PRIORITY: A comprehensive ocean/atmosphere/ice interactive study in the marginal ice zone and related features, such as leads and polynyas in the polar pack, should be undertaken, with special attention to the processes that control the location of the sea-ice edge and the associated ocean-atmosphere feedbacks.

PRIORITY. The climatic consequences of the interaction of freshwater and seawater on the Arctic shelf should be investigated.

PRIORITY. The role of frazil ice may be crucial to the energy balance of Antarctic sea ice, and a systematic analysis of its occurrence, in both horizontal and vertical dimensions, is needed.

RESEARCH ON RIVER AND LAKE ICE

River Ice

Frazil ice, anchor ice, and aufeis are typical ice forms associated with moving water in cold climates. Frazil-ice crystals characteristically are small discs measuring up to ≈ 4 mm in diameter and 25-100 μm in thickness. Anchor ice also forms in supercooled water, probably by deposition and adhesion of frazil-ice crystals to the river bottom and obstacles in the river flow. Aufeis growth is caused by the freezing of an overflow of river water on a continuous ice cover.

Progress toward the understanding of dynamics of river ice has been uneven since the 1970 Survey.

A quantitative understanding of the formation, growth, and decay of river ice requires careful measurements of the thermal regime of a river. Studies of the temperature history of streams during frazil events have been used to assess the rate of ice formation and subsequent concentration of frazil ice. Measurements of supercooling in flowing water have shown that it is at most a few tenths of a degree. Mass-exchange mechanisms at the water surface have been proposed to explain nucleation of frazil ice with small supercooling. Qualitative descriptions of the evolution of frazil ice from discs to flocs, pans, and floes are available, but the thermodynamics and dynamic forces underlying this evolution are largely unknown. A mechanism for the multiplication of ice nuclei through "collision breeding" has been identified in streams.

Although most analyses of the river thermal regime make use of standard procedures for assessing the surface heat exchange, recent research suggests that the net surface heat loss in turbulent water is underestimated by most models, emphasizing a need for research into the basic physics of mass and heat transport at the water-air interface.

The year-round maintenance of open water is essential in certain river reaches for ship or barge passage or for hydroelectric facility headwaters.

However, a solid ice cover is necessary at traditional Arctic river crossings and upstream of hydroelectric facilities to minimize frazil-ice deposition on trash racks and flow gates. Therefore, there is interest in the development of criteria for the maintenance of open-water or ice-covered areas. Studies of artificial methods for maintaining open water have examined the effectiveness of buoyant discharges, including bubbler systems and warm water discharges. Other more basic studies define critical combinations of water temperature and surface velocity for the maintenance of open water or suggest criteria for the evolution of a well-mixed frazil-ice-laden flow into a stratified two-layer flow.

Most studies of the hydraulic resistance of river ice have involved determination of the ice-cover roughness coefficient (usually Mannings, Chezy, or roughness length scale). There is some evidence that hydraulic resistance is strongly related to frazil-ice concentration. Determination of the roughness coefficient is important for the calculation of backwater curves with an ice cover and the evaluation of possible flooding.

Frazil ice is produced in large quantities in rapids or other open-water areas and subsequently deposited downstream on the underside of an ice cover. The frazil ice may be carried to considerable depth and deposited in quantity sufficient to jam the river and cause flooding. Predictive models for the deposition of frazil ice have been devised, but field measurements are few.

Also lacking are field measurements of controlling parameters in the formation, growth, and breakup of ice jams. Analysis has concentrated on theoretical and laboratory modeling of ice jams. Froude-number criteria for the deposition of ice below an ice cover and for the limit of upstream progression of an ice cover by juxtaposition have been devised. The latter criterion might be useful for the determination of maximum water depth occurring during an ice jam. Initiation of the full-width ice cover begins at critical sections where the ice floes first arch or bridge the river. These processes have been studied recently with laboratory models. Analysis of so-called wide river ice jams, in which the force of the ice floes is transmitted through the cover by shoving, calls for the determination of the internal friction of the jam, a parameter that may not be readily modeled in the laboratory. There is evidence that breakup of river ice may be strongly linked to the hydraulic transients in the river system, including the rate of rise, total rise, ice thickness, and ice strength. Power companies are concerned about the dynamics of the breakup of river ice because of the relationship to peaking procedures and ice-cover stabilization downstream from power plants.

Qualitative descriptions of the formation and growth of anchor ice by adhesion of frazil-ice particles to obstacles in the river have been available for some time, but there is little quantitative information about anchor ice. How it forms is still in doubt, and effects on the thermal and hydrologic regimes of a river are unknown.

Recent numerical-modeling efforts for prediction of river- ice conditions have relied heavily on the Froude-number criteria for ice jams, empirical relations for ice roughness, and surface-heat-loss calibrations. Unfortunately, several of these models have been included in proprietary studies, thus verification is impossible.

The viscous and adhesive properties of frazil-laden flows are particularly relevant to the design of cooling-water intakes, hydroelectric project trash racks, and other river structures. Significant differences have been observed in adhesive bonding between freshwater and saltwater frazil-ice slurries grown in the laboratory.

Remote sensing offers another method for observation and assessment of properties and characteristics of river ice. Visual and infrared imagery have been used to document frazil- and brash-ice accumulations; photographic surveys and LANDSAT images of rivers during freeze-up have been used to determine critical sections where ice jam formation commences.

Lake Ice

A recent review on northern lake modeling lists only two lake models that include the effects of snow and ice, and neither of these models presents comparisons with field data during ice conditions. The dearth of research into dynamics of lake ice contrasts sharply with recent significant advances in understanding the hydrodynamics and thermodynamics of lakes and reservoirs in more temperate regions. These advances are potentially applicable to studies of lake ice.

Recent progress in research on lake ice has concentrated on remote-sensing methods, thermodynamics of ice formation, and the problems of ice interactions with structures. Several surface-heat-exchange formulae for open-water surfaces yield realistic models of surface heat losses during calm days. Other studies relevant to the lake thermal balance include measurements of heat flux from the bottom sediment and the development of convective boundary currents due to the sediment heat flow. The growth of static ice covers in lakes is usually determined by degree-day methods based on the Stefan model. Efforts to improve the degree-day formulation have centered on empirical corrections to degree-day coefficients. The climatic effects of a large ice cover on nearby regions are just beginning to receive attention.

LANDSAT imagery has been used to determine the extent of ice cover and snow cover and to study the breakup of river and lake ice. Ice quality can also be assessed by visual and infrared imagery. A new development is the use of radar techniques for measuring ice thicknesses in lakes with known bathymetry.

The construction of large reservoirs at hydroelectric facility sites poses a number of scientific problems. The thermal regime in the reservoir is critical for downstream water quality and temperature, factors important to local fisheries. Ice-cover formation on the reservoir can cause damage to facility structures by the expansion of the ice sheet or by ice override during severe wind episodes. Pumped storage facilities, characterized by high water-exchange rates to temporary storage basins, are particularly prone to severe ice problems. A few site-specific engineering techniques have been applied to these ice problems at hydroelectric sites, but fundamental questions regarding freshwater ice strength and adhesive properties are still unanswered.

A series of particularly cold winters in the U.S. northern tier states drew attention to the maintenance of open-water channels for ship and barge passage on large lakes and rivers. "Refill" processes in the wake of ships have been subjects of recent engineering research.

RESEARCH NEEDS--RIVER AND LAKE ICE

There is a critical need for research relevant to freshwater ice hazards. Problems include ice jams, flooding, erosion, ice interactions with bridges, piers, and shorefront property, the effects on impounded and downstream water temperature and quality from construction of hydroelectric reservoirs in arctic regions, and ship and barge traffic in ice-covered lakes and rivers.

Recommendations

HIGH PRIORITY. Field studies and observational programs should be undertaken to document the locations, stability, and mechanics of ice jams and the resulting changes in river stage. Investigations of both frazil-ice jams, commonly formed during freeze-up, and of large-scale ice jams, formed during breakup, should be undertaken. Quantitative theoretical models should be developed of breakup progression, the dynamics of moving ice fronts, processes of pressure- and sheer-ridge formation, large floe development, and the hydrodynamics of two-phase frazil-ice-laden flow.

PRIORITY. A model for assessment of water quality in northern lakes and reservoirs should be developed. The model should include the coupled effects of thermodynamic, hydrodynamic, and mass-exchange mechanisms at the water surface and thermal regime under an ice cover.

PRIORITY. Laboratory model studies should be undertaken to test theoretical developments in the analysis of ice jams. These should include the effects of hydraulic transients on the stability of an ice cover, lateral ice growth, ice transport beneath an ice cover, and the changes in the mechanical properties of ice at the melting point.

PRIORITY. Studies of "refill" processes in channels made by ice breakers should be undertaken to guide the development of shipping in northern lakes and rivers.

PRIORITY. Other research associated with ice-covered rivers should deal with sediment transport and scour processes during freeze-up and breakup and changes in bedform regime and with pollutant mixing and transport under ice covers.

PRIORITY. To facilitate development of a model for northern lakes and reservoirs, field investigations should be undertaken of stratification effects under an ice cover, heat flux budgets at the bottom of lakes, particularly in permafrost areas, and drawdown of ice covers on reservoirs.

RESEARCH ON ICEBERGS

Although icebergs are derived from glaciers by calving, they float in the world's oceans, may be associated with sea ice, and may present floating hazards to vessels and structures. Therefore, icebergs are covered in this chapter; the iceberg calving processes are discussed in Chapter 6, Section on "Energy Balance," subsection "Calving Processes."

Two quite different types of icebergs exist: huge tabular icebergs, often measuring kilometers in horizontal extent, that are derived from ice shelves in Antarctica and northern Ellesmere Island; and blocky icebergs, ranging in size from a few meters to a kilometer or so in greatest dimension, that are derived from outlet glaciers in Greenland, Alaska, and many other areas. Tabular icebergs from Ellesmere Island are known as ice islands in the Arctic Ocean. There is currently some interest in the Antarctic tabular icebergs as possible sources of freshwater supply for coastal desert regions.

