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REPORT GD-11

GLACIOLOGICAL DATA

SNOW WATCH 1980

World Data Center A
for
Glaciology
[Snow and Ice]

October 1981

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NOTES:

1. World Data Centers conduct international exchange of geophysical observations in accordance with the principles set forth by the International Council of Scientific Unions. WDC-A is established in the United States under the auspices of the National Academy of Sciences.

2. Communications regarding data interchange matters in general and World Data Center A as a whole should be addressed to: World Data Center A, Coordination Office (see address above).

3. Inquiries and communications concerning data in specific disciplines should be addressed to the appropriate subcenter listed above.

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REPORT GD-11

SNOW WATCH 1980

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DESCRIPTION OF WORLD DATA CENTERS[1]

WDC-A: Glaciology (Snow and Ice) is one of three international data centers serving the field of glaciology under the guidance of the International Council of Scientific Unions Panel of World Data Centers. It is part of the World Data Center System created by the scientific community in order to promote worldwide exchange and dissemination of geophysical information and data. WDC-A endeavors to be promptly responsive to inquiries from the scientific community, and to provide data and bibliographic services in exchange for copies of publications or data by the participating scientists.

1. The addresses of the three WDCs for Glaciology and of a related Permanent Service are:

World Data Center A
University of Colorado
Campus Box 449
Boulder, Colorado, 80309 U.S.A.

World Data Centre C
Scott Polar Research Institute
Lensfield Road
Cambridge, CB2 1ER, England

World Data Center B
Molodezhnaya 3
Moscow 117 296, USSR

Permanent Service on the Fluctuations of Glaciers - Department of Geography
Swiss Federal Institute of Technology
Sonneggstrasse 5
CH-8092 Zurich, Switzerland

2. Subject Matter

WDCs will collect, store, and disseminate information and data on Glaciology as follows:

Studies of snow and ice, including seasonal snow; glaciers; sea, river, or lake ice; seasonal or perennial ice in the ground; extraterrestrial ice and frost.

Material dealing with the occurrence, properties, processes, and effects of snow and ice, and techniques of observing and analyzing these occurrences, processes, properties, and effects, and ice physics.

Material concerning the effects of present day and snow and ice should be limited to those in which the information on ice itself, or the effect of snow and ice on the physical environment, make up an appreciable portion of the material.

Treatment of snow and ice masses of the historic or geologic past, or paleoclimatic chronologies will be limited to those containing data or techniques which are applicable to existing snow and ice.

3. Description and Form of Data Presentation

3.1 General. WDCs collect, store and are prepared to disseminate raw[+], analyzed, and published data, including photographs. WDC's can advise researchers and institutions on preferred formats for such data submissions. Data dealing with any subject matter listed in (2) above will be accepted. Researchers should be aware that the WDCs are prepared to organize and store data which may be too detailed or bulky for inclusion in published works. It is understood that such data which are submitted to the WDCs will be made available according to guidelines set down by the ICSU Panel on WDCs in this Guide to International Data Exchange. Such material will be available to researchers as copies from the WDC at cost, or if it is not practicable to copy the material, it can be consulted at the WDC. In all cases the person receiving the data will be expected to respect the usual rights, including acknowledgement, of the original investigator.

[1]International Council of Scientific Unions. Panel on World Data Centers. (1979) Guide to International Data Exchange Through the World Data Centres. 4th ed. Washington, D.C. 113 p.

+The lowest level of data useful to other prospective users.

This Guide for Glaciology was prepared by the International Commission on Snow and Ice (ICSI) and was approved by the International Association of Hydrological Sciences (IAHS) in 1978.

3.2 Fluctuations of Glaciers. The Permanent Service is responsible for receiving data on the fluctuations of glaciers. The types of data which should be sent to the Permanent Service are detailed in UNESCO/IASH (1969)*. These data should be sent through National Correspondents in time to be included in the regular reports of the Permanent Service every four years (1964-68, 1968-72, etc.). Publications of the Permanent Service are also available through the WDCs.