The main impact of icebergs on society is that they can be floating hazards to vessel traffic and to fixed installations such as drilling platforms and pipelines on the seabed. Most of the direct hazard is due to blocky icebergs derived from Greenland outlet glaciers. These icebergs tend to move counterclockwise around Baffin Bay, then to drift south in the Labrador Current where they may approach offshore oil and gas installations, or drift further south and east into the North Atlantic steamer lanes. Icebergs may produce local problems in many other northern waters, such as the Valdez Arm, Alaska.

Research problems connected with icebergs include the difficulty of detection and measurement, especially of underwater shape; prediction of drift trajectories, which depend on wind, water currents, Coriolis force, and the ever-changing shape of the iceberg due to melting, rotation, or breakup; towing characteristics; and mechanical properties, including ice strength profiles, which may be important to predicting breakup or the consequences of impact on a man-made structure.

Recommendation

HIGH PRIORITY. Research should be continued on the remote detection of icebergs and the mapping of their shapes using acoustic, radar, or other types of instruments as well as on the use of these data for the modeling of natural iceberg drift and for their drift under towing forces. Research is needed on ablation rates of icebergs and on ways that ablation affects the hydrodynamic and mechanical stability of icebergs.

OTHER RESEARCH OBJECTIVES: ICE FORMATION, GROWTH, AND DECAY

Estimates of the heat energy fluxes over the pack ice are relatively few and unreliable, particularly in the Antarctic; various models have supplied data in the absence of actual field observations. Dynamic and thermodynamic processes in leads and at the ice edge are especially important for the understanding of Arctic and Antarctic heat and mass budgets. These processes are complicated by ice movement, changes in salinity structure with summer meltwater or with winter brine rejection, ice thickness, waves, currents, and mechanical erosion.

There are also fundamental unanswered questions concerning mass and heat transport at the interface between turbulent fresh water and the atmosphere. The effects of frazil-ice crystals on the turbulent intensity and the mechanisms associated with flocculation and adhesion of frazil ice should be explored.

Recommendations

HIGH PRIORITY. Research on freshwater ice should focus on heat- and mass-exchange mechanisms at the turbulent water surface, secondary nucleation during freeze-up, and melting rates and radiation balances during breakup. These studies should include the thermal regime of the water during freeze-up and breakup and the characteristics of the frazil ice, especially adhesion, during its formation, evolution, and flocculation. Field investigations should be emphasized.

HIGH PRIORITY. Research on sea ice should be directed to measurements of ice growth, drift, and decay and to interactions of ice with the thermohaline structure in the marginal ice zone. These studies should include a winter lead experiment on freezing processes, convection, and haline-driven circulations and atmospheric fluxes and a summer field experiment to measure ice melting rate, radiation balances, and the structure of the pycnocline.

PRIORITY. Other research on freshwater ice should include studies of growth of aufeis, the formation of anchor ice, and the growth of lateral ice cover (e.g., border ice growth).

6
Research on Glaciers

Since Polar Research - A Survey was published in 1970, more specialized documents on Antarctic glaciology (Panel on Glaciology 1974), on glacier and ice-sheet sliding (Ad Hoc Study Group on Glacier and Ice Sheet Sliding 1976), and on the program plan for the Greenland Ice Sheet Project (GISP) have reviewed and expanded its recommendations. Nevertheless, a reappraisal of the broad lines to be followed in glaciological research is best made by comparing the 12-year-old recommendations with the results they have produced over the intervening years.

GLACIER SURGING AND SLIDING

In regard to glaciers, the 1970 Survey gave top priority to the problems of surges and the sliding of a glacier on its bed. Some of the specific recommendations have been met. Field studies of Variegated and Black Rapids glaciers, both expected to surge in the 1980s, are in progress; in fact, the surge phase of Variegated Glacier appears already to have started. Studies on Variegated Glacier are extensive and meet many of the recommendations for measurements: surface motion and geometry and their change with time, temperature, water discharge at the terminus, water pressure under the glacier, and basal sliding. Both glaciers were found to be temperate, and the study of their motion indicates that water in and below the glacier must play a key role in the triggering of surges.

Other recommendations have been partially met. Cyclic flow regimes have been simulated in general accord with the observed characteristics of several surging glaciers by using a simple model with a single adjustable "lubrication factor" to parameterize the water produced by friction at the base of a glacier. Although greatly simplifying the physical situation, this model analysis suggests that periodic surging represents an intermediate mode between normal deformation flow and steady fast sliding. The role of water from the glacier surface as a possible trigger of surges remains unclear, and there is not yet a single agreed-on theoretical model for the sliding of a glacier on its bed. The careful study of the dynamics of quiescent surge-type glaciers has raised basic questions about the dynamics of normal temperate glaciers. The possibility of surges within the very large ice sheets remains. Another unanswered question concerns the explanation of the nonrandom geographic distribution of surging glaciers.

From our present perspective, it appears that the relative importance of surging vis-à-vis the sliding of a glacier on its bed was reversed in the 1970 Survey. It is clear that the mechanics of the coupling of the glacier or ice sheet to its bed is the central unsolved problem in the field of glacier dynamics. Although several theoretical models of sliding exist, as they did 10 years ago, none is generally accepted as quantitatively applicable to real glaciers. Observations suggest that bed separation is an important factor in sliding and that it is influenced by hydraulic conditions at the bed. There is a growing recognition of the importance of basal rock debris and rock-to-rock friction in the sliding process. Although there has been progress in the last decade, much research is needed before dependable models of sliding can be achieved.

Glaciers are complicated dynamic systems that respond to variations in their boundary conditions. Although it is known that motion occurs by a combination of internal deformation and basal sliding, the rates of neither process can be predicted with confidence. The internal deformation is affected by variations of structure and temperature with depth. These variations have been examined by core drilling at a limited number of locations, and laboratory and field observations have provided some information about the effect of texture, fabric, and impurity content on the flow law of ice, but their influence on the flow law still has not been quantified. Most serious is the lack of physical understanding of the basal sliding process and a practical and effective observational means to study it. Often it is feasible to establish basal temperatures, which would determine where sliding could take place. To understand the sliding process, however, it will be necessary to make detailed observations of the structure of the basal zone and the physical processes acting there by any direct or indirect means possible.

The drilling of deep holes in the ice is as important for studying ice dynamics as it is for studying paleoclimates. The difficulty and expense involved in drilling ice-core holes, particularly deep holes on ice sheets, makes it essential that full advantage be taken of each hole, including completion of a full set of measurements on the ice cores and in the drill holes.

Ultimately, any prediction of future changes in glaciers must involve numerical modeling. Models can simulate present ice dynamics, rates of change, and past variations and can be checked against observed data when they are obtained. Progressive improvement of the models results from applying them to different regions and testing the results. When reasonable success has been obtained in modeling past and present changes, then some confidence in future predictions is warranted.

Processes at the Glacier Bed

The processes by which a valley glacier or grounded ice sheet slides across its bed are not understood. Knowledge of these processes would form a bridge between glaciology and quantitative geomorphology, which is concerned with glacial erosion and deposition. There still is no general agreement about the principal controlling factors in the sliding process; even qualitative physical understanding is lacking. Direct observations in tunnels and indirect evidence of chemical deposits on exposed glacier beds show the occurrence of creep and regelation of ice around small bed roughness features. However, recent evidence also points to a significant involvement of rock debris embedded in the basal ice and in a subglacial till sheet. Effects from subglacial water have long been known, and recent field studies have begun to provide some quantitative information. Theories incorporating these factors exist, but conclusive quantitative tests are still lacking.

Several methods of study are available and should be combined. Most important are measurements in boreholes to determine basal water pressure, interface morphology, and slip rate. These should be coupled with measurements of surface movement, both horizontal and vertical, on short time scales. Already, these methods have provided some observational base for establishing the effect of water pressure on sliding rates and the role of the opening of gaps at the bed. Also important are any remote means of measuring sliding changes, for example, from surface velocity and strain, the condition of the bed, or the water level in the natural internal drainage system as determined by echo sounding. These methods can provide spatial coverage and have already aided in the discovery of propagating waves of motion and associated hydraulic waves, the speed of which provides additional constraints on the basal hydraulic system. Water discharge rates, water chemistry, tracer studies, and sediment suspended in the outflow may supply additional information about the hydraulic system. Tunnel access, for example, in the Alps and Scandinavia as a result of commercial operations, affords the most detailed examination of basal processes; such opportunities should be exploited whenever possible. In addition, the study of deglaciated bedrock surfaces and the chemical deposits on them and of tills and other deposits will still be useful.

Surge-type glaciers, in particular, should be studied because they display a full range of sliding speeds from low to very high on a fixed-bed geometry over the course of a surge cycle. Some outlet glaciers in Greenland and Antarctica flow continuously at surge speeds, and these should be studied to determine how such speeds can be maintained. Studies of both types of fast-sliding glaciers should add fundamental insight into the problem of glacier sliding.

Ice streams and outlet glaciers discharge most of the ice from the inland ice sheets. They are typically characterized by small surface slopes and high speeds and are obviously sliding. The processes that determine the location of the transition zone between slower-moving ice and a fast-sliding ice stream are not known; not only is it important to understand the factors that govern the spatial transition, but it is also vital to understand how changes with time can occur at any particular location.

Of special interest is the Jakobshavn Glacier in Greenland, which flows at a sustained speed greater than that of any other glacier in the world (21 meters per day). It also forms as an ice stream from sheet flow in the Greenland Ice Sheet, thus study of it may assist in understanding the formation of Antarctic ice streams.

Another special case of some interest is Vatnajokull, in Iceland. At least six of the outlet glaciers from this ice cap exhibit surging behavior and provide opportunities to study the interaction between volcanic heating of the glacier bed and rapid sliding behavior.

Recommendations

HIGHEST PRIORITY. The ongoing field studies and remote sensing of surging glaciers should be continued through and beyond the surges now occurring and expected in the 1980s. Support should also be provided for interpretation of the data.

HIGHEST PRIORITY. The several types of measurement related to processes at the glacier bed should be made on both normal and surge-type glaciers, and they should be conducted simultaneously on any particular glacier. A similar measurement program should be instituted on a continuously fast-sliding glacier, such as the Jakobshavn Glacier.

PRIORITY. Topography, deposits, and structures related to sliding in deglaciated areas should be studied more extensively to understand basal glacier processes. Laboratory experiments should be included.

HIGH PRIORITY. Field programs on ice streams should emphasize examination of the transition zone between slow-moving and fast-moving ice.

Processes Within the Glacier

Mechanisms of internal deformation within glaciers are vitally important. Understanding them requires a better knowledge of the physical properties of ice, as discussed in Chapter 3, principally the effects of various parameters, such as fabric, grain size, temperature, internal water, and impurities, on the creep of ice. These internal conditions can be determined by core drilling and, potentially, by remote sensing. Measurements of surface velocities and strain rates should be made extensively and should be concentrated in places in which measurements of internal characteristics have been, or can be, made.

The distribution of water within a glacier affects glacial hydrology and dynamics. A quick way of surveying englacial water would be of great value; some success has already been obtained in doing this by means of radar.

A special need is the correlation of measurements of internal properties with movement studies on ice sheets. Where extensive flow-line and contour-line programs have already been carried out, such as in the International Antarctic Glaciological Program (IAGP) area, measurements in drill holes and concentrated remote sensing should take place along those same lines. Conversely, a full complement of strain and velocity measurements should be made wherever a deep drill hole exists or is drilled in the future.

Recommendations

HIGH PRIORITY. Tilt measurements should be made in as many deep boreholes as possible and should be combined with temperature, sonic logging, and surface-strain measurements to provide a three-dimensional picture of ice deformation. To the extent possible, boreholes should be aligned along flow lines to examine the progressive development of fabric and texture.

HIGH PRIORITY. The fabric, texture, and impurity content of available and future ice cores should be measured, with particular emphasis on the deepest ice and the margins of glaciers and ice streams, in which creep can be expected to be greatest.

ENERGY BALANCE

Another major problem selected for special attention in the 1970 Survey was the energy balance of glaciers. Included were two specific recommendations for: (a) continuous energy-balance measurements at selected sites and (b) extension of results obtained at those sites to energy balances over large areas using new developments in remote sensing. A program of the International Hydrologic Decade attempted to encourage these studies on an international scale, but developments in instrumentation and remote sensing were slower than expected, and many of the questions remain. However, the physical processes that couple glaciers to their climatic environment are better understood now than in 1970. In Antarctica, careful studies of the energy balance and of associated features of the boundary structure and flow have been carried out at a number of representative sites; the task now is to synthesize these in a description of the large-scale energy balance of the ice sheet. In regard to mass balance, significant regional features established since 1970 include positive balances in inland East Antarctica coupled with negative balances near the coast, suggesting a rising and steepening of the surface of the ice sheet. Major advances could result from the discovery that passive-microwave radiation, which can be observed by satellites, is affected by snow properties such as temperature, density, and grain size. Thus, it may be possible to extend mass-balance results from direct observation sites to cover large areas, even complete ice sheets, by remote sensing.

Several other research recommendations specifically concerned with the relationship between glaciers and climate in the Arctic or Antarctic included determination of: (a) thermal regimes and mass, heat, and water balances of representative Arctic glaciers and (b) the mass balance of the Antarctic ice sheet. The Antarctic mass-balance problem was further divided into a series of specific recommendations calling for:

1. Determination of spatial and temporal variations in accumulation rates;
2. Determination of the mass balance of specific drainage basins;

3. Detailed studies in areas about 100 km across;
4. Determination of the mass and heat exchanges of the undersides of ice shelves;
5. Study of the effect of the varying sea-ice cover on snow accumulation on the continent; and
6. Measurement of calving from ice streams and ice shelves using satellite images.

These recommendations remain valid today, although much progress has been made.

Recent studies have suggested that the global rise in sea level during the last century is due in part to the melting of glaciers on land, although thermal expansion of seawater from heating accounts for much of the rise. Measured changes in the earth's rate of rotation have been attributed to the transfer of mass from polar ice to the world ocean. Yet recent studies of the present mass balance of Antarctica continue to suggest, as did older ones, that the major drainage systems are increasing, not decreasing, in volume. This enigma further emphasizes the importance of determining the mass balance of the Antarctic ice sheet and of lower-latitude glaciers as well.

Two different aspects of the net mass balance of a glacier are important: first, the continuing mass input over part of the glacier and removal over another part is the basic process that keeps the glacier active; second, any deviations from zero net mass balance require growth or shrinkage of the glacier. The processes relevant to all glaciers may be divided conveniently into mass balance at the upper surface and calving at the glacial terminus or outer margin. Melting and freezing on the underside of ice shelves is a problem relating principally to Antarctic ice sheets.

Calving Processes

Most of the loss of mass from the Antarctic ice sheet occurs as iceberg calving. The calving flux is also a significant part of the mass loss of the Greenland ice sheet and of many much smaller tidewater glaciers. The stability of marine glaciers depends on the position of the grounding line, and this depends in part on the position of the terminus, which is determined by the balance of ice flow and calving. Thus, the physics of calving must be understood to analyze the stability of such widely different marine glaciers as the West Antarctic ice sheet and the Columbia Glacier in Alaska, and also perhaps to explain the rapid disappearance of parts of the Pleistocene ice sheets in the Arctic. An understanding of calving rates and how they vary with external factors is also important to an understanding of iceberg production. This is a matter of considerable practical interest, especially in view of the increasing development, with drilling platforms and vessel traffic, in northern waters.

Recommendation

HIGH PRIORITY. Complete calving laws for glaciers should be developed. Although the main difficulty is understanding the physics of the process, additional field studies are required on rapidly calving glaciers as a necessary part of studies of the possible drastic retreat of marine ice sheets.

Thickness Change and Stability of Ice Sheets

As a result of extensive airborne radar sounding, both surface elevation and ice thickness of most of Greenland and about two thirds of Antarctica have been mapped to an accuracy of about $\pm$ 50 m. This work should be completed. The 50-m accuracy suffices for ice thickness, but an order-of-magnitude better information is needed for surface elevations and can be obtained from satellite altimetry. Satellite measurements so far have been limited to latitudes less than 72^{o} and have not been fully used where available. In measuring surface elevations, a radar altimeter has sufficient accuracy for basic mapping purposes, but a laser altimeter is needed to study changes.

Ice sheets have the potential for relatively rapid change, including the rapid shrinkage of marine portions of an ice sheet and surges affecting all or most of a drainage system (Bentley 1982). A physical theory that can treat these problems is needed but cannot be developed until basal and intraglacial processes are better understood. Until then, empirical models continue to be useful. To determine whether there are current changes in the volumes of the Antarctic and Greenland ice sheets, their elevations must be monitored.

Recommendations

HIGHEST PRIORITY. Every effort should be made to bring about, as soon as possible, the emplacement into a polar orbit of a satellite carrying radar and laser altimeters that are designed for effective use over ice sheets.

HIGH PRIORITY. Development of models concerned with the stability of ice sheets should be continued, and the models should be improved. The fundamental task is to develop models that can reproduce the histories of different drainage basins with their contrasting regimes, and of the ice sheets as a whole, in accordance with the complete evidence from ice cores. Once this has been accomplished, the models should be used to investigate the future response of the ice sheets to predicted changes in boundary conditions, in conjunction with atmospheric and ocean circulation models.

HIGH PRIORITY. Airborne radar sounding of Antarctica and Greenland should be completed, and a thorough analysis of the existing airborne and satellite data carried out.

Basal Mass Balance on Ice Shelves

Knowledge of the mass balance on the underside of the Antarctic ice shelves is a critical factor in the assessment of the mass balance of the ice sheet.

Recommendations

HIGHEST PRIORITY. Determining and understanding oceanic circulation beneath the Antarctic ice shelves and the mass and heat exchange between the water and ice should be major goals of research.

HIGH PRIORITY. A program should be undertaken to develop instruments, and methods for their rapid emplacement, for the study of bottom balance rates on ice shelves. Whether to emplace the instruments in boreholes or to employ robot meltsondes should receive careful consideration. Many more boreholes should be drilled through ice shelves for direct measurement of basal balance, particularly in areas of accretion. Because of the small number of holes that can be expected, however, use of remote-sensing techniques for the determination of basal mass balance is also essential.

Grounding Zones

The grounding zone that separates the inland ice of the Antarctic ice sheet, particularly its ice streams, from its ice shelves is critically important. Where the angle between the ice and bedrock is small, small changes in ice thickness or sea level result in large horizontal shifts of the grounding zone. This process is fundamental to the potential instability of a marine ice sheet. For this reason, careful measurements should be made of the characteristics of the grounding zone and its variations with time. Because of irregularities in submarine topography and ice thickness, the grounding zone in places may extend over a considerable area within which there may be several individual grounding lines.

Recommendation

HIGH PRIORITY. Research should be undertaken to locate grounding zones of ice streams and measure their characteristics and changes with time, including elevations, ice thickness, velocities, and strain rates.

Ice Shelves and Ice Streams on Outlet Glaciers

Recent studies on ice shelves have focused on ice rises as obstacles controlling the velocity of the ice shelves;

therefore, these ice rises might be crucial to the balance of marine ice sheets, and they are susceptible to rapid changes in size. Many of these features occur within the grounding zones, but others that may be of particular importance are far removed from the inland ice. Another problem that needs attention is the drag of ice shelves, ice streams, and outlet glaciers along their lateral margins, particularly the possibility that strain softening could cause effective decoupling.

Recommendations

PRIORITY. Surface strain rates and a temperature profile to bedrock should be measured on ice rises, and the role of ice rises should be studied in the continued development and refinement of time-dependent dynamic models of ice shelves.

PRIORITY. Extensive measurements made on the Ross Ice Shelf should be extended inland to the West Antarctic ice sheet and its ice streams, and to the fast outlet glaciers feeding the ice shelf from East Antarctica.