3.3 Inventory of Perennial Snow and Ice Masses. A Temporary Technical Secretariat (TTS) was recently established for the completion of this IHD project at the Swiss Federal Institute of Technology in Zurich. Relevant data, preferably in the desired format**, can be sent directly to the TTS or to the World Data Centers for forwarding to the TTS.

3.4 Other International Programs. The World Data Centers are equipped to expedite the exchange of data for ongoing projects such as those of the International Hydrological Project (especially the studies of combined heat, ice and water balances at selected glacier basins***), the International Antarctic Glaciological Project (IAGP), the Greenland Ice Sheet Project (GISP), etc., and for other developing projects in the field of snow and ice.

4. Transmission of Data to the Centers

In order that the WDCs may serve as data and information centers, researchers and institutions are encouraged:

4.1. To send WDCs raw+ or analyzed data in the form of tables, computer tapes, photographs, etc., and reprints of all published papers and public reports which contain glaciological data or data analysis as described under heading (2); one copy should be sent to each WDC or, alternatively, three copies to one WDC for distribution to the other WDCs.

4.2. To notify WDCs of changes in operations involving international glaciological projects, including termination of previously existing stations or major experiments, commencement of new experiments, and important changes in mode of operation.

*UNESCO/IASH (1969) Variations of Existing Glaciers. A Guide to International Practices for their Measurement.

**UNESCO/IASH (1970a) Perennial Ice and Snow Masses. A Guide for Compilation and Assemblage of Data for a World Inventory; and

Temporary Technical Secretariat for World Glacier Inventory. Instructions for Compilation and Assemblage of Data for a World Glacier Inventory.

***UNESCO/IASH (1970b) Combined Heat, Ice and Water Balances at Selected Glacier Basins. A Guide for Compilation and Assemblage of Data for Glacier Mass Balance Measurements; and

UNESCO/IASH (1973) Combined Heat, Ice and Water Balances at Selected Glacier Basins. Part II, Specifications, Standards and Data Exchange.

+The lowest level of data useful to other prospective users

FOREWORD

This issue constitutes a new departure for publications in the Glaciological Data series. It reports the results of a workshop sponsored by the National Science Foundation, Washington, D.C. to review the status of data on large-scale snow cover extent and depth. The results of the SNOW WATCH meeting represent an extension of the first Workshop on Snow Cover and Sea Ice Data, held at the World Data Center-A for Glaciology in November 1978. We are, therefore, pleased to assist in disseminating this new information to the wider glaciological community. The publication of this issue is supported in part by the National Science Foundation, Climate Dynamics Program.

The next issues will feature a bibliography on the hydrology of glacierized areas and a report on the WDC's September 1981 Workshop on Radio Glaciology.

R. G. Barry
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Glaciology (Snow and Ice)

PREFACE

Snow is one of the key variables of the climate system. Before weather satellites, it was impossible to monitor seasonal snow and pack ice fields in both hemispheres. Variations in their extent and duration are studied as possible indicators of trends and large scale changes in weather patterns.

The world wide contamination of the atmosphere by carbon dioxide released from fossil fuels is expected to show its first detectable climatic effects in the snow and ice fields of the two hemispheres (Manabe and Wetherald, 1975; Ramanathan et al., 1978). In only a few decades the rising CO_2 level could profoundly change the climate of the high latitudes.

No wonder that the number of researchers using snow and ice data is growing rapidly. To provide for better coordination among these researchers and to prevent possible data misinterpretation, a number of small workshops have been organized. The first took place in Boulder, Colorado, 2-3 November 1978. Results of that meeting are described in Glaciological Data, Report GD-5, World Data Center-A for Glaciology, May 1979.