PRIORITY. Field and theoretical studies of the interaction between ice shelves, ice rises, ice streams, and outlet glaciers and their lateral margins should be undertaken. The Jakobshavn Glacier in Greenland, a fast-moving, laterally bounded, floating-outlet glacier, could be particularly amenable to such study.

Monitoring the Antarctic Ice Sheet by Satellite Imagery

For monitoring the ice sheet, it is mandatory that images of Antarctica, especially of coastal areas, be acquired from all U.S. and other earth-sensing satellites with spatial or pixel resolutions better than 80 m. Unless an interim recording station is established in Antarctica, acquisition of multispectral-scanner and thematic-mapper data of Antarctica by the LANDSAT-D spacecraft will be impossible until the tracking-data and relay-satellite system becomes operational in 1983 or 1984.

Recommendation

PRIORITY. Either an air-transportable LANDSAT receiving station at the South Pole or McMurdo Station, or several stations operating at various positions around the coast of Antarctica, should be provided as soon as possible.

QUATERNARY GLACIOLOGY

Another problem relating to glaciers that was emphasized in the 1970 Survey is Quaternary glaciology. Here, the advances have been dramatic. The recommendations given in the 1970 Survey can be summarized succinctly: drill more ice cores in Antarctica and Greenland and on other glaciers; analyze new and existing cores and the drill holes themselves as fully as possible. In the intervening years, a number of shallow, intermediate, and deep ice cores have been recovered and analyzed for a continually expanding list of isotopic, chemical, and physical properties. Interpretation of these and other stratigraphic and thermal records in ice sheets and glaciers has provided extraordinarily valuable, detailed information on the environmental conditions of the recent and prehistoric past. These records shed light on the past history of the dimensions and dynamics of ice sheets that is crucial to the understanding of the response of glaciers to climatic change. Measurements on ice cores have also yielded values of parameters (e.g., density, crystal orientation, electrical conductivity) necessary for the interpretation of remote-sensing information, such as radar, seismic, and electrical resistivity surveys, that can be obtained widely on large ice masses.

Major advances have been made in measuring the size and movement of the ice sheets. In 1970, airborne radar sounders had not yet reached routine operational capability. Now, the thickness of two thirds of the Antarctic ice sheet and much of the Greenland ice sheet has been mapped. Furthermore, with the advent of highly precise positioning by satellite, measurements of ice movement, even on the interior East Antarctic Plateau, have advanced, particularly in the sector under study by the IAGP.

Determination of Past Environmental Conditions

Ice sheets and ice caps contain much information on past climates and environmental conditions (see Table 1 and Committee on the Role of the Polar Regions in Climatic Change, in press). These can be inferred from the isotopic and chemical composition of the ice, the incorporated terrestrial and extraterrestrial material, the inclusions of air, and the temperature-depth profile of the ice sheet. The stratigraphic profiles of the Antarctic and Greenland ice sheets are obtained from ice cores that contain the precipitation accumulated over intervals as great as hundreds of thousands of years. The core data are highly resolvable, frequently permitting distinction of one season's snowfall from the next. These high-resolution data are available nowhere else, and they complement other data of less resolution but larger time span obtained from the study of ocean and lake sediments and from glacial geology.

More types of analyses will become routine in the next decade, and new environmental parameters will be introduced. One new development is the application of accelerator-mass spectrometry to the measurement of cosmogenic radionuclide concentrations in ice cores, which may provide a detailed history of solar activity and its effect on climate as well as a relationship between absolute age and depth in ice sheets. Another is the detection of historical volcanic eruptions, which also have a direct impact on climate. A record of these eruptions can be obtained from measurements of conductivity and sulfate ions in ice cores. The potential scientific benefits from the study of ice cores remain immense.

Four major problems should be attacked in the coming decade:

1. Extracting the climatic and environmental record through the last several hundred thousand years;

Table 1 Past Environmental Information Currently or Potentially Available from Stratigraphic Analysis of Large Ice Masses

Environmental Parameter	Ice-Core Signal
Natural Causes	
Annual temperatures	$^{18}O/^{16}O$, $^{2}H/^{1}H$, borehole temperatures
Summer temperatures	Ice-melt features
Precipitation rates	Seasonally varying signals, including $^{18}O/^{16}O$/, $^{2}H/^{1}H$, Cl, Na, NO_3^-, conductivity, microparticles, Al
Antarctic sea-ice extent	Cl, Na
Solar activity	^{14}C, ^{10}Be, 36 Cl, ^{26}Al, NO_3^-
Volcanism	$SO_4^{=}$, pH, Zn, Cd, conductivity, microparticles
Extraterrestrial influx	Ni, Fe, Mg, Ir
Atmospheric composition	CO_2, N_2, O_2, Ar in bubbles
Desertification, global	Microparticles, Al, Si, Ca
Ice-sheet elevation changes	Total air content in bubbles
Biological productivity	Organics, pollen
Forest fires	Carbon
Human-Induced Causes	
Pollution, acid precipitation	Pb, Zn, $SO_4^{=}$, NO_3^-, pH, pesticides
Nuclear weapons testing	^{90}Sr, ^{137}Cs, ^{3}H, Pu^-, Am^- isotopes
CO_2 greenhouse effect	CO_2 in bubbles

2. Determining whether the West Antarctic ice sheet has been in existence through the last 120,000 years and assessing the likelihood of a major change in the future;

3. Defining the relationship between climatic signals contained in polar ice cores and the local weather, signals from Arctic and subpolar glaciers, and appropriate data from other sources, such as tree rings, glacial geology, and ocean sediment cores; and

4. Developing, refining, and using old and new techniques for detection of paleoenvironmental conditions from existing and future ice cores.

Long-Term Environmental and Climatic Records

The deep ice cores from Greenland and Antarctica contain ice probably no older than about 100,000 years--only through the most recent glaciation. This glacial age may have been characterized by reduced solar activity, large-scale volcanic eruptions, lower CO_2 concentrations, and increased atmospheric turbidity from eolian dust. Each of these features could have contributed to the severity of the climate; volcanism and solar emissivity changes are possible causes of glaciation. However, ocean-sediment core analysis indicates that the climate of the last several hundred thousand years has followed variations in the earth's orbit.

Deep, continuous high-quality ice cores with basal ages of several hundred thousand years or more will help to answer questions regarding the causes of glacial ages, the relative severity of the major glacial stages, and the past and future response of ice sheets to climatic change. Ice cores to meet these demands can be obtained only from East Antarctica or Central Greenland.

The successful interpretation of these cores is entirely dependent on a knowledge of the glaciological conditions and history "up-glacier" from the drilling sites, and the incorporation of these data in realistic flow models.

Recommendation

HIGHEST PRIORITY: A long-term program of shallow-, intermediate-, and especially deep-core drilling in Central Greenland and is Antarctica should be implemented, including the development of techniques that will produce continuous, high-quality ice cores suitable for scientific analysis.

Such a commitment requires that substantial time be allocated to: (a) develop the new technology necessary for drilling in the extremely cold environment of East Antarctica, (b) allow consultation between scientists and engineers to ensure that the drill design is compatible with specific requirements of core users in regard to dimension, quality, and continuity of the core, and (c) develop a program to select the optimum site that will increase the probability of definitive scientific results. Therefore, the Committee on Glaciology believes that a workshop should be convened to document the types of ice-core drills and sampling techniques potentially available for deep-ice collection, the types of climatic and environmental information available from ice-core analysis, the factors concerned in site selection, and the limits that ice-core drilling techniques and particular sites place on the environmental and climatic information that can be obtained. Thereafter, the type of drills to be used and the sites to be drilled should be chosen, the required equipment should be built, and core drilling to bedrock should be carried out. A program of shallow-and intermediate-depth core drilling will have to precede selection of the site for deep core drilling.

History of West Antarctica

About 120,000 years aro, the West Antarctic ice sheet may have largely disappeared, thereby discharging enough ice to raise sea level several meters. A large fraction of the world population now occupies coastal areas that were then flooded. Because the West Antarctic ice sheet may be inherently unstable, a similar rise in sea level might occur in the future, perhaps in response to climatic modification by human activities.

The possibe instability of the West Antarctic ice sheet should be a focus of multidisciplinary research in the coming decade. Variables that can provide information on the past history of the West Antarctic ice sheet, such as former elevation of the ice sheet, extent of sea ice, and paleoclimatic data should be measured on a core to bedrock and on intermediate-depth cores from the ice streams that drain West Antarctic ice. This information could be combined with geological and oceanographic evidence of past ice-sheet configurations and models of the current stability of the ice sheet.

Recommendation

HIGHEST PRIORITY. A continuous ice core to bedrock should be obtained from a site that will permit determination of the presence or absence of the West Antarctic ice sheet during past interglacials and will provide paleoclimatic data. These data can be supplemented by data from other cores and geophysical surveys within the Ross Embayment.

Identification of Climatic Information From Ice Cores

A major effort should be directed to establishing the transfer functions relating the signals measured in ice cores and the environmental and climatic processes responsible for them (see Committee on the Role of the Polar Regions in Climatic Change, in press). Large concentrations of some chemical elements may reflect a change in atmospheric composition or an extended period of low snowfall. Similarly, a change in the ratio of summer to winter snow accumulation will produce a stable-isotope signal equivalent to that produced from a change in average temperature. Thus to understand the true environmental record of ice cores, we must define clearly the relationship between local atmospheric conditions and the composition of recently deposited snow.

An ice-core signal reflects the combined contributions of global, hemispheric, regional, and local conditions. Addressing this problem requires comparison of polar ice-core signals with signals in cores from subpolar regions, with historical weather records, and with other sources of climate data (e.g., tree rings).

Recommendations

HIGHEST PRIORITY. The climatic and environmental information contained in ice cores should be compared with local or regional meteorological information, historical records of climatic and environmental changes, including past solar activity and volcanism, and long-term data from tree rings, lake and ocean sediment cores, and glacial deposits. To aid in this comparison, intermediate-depth ice cores should be obtained from a number of polar and nonpolar latitude bands and from diverse meteorological and glaciological environments.

HIGH PRIORITY. Air samples and pit and shallow core samples should be analyzed to:

1. Ensure the reliability of analytical procedures;
2. Investigate the relationship between atmospheric composition and the composition of fresh and aged snow;
3. Determine the short-range geographical variability of various ice-core signals; and
4. Explore the feasibility of using particular signals for dating ice cores.

Development and Application of Techniques

Recently, specialists have applied many analytical techniques to extract information from ice cores. The analytical problems are difficult because of the low concentrations present in the snowfall of Greenland and Antarctica. Yet each successful application of a new methodology has added a new dimension of insight into past environmental conditions. The development and improvement of methodologies should continue, as should their application to cores already obtained and future ones.

Recommendation

HIGH PRIORITY. Analytical methods should be developed, refined, and applied to the extraction from ice cores of information related to global anthropogenic pollution, climatic and environmental history, absolute age, and the past configuration and motion of the ice sheet.

RELATIONSHIPS BETWEEN GLACIERS AND CLIMATE

Glaciers form part of the global climate system. The smaller glaciers react passively to the climate, whereas ice sheets interact with or even control it. On intermediate scales, the processes and effects are not clear-cut: a large mountain glacier system may dominate the local climate; a large tabular iceberg may carry climatic anomalies with it during its drift. At the other extreme, some modeling results suggest that the deterioration of global climate to full glacial conditions may have trailed the development of ice sheets in North America and Scandinavia.

The relationships between glaciers and climate involve complex interactions on various spatial and temporal scales. More detailed descriptions can be achieved through two distinct but complementary approaches: observation of changes in the entire climatic system and formulation of deterministic or empirical rules from an adequate number of reoccurrences; construction of models and testing on one or more observed events to ensure that the essential physics of the problem is represented. For long time scales, observations simply lead to descriptions of existing conditions; modeling is then the only objective way to test understanding of both past and future relationships between ice and climate. We considered and assigned priorities to problems representing three different scales: mountain-glacier scale, mountain-range scale, and ice-sheet scale.

Problems of Mountain-Glacier Scale

Mountain glaciers and small ice caps have response times on the order of decades to centuries. On some glaciers, fluctuations have been observed over decades; for some of them, the climate of the surroundings is also adequately defined for at least part of that history. All the basic measurements needed to determine the response of a few glaciers to climatic variations have been made; these "classical" glaciers are the most suitable for combined observational studies and modeling experiments. The problems concern the selection of the most relevant meteorological parameters, and the model description of mass and energy exchange with the atmosphere, mass and energy transfer within the ice, and the processes of deformation and sliding.

Long-term measurements of meteorological factors, mass balances, and dynamics of representative glaciers are essential to an understanding of the coupling of climate to glaciers and the validation of models.

Recommendations

HIGHEST PRIORITY. Long-term measurements of the relevant aspects of the meteorological environment, together with basic glacial processes, should be continued on a few representative glaciers. The basic data sets should be put in a form that is understandable and communicated to the World Data Center-A for Glaciology and the Permanent Service on the Fluctuations of Glaciers.

PRIORITY. Detailed studies should be made of how meteorological processes control the mass and energy balances of glaciers in several environments.

Problems of Mountain-Range Scale

The results of studies of energy and mass balance on mountain glaciers should be extended to whole ice-clad mountain ranges. Of importance to North American investigators are the ranges bordering the North Pacific Ocean in Alaska, the Yukon Territory, and British Columbia, which contain the fourth-largest ice mass in the world and are a major climatic barrier. Large storms move across the Gulf of Alaska and impinge on these mountains, producing snow accumulation rates exceeding 10 m per year. The winter climate of much of North America may be affected by processes at this ice-covered border of the North Pacific. The rates of mass flux through these ice fields are among the highest in the world, with copious meltwater runoff that affects the environment of the productive near-shore waters of the Gulf of Alaska.

The glaciers also lie in a region of ever-increasing human activity, yet few comprehensive glacier-climate investigations have been conducted, and there are no long-term monitoring results. Only one cursory treatment of the regional mass balance exists.

Sources of energy and water vapor in the North Pacific are being studied through the Storm Transfer and Response Experiment. We need to examine this mountain glacier system as an energy and water-vapor sink and as a climate barrier.

Recommendations

HIGH PRIORITY. The regional glacial meteorology and mass exchange of the high mountains bordering the Gulf of Alaska should be determined.

PRIORITY. Less-detailed regional studies of mass and energy exchange in other areas should be conducted and the findings compared with those for the Gulf of Alaska.

Problems of Ice-Sheet Scale

The Greenland ice sheet contributes regionally to the thermal forcing of the atmosphere. How it interacts with the atmosphere is incompletely understood, especially its mass-balance regime and modification of the regime due to natural and human-induced atmospheric and oceanic changes. The Antarctic ice sheets and, formerly, the large Northern Hemisphere ice sheets have a much broader impact; they influence climate on a global scale.

Greenland Ice Sheet

Knowledge of the present precipitation and temperature regimes of the Greenland ice sheet is essential to the interpretation of the ice-core records. The precipitation and temperature patterns not only are related to the paths followed by the North American storms but also are influenced by new storms generated in the Icelandic "center of action," which is partly due to the ice sheet itself. Time and space variations in mass balance are imperfectly known, limiting verification of atmospheric circulation models. Until such problems are solved, the full value of ice-core results will not be realized.

Recommendation

HIGH PRIORITY. Research should be directed to understanding of the present climatologic regime of the Greenland ice sheet, the relation of its regime to atmospheric circulation patterns, and the verification of ice sheet/climate models.

West Antarctic Ice Sheet

The response of the West Antarctic ice sheet to climatic change is critical in view of the potential instability that might be triggered by CO_2-induced atmospheric and oceanic warming. Detailed recommendations for Antarctic climate research, many glaciological in nature, have been developed by the Group of Specialists on Antarctic Climate Research (1981). Bentley (1982) has examined research needs specifically for the West Antarctic ice sheet. We fully support both sets of recommendations. These two studies emphasize our lack of knowledge about components of surface mass balance, their relation to atmospheric and oceanic circulation, and the extent of sea ice. The studies emphasize the need to explore the use of satellite techniques, especially passive-microwave radiometry and altimetry, to determine the areal distribution of surface mass balance and changes in ice thickness and to monitor the changing coastline and grounding lines. Processes under ice shelves are also important, as discussed earlier in this chapter.

Recommendation

HIGHEST PRIORITY. Ground-based measurement of the surface mass balance and relevant meteorological variables for one or more complete drainage basins should be completed, and the results should be extended by satellite radiometry to the whole of the West Antarctic ice sheet and incorporated into atmospheric circulation models.

East Antarctic Ice Sheet

The size and long reaction times of the East Antarctic ice sheet and Pleistocene continental ice sheets pose problems of interpretation. Climate-related indicators measured in ice and ocean cores must be evaluated in relation to a climatic environment different from that of today.

The Group of Specialists on Antarctic Climate Research (1981) cites deficiencies in knowledge, particularly relevant to East Antarctica: insufficient climate-related observations for most of the ice sheet area; poor performance of general circulation models and other climate models, probably because of inadequately known boundary fluxes at the ice-sheet surface; inability to relate energy fluxes to katabatic winds and radiation transfer through clouds; and lack of a comprehensive climate-data archive.

Recommendation

HIGH PRIORITY. The atmospheric processes that control the mass balance of the East Antarctic ice sheet should be determined, including the tasks listed by the Group of Specialists on Antarctic Climate Research (1981).

7 Other Considerations

INSTRUMENTS AND TECHNIQUES

During the last decade major advances have occurred in measurement methods for the study of natural ice masses. On the ice sheets, notable ones are airborne radar sounding of bed and internal layers, satellite-altimetry measurement of surface elevation, satellite sensing and positioning systems, and more efficient determination of stable isotopes and other geochemical properties in ice-core samples. For the study of temperate glaciers, advances include monopulse radar systems to measure ice thickness, application of highly accurate surveying methods and recording strain meters to achieve high resolution of glacial geometry and motion changes, and new methods for direct observation of basal conditions and sliding. With the goals recommended in previous chapters in mind, continued advances in core drilling and analysis and in remote sensing--techniques that resulted in dramatic progress during the past decade--are especially desirable.

Many recommendations for the development of instruments and techniques applied to specific research tasks can be found in the preceding chapters. Although some of these needs are also mentioned here, the only formal recommendations listed are those of a general nature.

Drilling and Coring

In light of the high priority assigned to deep-ice-core and borehole investigations, there is a vital need to develop the capability of coring to the base of cold ice sheets. A comprehensive plan should be developed to provide for the application of shallow- and intermediate-core drilling and other techniques to the achievement of deep-coring objectives. The drill must recover continuous high-quality cores with sufficiently large diameters to permit analysis for a wide range of environmental information.

In addition, there is need for a drill that produces cores with a diameter larger than 100 mm; such cores can be pared down to their clean interiors for precise chemical analyses. Still-larger-diameter holes are needed for access to internal layers, to the glacier bed, and to the water beneath ice shelves.

Shallow-core (up to 100 m) drilling should continue to provide useful results, but shallow drills require substantial improvement. The main emphasis should be on light weight, speed, and reliability, so that cores can be obtained in remote locations without a drilling engineer. Intermediate-depth drilling capability, that is, to the maximum depth that can be obtained in an open hole, should also be improved.

Some deep-ice information, such as temperatures and shear strain rates, can be obtained, in principle, from meltsondes (robot probes). With some development, such probes could also be used for measuring mass balance on the underside of ice shelves and perhaps to determine ice fabrics or make in situ chemical analyses. Although meltsondes cannot replace drills, they could be valuable in helping to select suitable sites for deep drilling and in assessing the lateral variation of glacial parameters.

Finally, for glaciological as well as geological purposes, good bedrock samplers should be developed for use in any drill hole that reaches the base of a glacier.