SNOW WATCH participants met again 1-2 October 1980 at the National Science Foundation, Washington, D.C. Attendees are listed on p. 9 this volume. The contributions presented during the workshop are summarized in this publication.

The focus of the meeting was on the large-scale climatic impact and climate modeling of seasonal snow fields deposited either on land or on sea ice. The following questions were asked:

1. What are the data on the large-scale extent of seasonal snow and how accurate are in space and time?

2. What data exist on the regional reflectivity of snow and ice fields, and how accurate are they?

3. What data exist on snow thickness and water equivalent and how accurate are they?

The contents of this volume are divided into five sections. The first lists the recommendations made by workshop attendees; the second section gives a list of mailing addresses of the participants; the third describes the role of snow in modeling and climate analysis: the fourth, the content and accuracy of snow and ice cover charts; the fifth and last section discusses the digital products and indices related to snow and ice.

References

Manabe, S.; Wetherald, R.T. (1975) The effects of doubling the CO_2 concentration on the climate of a general circulation model. Journal of the Atmospheric Sciences, v.32, p.3-15.

Ramanathan, V.; Lian, M.S.; Cess, R.D. (1978) Increased atmospheric CO_2:zonal and seasonal estimates of the effect on the radiation energy balance and surface temperature. Journal of Geophysical Research, v.84, p.4949-4958.

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CONTENTS

Kukla, G; Hecht, A.; Wiesnet, D. eds. (1981) SNOW WATCH 1980. Proceedings of the Workshop held 1-2 October 1980 in Washington, D.C. Boulder, Colorado, World Data Center A for Glaciology (Snow and Ice), Glaciological Data, Report GD-11, p. 1 - 7 .

SNOW WATCH 1980
RECOMMENDATIONS

The participants divided into four working groups; each group discussed the state of the art in a given area and recommended actions deemed to be of the highest urgency.

The working groups were:

I. Snow and Ice Charts
II. Digital Products and Archiving
III. Climate Research Application of Snow Data
IV. Need for International Cooperation

Snow and Ice Charts: Working Group I

Edited by F. Smigielski and G. Kukla

1. With the present available operational technology, snow charting for climate-related studies is interactive (man-computer-combination). Interpretation of combined conventional and satellite data by a skilled analyst is considered an essential part of the process. We do not foresee a possibility to obtain, in the near future, a reliable snow chart of sufficiently high quality for climate-related studies by a completely automated process.

2. The methodology, accuracy, and limitations of existing operational snow and ice cover charts has to be described in open literature so as to be available to any potential user of the data.

3. Past snow cover charts should be upgraded so as to achieve consistency with the more recent products.

4. Apart from operational products, a climatologic series of snow charts based on combined ground and satellite information should be produced. This is because serious time limitations are imposed on the quality of operational charts which are produced for immediate release. The climatic charts, however, can be thoroughly crosschecked and verified, and distributed with a delay of several weeks. Such delay would allow for the use of high-quality semi-processed satellite products, of verified ground station data, and of sophisticated image-analyzing techniques needed for realistic assessment of the reflectivity values. The charts could show the relative reflectivity of snow fields and ice over land as well as over the ocean in at lease 6 classes, snow or ice thickness where available, 0°C, +5°C, and -10°C air surface temperature isolines, and other pertinent data.

5. Areas of high snow cover variability should be charted in more detail. For that purpose, for instance, the unused capacity of the NOAA-AVHRR sensor in the Asian and European sectors may be utilized and the high resolution DMSP data from Central Asia received in Korea could be analyzed on a regular basis.

6. Terms used to characterize different snow and ice cover features should be standardized and quantitatively defined (for example, the different relative brightnesses of the snow fields or percent of open water within the pack ice).