Core Analysis

The principal need in core analysis is an effective method of age determination. For this purpose, the development of accelerator and laser dating methods, using minute quantities of radioactive isotopes, should be strongly encouraged. Other geochemical advances that await full exploitation require more efficient stable-isotope mass spectrometry for the rapid, complete analysis of large ice cores and an improvement in the detection of sub-ppb (parts per billion) concentrations of organic compounds by chemically sensitized electron capture. Improved quantitative methods are needed for nondestructive continuous scanning of physical properties along the core, such as the successful method for measuring electrical properties. Bulk physical (e.g., ultrasonic) methods of defining texture and fabric of ice should be complemented by methods of analyzing thin sections, perhaps using modern image-analyzing techniques, which are more efficient than manual measurements with a universal stage. To minimize the effect of the relaxation that occurs when deep-ice cores are brought to atmospheric pressure, development and use of methods to measure mechanical properties at the drill site should be continued, with storage of selected core samples in pressurized containers.

Borehole Equipment

Not only the cores but the drill holes themselves yield valuable information. Some examples of improvements to be sought in borehole equipment include: (a) the capability for in-hole chemical measurements and for study of both vertical and horizontal components of strain rates; (b) methods to supplement sonic logging in obtaining information about ice texture and fabric; (c) the means to improve continuous observations of glacier beds and glacial sliding, in particular, a method of stabilizing active subsole drift in the bottom of boreholes, perhaps by casing the hole bottom; and (d) methods for continuous monitoring of basal water pressure with systems that can survive unattended over a winter or the course of a surge.

Remote Sensing From Satellites

For reasons stated in Chapter 6, highest priority is assigned to placing into polar orbit a satellite with both a laser altimeter for high accuracy and a radar altimeter for complete surface elevation measurements. Another high priority is further development of techniques for separating and quantifying the effects of snow-layer thickness and structure and the physical temperature on microwave brightness temperatures. The study should include the examination of available microwave data, further theoretical analyses of emissivity from ice sheets, and coordination with field programs that can include direct measurements of mass balance. The development of horizontal-positioning (i.e., laser-ranging) systems with decimeter accuracy would be exceedingly useful.

Visual imagery from satellites, such as that obtained from LANDSAT, could be used for measuring the speed of outlet glaciers and changes in the glacial coastline of Antarctica as well as for monitoring the fluctuations of other glaciers. That satellite imagery might reveal blue-ice areas favorable for the accumulation of meteorites is a possibility that should be explored. Furthermore, the development of a stereoimage technique that would make possible three-dimensional mapping of Antarctica and other remote areas should be encouraged.

Other Remote Sensing

The Committee on Glaciology urges that the U.S. capability for airborne radar sounding be reactivated, with improved instrumentation. Particularly important is the inclusion of digital recording that will permit the use of modern signal-processing techniques to determine the properties of internal and basal reflectors. Signal-processing techniques should also be more widely applied to seismic measurements. Digital recording of various remotely sensed data will permit the application of geophysical inverse methods now commonly used to infer the internal structure of the earth. Radar techniques, with digital recording, should be emphasized for such applications as detecting the distribution and changes of internal voids in glaciers and their water content, measuring basal mass balance, determining englacial temperatures, and measuring the thickness of sea ice. In addition, other geophysical techniques, such as seismic or electrical-resistivity surveying, that will yield such information should also receive attention.

Frequency-modulated probing systems for measuring freshwater ice thickness should be tested. These systems might yield better data than impulse sounders, without the need for high voltages. The use of remote-sensing systems to monitor potential ice jams, breakup of river ice, and the details of lake-ice cover should also be explored.

Remote sensing of snow cover is vitally important.

Many approaches to sensing the snow inventory are possible because snow responds to electromagnetic radiation of different wavelengths in different ways.

Many of the problems encountered with sea ice, particularly those in the sheer zone and marginal ice zone, are ideally suited for the application of remote-sensing techniques to facilitate a quantitative characterization of the upper surface of the ice. All major sensor types (visible, infrared, and microwave imagers, radar, and laser) can contribute to an improved assessment of many ice problems. In particular, analytical techniques for determining basic sea-ice parameters from passive and active microwave data should be further developed. Data buoy capabilities should be improved, with emphasis on the develoment of sensors capable of stable unattended operation in a hostile environment.

An array of air-deployed buoys measuring atmospheric surface pressure, air temperature, and position (ARGOS) has been in operation since early 1979 in the central Arctic. Such unmanned data buoys provide a logistically "neat" way of acquiring, on a routine basis, oceanic and meteorological data that could be used to assess dynamic and thermodynamic simulations of ice distributions. All these remote-sensing techniques should be systematically applied in both polar regions, but particularly in Antarctica.

Other Field Equipment and Techniques

Several instruments and methods for studying the sliding of a glacier on its bed have been mentioned; important for the same purpose are techniques to measure forces and temperature in bed features, for example, where access is provided by tunnels, and a simple, if only approximate, method for continuously measuring discharge and sediment transport in glacier-fed streams. Instruments and techniques are needed for making in situ tests of snow cover without disturbing the snow. Measurements of the strength and liquid-water content are particularly important. Another need is techniques to measure, in situ, liquid water in temperate ice and brine in sea ice and to study the mechanical behavior of ice with a liquid phase. Both liquid water and brine affect the mechanical properties of ice, and both are subject to change during transport to the laboratory.

Laboratory Studies on Ice Techniques

Techniques are needed: (a) for running tests on the mechanical behavior of ice in response to large strains, in either compression or tension, without unduly distorting sample geometry and (b) for determining the behavior of ice at low (< 0.5 bar) stresses and low temperatures over shorter time scales of a year or less. Some results suggest that tests might be started at higher temperatures and run nearly to the point of minimum strain rate before lowering the temperature; this approach should be studied further. In view of the widely varying results obtained in ostensibly similar mechanical tests, both within a given laboratory and between laboratories, the need for standardization of test procedures is evident. Basic requirements are that the minimum linear dimension of a test sample be at least 10 times the maximum grain size and that length-to-diameter ratios be kept in excess of 2. In addition, the texture, fabric (including orientation with respect to applied stress), and impurity content of the samples should be reported. Thermal stresses induced on a sample by fluctuations (cycling) of cold-room temperature may enhance creep rates; this possibility should be explored.

New approaches to glaciologically pertinent problems include the use of dopants and other chemicals to create artificial and synthetic ices as substitutes for natural ice in physical modeling and scaled-down tests of engineering design. Correct scaling of the physical and structural properties of artificial ice is imperative, and promising results have been obtained with urea (carbamide) ice as a substitute for sea ice.

LOGISTICS

Support for Antarctic Ground Programs

Studies that involve extensive measurements on the surface or at relatively closely spaced stations lie at the heart of the investigation of the West Antarctic ice sheet and its response to climatic change. Techniques for making the measurements are largely available, but the necessary supporting vehicles are not. Adequate logistic support is essential for successful study of the West Antarctic ice sheet.

Airborne Field Laboratory

An efficient means of supporting systematic shallow-, and perhaps even intermediate-core, sampling of Antarctica and Greenland might be a moderate-size airplane, equipped as a geophysical and geochemical laboratory and capable of open-field landings. Complementary work to be carried out at each drilling site would include Doppler-satellite 3D positioning; measurement, by radar and other remote-sensing techniques, of ice thickness, internal layering, crystal sizes and orientations, and temperature; and on-the-spot core measurements, such as isotope and trace-element analyses and the determination of mechanical properties and crystal fabrics. The Committee on Glaciology urges that serious consideration be given to the development of an airborne field laboratory for core drilling and concomitant studies on ice sheets.

Logistics Support in the Alaska/Yukon Region

Even though commercial facilities are available and the net costs are lower than they are in the Antarctic, logistic support for many projects in the Alaska/Yukon region has been inadequate because these costs must be included explicitly in research budgets. Research operations can become hazardous when they are conducted without adequate logistic backup. Federal agencies supporting glaciological research programs in the Alaska/Yukon region should ensure that adequate logistic support is provided.

Operational Use of Data on Arctic Sea Ice

Some data on Arctic sea ice are of immediate use for operational purposes. As a guide to data-processing requirements, the types of data products, their users, and the time constraints in processing and use should be defined. If, for example, SAR images of the marginal ice zone at noon each day are to be made available to fishermen in the Bering Sea three hours later, what data-processing and distribution facilities will be required? Some balance must be struck between the amount of raw data that can be collected and the volume that can be processed and distributed in a given time interval.

INTERNATIONAL COOPERATION

The International Geophysical Year (IGY) demonstrated the value of international cooperation in polar research, and numerous subsequent projects have confirmed it. Several important studies of Arctic sea ice and its relation to climate have succeeded in part because of the strong component of international cooperation, organized by the Global Atmospheric Research Program (GARP) and other international bodies.

Multinational composition was an important element in the success of the Greenland Ice Sheet Project (GISP) and the Ross Ice Shelf Project (RISP) and has been particuarly productive in the study of ice cores. Teams of researchers from several different countries have combined their talents in obtaining a wealth of data on the basic physical properties of ice cores from a number of locations in Antarctica and the Arctic. The large and expanding number of productive studies on ice cores, and the limited number of laboratories capable of undertaking such studies, make it essential that international cooperation in the study of ice cores continue. Furthermore, continued cooperation on drilling should help to avoid the redundant development of highly expensive drilling equipment.

The International Antarctic Glaciological Project (IAGP), which now joins six expeditions for the study of a large part of the East Antarctic ice sheet, is a broad cooperative venture. The IAGP has a Coordinating Council with equal glaciological and logistic representation, which enables the IAGP to react flexibly to changes in national situations. This concept should be considered for future projects, such as the proposed intensive study of the West Antarctic ice sheet.

Another area for international cooperation is the use of LANDSAT images to produce accurate 1:250,000-scale planimetric image maps and aeronautical charts of Antarctica. The United States, the United Kingdom, Australia, and Japan have all published one or more LANDSAT image maps, and New Zealand, Germany, and South Africa plan to in the near future. The United States could work with other interested countries to produce optimum LANDSAT images through computer-enhancement techniques (see section on "Management of Glaciological Data"), then publish the desired maps.

Other glaciological projects that already involve a large degree of international cooperation include the evaluation and utilization of the worldwide, International Hydrological Decade (IHD) combined heat/mass/water-balance studies and the surveys of the world's glaciers and their fluctuations. These activities are coordinated by the International Commission of Snow and Ice (ICSI) and its specialized subdivisions (see section on "Organization of Snow and Ice Sciences"). The ICSI also has organized international reviews of basic problems. Of equal polar significance are some of the symposia organized by the International Glaciological Society (IGS).

Advancing theoretical understanding and numerical modeling of glaciers and ice sheets is an international effort that proceeds through publications and symposia. Progress on specific problems has been accelerated at times by bringing the best talent and experience together for intensive interaction. Examples are the workshop of theoretical specialists that developed the broad research strategy for the IAGP in Moscow in 1971, the 1973 Cambridge Workshop on the Interpretation of Isotope and Temperature Profiles in Ice, the 1979 ICSI Workshops on the Flow Law of Ice, and the 1981 Cambridge meeting of experts on a SCAR contribution to the World Climate Research Program (WCRP). The continuing need of the WCRP for polar information and expertise is shown by the support for a 1982 workshop on the role of sea ice in climate variations and for the planned IGS Symposium on Ice and Climate Modeling at Evanston, Illinois, in 1983. The United States should continue to support such workshops and symposia.

International sharing of expertise and experience in the study of physical properties of snow and ice is in the best interests of all concerned nations in order to avoid unnecessary duplication of effort. Such cooperative studies can lead to improvement in experimental techniques and to the identification of physical or chemical processes previously considered to be unimportant. In the study of mechanical properties, an interlaboratory exchange of samples, similar to that carried out by many geochemical laboratories, might help to resolve some of these discrepancies currently characterizing the data.

Programs for the exchange of personnel are especially productive; such exchanges should take place for field work as well as for laboratory measurements and data analysis.

The mechanics of cooperative work are more difficult than for mainly U.S. programs, but the scientific returns can be great. Other nations have expertise that the United States lacks; the exchange of results and ideas is valuable for all participants.

MANAGEMENT OF GLACIOLOGICAL DATA

Status

A so-called information explosion is occurring in the geophysical sciences as a result of the new high-volume data-retrieval systems associated with remote-sensing and computer-processing techniques. Although the collection of certain types of snow and ice data will continue to be associated with specialized research activities, there is an accelerating trend toward automated acquisition of large-scale digital information from satellites, aircraft, and data-collection platforms.

The framework for archiving and distributing snow and ice data internationally was established in connection with the IGY in 1957, through the International Council of Scientific Unions (ICSU) system of World Data Centers. In the case of glaciology, information exchange has been limited largely to published reports. Moreover, the information deposited in the World Data Centers for Glaciology has pertained principally to glaciers and ice sheets. Indeed, the full scope of glaciology--embracing all phenomena and processes of naturally occurring snow and ice--is often not appreciated by atmospheric and oceanographic scientists. In the national setting, snow and ice research is scattered among several federal and other agencies and institutions (see section on "Organization of Snow and Ice Sciences"). As a result of this fragmentation, there are no comprehensive archives of snow and ice data, and, as yet, there is no national umbrella organization to oversee "distributed" data sets as these begin to be assembled in each of the subfields. The principal centers for glaciological data and information at the present time are World Data Center-A (WDC-A) for Glaciology and the associated National Snow and Ice Data Center, operated by the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder, for NOAA; and the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. In addition, ice-core material is held by the Central Ice Core Storage Facility at Buffalo, New York, and satellite data on snow and ice are collected and archived by NOAA and NASA.

To determine what basic scientific data from polar areas exist, WDC-A for Glaciology has undertaken inventories of data products pertaining to snow cover, sea ice, and ice cores. The need for specific types of data is best established by workshops that bring together the scientific groups generating data, the potential users, and data managers.

Data Management Needs

The archiving and management of data sets require that suitable data formats be established and that appropriate quality controls be applied. For ease of storage and retrieval of information, as many as possible of the data should be recorded in digital form. Data catalogs that describe changes in observational methods, resolution, and frequency should be prepared. This need is particularly critical in the case of remotely sensed data, for which the sensor specifications and data-processing algorithms change frequently.

A general problem in the geophysical sciences is that scientific projects are rarely provided with sufficient funds to assemble, document, and distribute processed data. The resources available to the national and world data centers are insufficient for them to handle all of the priority tasks that have been identified. To ensure optimal results from major national and international research programs, it is essential that plans for data management be made in conjunction with the scientific planning and that funds for their implementation be designated. Funding agencies could make such arrangements a requirement of their research awards. Suitable guidelines for the timely release of research data to data centers, and for their documentation, subsequent management, and dissemination to other potential users, should be prepared by the appropriate committees of the National Research Council.

PRIORITY. Funding agencies should ensure that there is adequate advance planning for data management and provision of funds and other resources for implementation of such plans in all research and operational programs that will generate data. Thus, proposals for major scientific experiments should include a plan for data management and archiving and for meeting the costs of these operations.

PRIORITY. The National Snow and Ice Data Center (NSIDC) should coordinate the preparation of inventories and catalogs describing data sets held by the various organizations and individuals involved in snow and ice research. There is particular need for standardized digital archives of global sea-ice concentrations and limits, depth of snow cover, dates of breakup and freeze-up of freshwater ice, glacier and ice-sheet topographies and thicknesses, and Antarctic cartographic information. Many of these data are now collected but are not readily accessible in digital form. The NSIDC should also undertake the rescue, archiving, and management of "historical" data sets.

Special Considerations in Antarctic Mapping

Because the existing source material for Antarctic mapping varies tremendously in the scale, availability, type, and accuracy of the data, because the basic geography is not yet entirely known, and because the floating ice margins of Antarctica change, maps repeatedly need revision. A digital data base would markedly simplify the revision of existing maps as new and better data become available. All images and photographs in the U.S. SCAR Photo Library (maintained by the U.S. Geological Survey) and other types of satellite images, too, should be recorded on random-access videodiscs, be entered into a computer data base for retrieval by geographic area, and made easily accessible to the scientific community. Other SCAR nations should be encouraged to record their aerial photos and satellite images of Antarctica similarly for international exchange. The United States could also take the lead in making all map and image data of Antarctica more readily accessible.

At least three sets of photographic records are in danger of being lost and should be preserved in a central data repository: (1) Classified photo-reconnaissance data of polar areas have special significance for monitoring fluctuations of glaciers. As these data will eventually be declassified, steps should be taken to ensure that they are not destroyed in the meantime. (2) Many of the early LANDSAT videotapes of polar areas have now deteriorated to the point that only the film archive remains for scientific use. Action must be taken to ensure that the remaining film data are properly stored, so that they can be used indefinitely. (3) Although the U.S. Geological Survey already archives all LANDSAT images of Antarctica on 70-mm film at the EROS Data Center (EDC), the computer-compatible tapes (CCTs) that are needed to make enhanced images for high-quality maps remain with NASA. Because NASA plans in the near future to discontinue storage of pre-December 1976 LANDSAT CCTs, and because most of the Antarctic data predate December 1976, it is imperative that action be taken to preserve all relevant CCTs.

Recommendations

PRIORITY. Steps should be taken to ensure that CCTs and film transparencies of all optimum LANDSAT images of Antarctica, in particular those predating December 1976, be permanently preserved by the United States. (Optimum LANDSAT images are defined as those that provide complete coverage of Antarctica from the coast to about 81° South latitude, and multiple, sequential coverage of areas where measurable dynamic change is occurring [e.g., termini of outlet glaciers]).

PRIORITY. Photographs in the SCAR Photo Library of the U.S. Geological Survey should be entered into a computer data base, and an index of these photographs should be made available through the WDCs. Other SCAR nations should be encouraged also to put their Antarctic aerial photographs on random-access videodiscs.

ORGANIZATION OF SNOW AND ICE SCIENCES

Snow and ice research is conducted by specialists in such diverse fields as atmospheric science, chemistry, engineering, geography, geophysics, hydrology, oceanography, and physics. Glaciologists, working in the small number of institutions and university groups that are involved in snow and ice studies, usually approach their problems from some specific standpoint, such as snow hydrology, avalanche protection, ice geophysics, sea-ice mechanics, ice and climate interactions, or remote sensing. As a result, many agencies and organizations are concerned with some particular facet of ice or snow research, but there are few focal points.

International Structure

Internationally, snow and ice studies are coordinated through:

1. The International Commission of Snow and Ice of the International Association of Hydrological Sciences (IAHS) and its specialized programs, such as the Temporary Technical Secretariat for the World Glacier Inventory, and long-term international projects, such as the International Hydrological Program of UNESCO/WMO;
2. The Scientific Committee on Antarctic Research, its Working Group on Glaciology (and ad hoc groups of specialists), and the Scientific Committee on Oceanic Research (SCOR);
3. The World Meteorological Organization, through various panels and ad hoc groups involved with the World Climate Program;
4. The WDCs for Glaciology (Snow and Ice) (WDC-A in Boulder, Colorado; WDC-B in Moscow, USSR; and WDC-C in Cambridge, England) and the Permanent Service for Fluctuations of Glaciers (PSFG) in Zurich, Switzerland, which have responsibility for the international exchange of snow and ice data and information, and for data on glacier fluctuations, respectively. Both operate under

the aegis of the International Council of Scientific Unions (see section on "Management of Glaciological Data").

In addition, there are short-term international collaborative programs such as those developed during the International Polar Years (1882 and 1932) and the IGY (1957), the recent International Antarctic Glaciological Program, and the Polar Experiment subprogram of the Global Atmospheric Research Program.

The principal scientific organizations involved in the publication of snow and ice research or in holding international symposia are the International Glaciological Society, the International Association of Hydrologic Sciences of the International Union of Geodesy and Geophysics, the International Association of Hydraulic Research, the Ports and Ocean Arctic Engineering conferences, and the International Union for Quaternary Research.