7. It is recommended that AFGWC, which currently produces daily charts of snow depth and age:

   a. produce a surface brightness chart, on at least a weekly basis, for archiving in WDC-A;

   b. flag climatological or predicted snow data to distinguish them from observations;

   c. develop data bases of background surface brightness (excluding snow), and of surface observations on water equivalent, daily snowfall, precipitation, and maximum/minimum temperatures;

d. provide and publish full documentation on algorithms used to compute snow/ice parameters from radiance data for inclusion with Level II and III archives.

8. Reflectivity of the sea ice should be charted and ice thickness indicated where data exist (NOAA-Navy). The extent and intensity of melting (puddled) snow on top of the Arctic sea ice should be charted on a weekly basis, or in shorter intervals.

9. Monitoring and archiving of the satellite and conventional (ground station) snow data should be considerably improved. The raw data sets should be made available for free exchange and distribution to interested scientists through the World Data Centers for Glaciology in Boulder, Colorado, U.S.A.; Cambridge, U.K., and Moscow, U.S.S.R. Copperation of the three mentioned centers should be intensified.

Digital Products and Archiving: Working Group II
Edited by R. Barry and M. Matson

1. The methodology, accuracy, and limitations of currently generated charts and digital snow and ice cover products should be clearly described in open literature so as to be available to any potential user.

2. In the future, climatic snow and ice cover charts, that passed a quality control check should be digitized for climate studies, rather than the raw operational charts. Data on snow/ice limits, reflectance categories, and ice concentrations on the weekly snow and ice charts prepared by NESS should be crosschecked with station data, adjusted, and then digitized. The archive should be extended backwards, after incorporating necessary crosschecking and revisions.

3. The element sizes, resolutions, and coverage needed for various cryospheric parameters as stated in various documents (beginning with GARP Publications No. 16) should be critically reviewed and updated.

4. The primary data streams that go into many operational snow/ice products are not currently preserved. Since these could be tape-archived from the teletype circuits, this possibility should be considred, especially for daily snowfall, temperature, and surface wind data at ground stations.

5. Global data sets on snow depth and water equivalent, to 0.5 cm resolution (including snow on sea ice) will be needed for verification of climate models. Daily values and monthly averages will be required. Data on snow cover and ice thickness collected by the U.S. Army Cold Regions Research and Engineering Laboratory throughout North America over 15-20 years should be archived at WDC-A following termination of that program.

6. It is recommended that selected digital data being produced as diagnostic model outputs be preserved. In hydrology, for example, basin data on percent snow cover, daily snowfall, water storage, runoff, and energy budget components could be archived at a resolution of approximately 50 km.

7. There is a wide need for "historical" series of sea ice and snow cover charts. Operational series should be carefully revised, incorporating data from all sources, before extensive and costly digitization is undertaken. Any re-analysis should be fully documented. It is important that estimated and interpolated values in data sets derived from chart series be flagged. Final digitized products should be crosschecked and their consistency documented.

8. Data on terrain parameters, soil, and vegetation cover types needed for climate modeling and assessment studies, with respect to snow and ice studies have to be specified.

9. A near-IR sensor for snow/cloud discrimination is expected to be operated on DMSP satellite in the 1980's. It is recommended that a data base be developed at AFGWC for subsequent archiving at WDC-A for Glaciology.

10. Since the 10-day time interval covered by the Composite Minimum Brightness charts, helpful in preparation of snow and especially sea ice charts, represents almost 10 percent of the snow cover decay season, it is recommended that the question of shortening this interval be reconsidered.

11. Problems that users currently encounter in accessing data sets should be identified and possible solutions for the provision of more manageable data products explored. Strategies must be devised to facilitate access to mass data bases with time and space dimensions as primary references. With regard to expected future higher-resolution satellite data, especially EDIS, NASA and other agencies should format daily tapes of global data so that individual geographic sectors can be readily accessed.

12. The views of the snow and ice research community on future satellite systems, their capabilities, resolution, and coverage, should be communicated to the appropriate agencies. The development of new systems which can provide on-board processing to generate statistics of very high resolution data for selected geographic areas is welcomed. There is an overwhelming need for compressed data from satellite systems to facilitate climatological studies covering month to several-year time scales. The need for continued collections and retrieval of ground truth data to verify remote sensing measurements is stressed.