National Coordination and Support

Planning of U.S. snow and ice research is coordinated by the Polar Research Board through its Committee on Glaciology, Committee on Permafrost, and ad hoc study groups. Research is conducted within and supported by many agency programs; the primary source of funds for university groups is the National Science Foundation's Division of Polar Programs. However, funding for nonpolar glaciology (such as snow hydrology) generally must be obtained from other divisions. Federal agencies with in-house programs that can provide limited support for external groups are:

1. The U.S. Department of Agriculture, including (a) the Soil Conservation Service for snow surveys, and (b) the Forest Service for avalanche studies);
2. The U.S. Department of Commerce--the National Oceanic and Atmospheric Administration, including:
   (a) Environmental Research Laboratories (Great Lakes ice--Great Lakes Environmental Research Laboratory);
   (b) the Pacific Marine Bering Sea Ice Environmental Laboratory;
   (c) the National Weather Service (Office of Hydrology), airborne snow surveys and snowmelt modeling; and

(d) the National Environmental Satellite Data and Information Services, satellite mapping of snow and ice cover and the National Snow and Ice Data Center, the National Climate Center, and the National Geophysical Data Center;

3. The U.S. Department of Defense, including (a) the U.S. Air Force, satellite mapping of snow cover; (b) the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), general snow and ice science and engineering; and (c) the U.S. Navy, forecasting and mapping of sea ice;

4. The U.S. Department of Energy (CO_2 program) for certain climate-related studies;

5. The U.S. Department of the Interior, including (a) the Geological Survey, glaciers and mountain snow; and (b) the Bureaus of Reclamation and Land Management and the Office of Water Resources Research, snow studies;

6. The U.S. Department of Transportation, snow and ice relating to highways and aviation; and

7. The National Aeronautics and Space Administration, climate, ocean, snow and ice studies and the collection and use of remotely sensed data.

In addition, there is substantial research in the private sector on snow and ice engineering, and many state governments conduct specific studies.

Major U.S. laboratory facilities for snow and ice research exist only at the U.S. Army Cold Regions Research and Engineering Laboratory at Hanover, New Hampshire (140 scientists and technicians). Several universities and government organizations have specialized small-scale laboratory facilities. In addition, there are small groups of researchers at about a dozen other institutions.

Successful large-scale cooperative national research programs have been organized in the Arctic (e.g., the Arctic Ice Dynamics Joint Experiment, the Greenland Ice Sheet Project) and the Antarctic (the Ross Ice Shelf Project). In the Antarctic, there are field facilities to support such activities, supplied by U.S. Navy ships and aircraft. The political framework for glaciological and other scientific work in the south polar region is the Antarctic Treaty. There is currently no permanent U.S. field base in the north polar region.

No single division of the National Science Foundation has responsibility to provide funds for all aspects of snow and ice science. No single agency or institution actively coordinates the snow and ice research of individual agencies and institutions in the United States. The implementation of the scientific aims of snow and ice research programs, national or international, necessitates some coordination or integration of field and laboratory programs, logistic and instrumental requirements, and data management and archiving. Traditionally, such activities have been handled in a largely ad hoc manner. It is increasingly apparent, however, that to ensure maximum returns for the funds and efforts invested, more coherent planning will be necessary in the future, including the design or scheduling of suitable specialized equipment for field use, the timely processing of field data, planning for ice-sample or data distribution to cooperating scientists, and the archiving of data. Support for coordination, planning, and data archiving is essential, but this funding frequently falls outside the purview of particular agencies. A first step in determining the scope of this problem would be to document the organizations, groups, and number of individuals currently involved in snow and ice research, and the available technical support and training programs, in relation to national needs and priorities in these areas. For example, the United States benefits from the scientific, technical, and logistical expertise of other nations, but the specific ways in which such cooperation might complement national capabilities is not clear.

Recommendation

PRIORITY. A survey should be made of the number of researchers and institutional facilities engaged in snow and ice studies in the United States.

Education

Scientific education and ways of attracting new talent into specific fields are broad questions that cannot be fully explored in this report. Briefly, the situation in glaciology is that graduate training programs exist in many universities and are more than sufficient for the number of people entering the profession. In fact, contrary to the view expressed in the 1970 Survey, relatively few investigators are currently engaged in research on the fundamental properties of ice. A major barrier to more rapid progress in the study of the physical properties of ice is a perceived lack of job opportunities, with a consequent lack of incentive for students to enter the field.

Employment opportunities are probably best for specialists in sea ice, because it poses major problems for energy production and transportation in the Arctic. The growing national concern with climatic change could lead to expanded opportunities for glaciologists of all kinds, but the present shortage of job opportunities is a major barrier to more rapid progress in academic glaciological research. Consequently, the guiding principle for specialized education in glaciology must be that the course of study prepare the student for a career in some other field as well. This requirement means that subjects in physics, chemistry, meteorology, oceanography, and solid-earth geophysics are desirable components of an educational program in glaciology. Such a broad-based program, of course, also is consistent with the multidisciplinary nature of the science. As the need for expertise in glaciology increases, in both private and the public organizations, employers can be expected to take serious note of such programs.

References

Ad Hoc Study Group on Glacier and Ice Sheet Sliding, Committee on Glaciology, Polar Research Board (1976). Glacier and Ice Sheet Sliding. National Academy of Sciences, Washington, D.C.

Andersen, B. G., W. F. Weeks, and J. Newton (Eds.) (1980). "The seasonal sea ice zone. Proceedings of an international workshop." In Cold Regions Science and Technology, Volume 2 (1-357). Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.

Arctic Ocean Energy Balance Working Group, Scientific Committee on Oceanic Research (1979). The Arctic Ocean Energy Balance. Scientific Committee on Oceanic Research, Halifax, Nova Scotia.

Baker, D. J., U. Radok, and G. Weller (1980). "Polar atmosphere-ice-ocean processes: A review of polar problems in climate research." In Reviews of Geophysics and Space Physics, 18(2): 525-543.

Bentley, C. R. (1982) Carbon Dioxide Effects Research and Assessment Program. Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change; Volume II, Part 1. DOE/EV/10019-02. U.S. Department of Energy, Washington, D.C.

Climate Research Committee, Climate and Atmospheric Sciences Board (In press). The CO_2-Climate Fingerprint. National Academy Press, Washington, D.C.

Committee on Arctic Seafloor Engineering, Marine Board (1982). Understanding the Arctic Seafloor for Engineering Purposes. National Academy Press, Washington, D.C.

Committee on Permafrost, Polar Research Board (In press). Permafrost Research: An Assessment of Future Needs and Priorities. National Academy Press, Washington, D.C.

Committee on Polar Research (1970). Polar Research - A Survey. National Academy of Sciences, Washington, D.C.

Committee on the Arctic Oil and Gas Reserves (1981). U.S. Arctic Oil and Gas. National Petroleum Council, Washington, D.C.

Committee on the Role of the Polar Regions in Climatic Change, Polar Research Board (In press). The Polar Regions and Climatic Change. National Academy Press, Washington, D.C.

Committee to Evaluate Antarctic Marine Ecosystem Research, Polar Research Board/Ocean Sciences Board (1981). An Evaluation of Antarctic Marine Ecosystem Research. National Academy Press, Washington, D.C.

Group of Specialists on Antarctic Climate Research, Scientific Committee on Antarctic Research (1981). Basis for an Action Plan on Antarctic Climate Research. Scientific Committee on Antarctic Research, Cambridge, England.

Hooke, R. LeB., M. Mellor, W. F. Budd, et al. (1980). "Mechanical properties of polycrystalline ice: An assessment of current knowledge and priorites for research." In Cold Regions Science and Technology, Volume 3 (pp. 263-275). Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.

Joint PRB/GARP/CAS/OSB Polar Experiment (POLEX) Panel (1974). U.S. Contribution to the Polar Experiment (POLEX). Part 1. POLEX-GARP (North). National Academy of Sciences, Washington, D.C.

Joint PRB/GARP/CAS/OSB Polar Experiment (POLEX) Panel (1976). U.S. Contribution to the Polar Experiment (POLEX). Part 2. POLEX-GARP (South). National Academy of Sciences, Washington, D.C.

Panel on Glaciology, Committee on Polar Research (1974). Antarctic Glaciology: Guidelines for U.S. Program Planning 1973-1983. National Academy of Sciences, Washington, D.C.

Panel on Glaciology, Committee on Polar Research (1967). "Glaciology in the Arctic." In Transactions of the American Geophysical Union, 48(2): 759-767.

Panel on Polar Ocean Engineering, Marine Board (1979). Engineering at the Ends of the Earth: Polar Ocean Technology for the 1980s. National Academy Press, Washington, D.C.

Panel on Sea Ice Mechanics, Marine Board (1981). Research in Sea Ice Mechanics. National Academy Press, Washington, D.C.

Science Applications Working Group, National Aeronautics and Space Administration (1979). Ice and Climate Experiment (ICEX). National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland.

United Nations Educational, Scientific, and Cultural Organization (1978). Climatic Roles of Ice . United Nations Educational, Scientific, and Cultural Organization, Geneva, Switzerland.

U.S. Army Cold Regions Research and Engineering Laboratory (1981). A Program for Mesoscale Air-Ice-Ocean Interaction Experiments in Arctic Marginal Ice Zones. I. Research Strategy. CRREL Special Report 81-19 (1981). U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Working Group on Snow and Ice Hydrology, U.S. National Committee for the International Hydrological Decade (1976). Snow and Ice Research in the United States - Current Status and Future Directions. Final Report. National Academy of Sciences, Washington, D.C.

World Meteorological Organization (1977). On the Role of Sea Ice in the Climate System. World Meteorological Organization, Geneva, Switzerland.

World Meteorological Organization (1982). Report of the WMO/CAS-JSC-CCCO Meeting of Experts on the Role of Sea Ice in Climatic Variations, with Special Reference to Antarctica (WCP-26) . World Meteorological Organization, Geneva, Switzerland.

World Meteorological Organization-International Council of Scientific Unions (1975). The Physical Basis of Climate and Climate Modeling. GARP Publication No. 16. World Meteorological Organization-International Council of Scientific Unions, Geneva, Switzerland.

World Meteorological Organization-International Council of Scientific Unions (1978). The GARP Polar Sub-Program. World Meteorological Organization-International Council of Scientific Unions, Geneva, Switzerland.