Global Atmospheric Research Programme (1975) The physical basis of climate and climate modelling. GARP Publication no. 16. WMO, 265p.

Climate Research Application of Snow Data: Working Group III
Edited by E. Rasmussen, J. Namias, A. Robock, and S. Warren)

Snow cover data may be potentially useful in three areas:

I. Diagnostic and empirical analysis,
II. General circulation models and extended forecasts, and
III. Energy balance models.

Temporal resolution for these studies need to be no finer than one week and spatial resolution no finer than 2x2 degrees. Data sets should be made available through the World Data Center A for Glaciology (Snow and Ice).

I. Diagnostic and Empirical Analysis

Diagnostic-empirical analyses are constrained by the nature of the data into three "time frames". These are: the satellite era - early 1970's to the present; the post World War II or "upper air data era" - late 1940's to the present; and the historical era - 100 years or more into the past.

A. Satellite Era Analyses

1. Data - satellite era data are described in detail in sections 1 and 2 of this volume. Efforts should be made to:

   a. Correct and upgrade the snow data from the early years of the satellite era to obtain a homogeneous 10-15 year long record.

   b. Continue digitization of snow data to expand the record length.

   c. Compile Southern Hemisphere snow cover data on a current basis for use as an indicator of climatic variability. These data should be archived.

2. Research Activities - these data should be used to:

   a. Identify areas and features of largest variability ("key regions" and/or "indices")

   b. Explore relative merits of different snow/ice indices in snow/climate analyses.

   c. Use weekly data in case studies or composite analyses of extremes and rapid changes in snow cover and weather. Temporal resolution of one week is necessary when snow cover is involved. Coarser time resolution may be adequate for seasonal studies.

B. Upper Air Data Era

1. Data - snow data are generally not digitized. They appear in hydrological publications and archives. Studies will be limited to regions with a high density of ground-based snow reports. Snow data may be synthesized using unconventional data. The procedure used to construct data sets must be carefully described in order to distinguish effects of "analysis change" from true "climatic change."

2. Research Activities

   a. Produce monthly/seasonal predictability statistics of snow/cause effect, and estimates of statistical significance, acknowledging the fact that this is a short time frame for establishing these statistics.

   b. This may be a useful time frame for evaluation of the role of snow cover in inter-seasonal climatic fluctuations (e.g. Himalayan snow/monsoon onset).

   c. Develop indices and methods of generating proxy data for incorporation of snow cover into long-range studies.

C. Historical Time Scale

1. Data - based on conventional surface data and proxy data developed below.

2. Research - analyze <u>interdecadal changes</u> (multi-year variations), and <u>trends</u> involving snow cover.

II. <u>General Circulation Models and Forecasts</u>

A. Global Circulation Models

1. Data - a climatology of snow amount and depth and sea ice thickness and concentration are needed.

a. Two climatologies of snow have already been prepared, one by the Air Force, the other by Schutz at Rand. These climatologies should be documented and published. This documentation should include the methodology and assumptions which went into the preparation of the climatology. In particular the assumed snow density used to convert depth to equivalent water amount should be stated.

b. A new climatology should be prepared from the Air For n operational snow depth charts and compared with the earlier climatologies.

c. A climatology of sea ice thickness and leads is needed to evaluate contemporary sea ice models. Climatology of snow amount and depth over ice is needed.

It is further recommended that:

d. All derived climatologies should be sent to the World Data Center-A for Glaciology for archiving and dissemination.

e. World Data Center-A should inform without delay all modeling groups on the availability of each newly received set.

2. Research - The work, already begun, on the albedo of various snow-covered surfaces should be continued, refined, and expanded to include the realistic data of snow-free surfaces as a function of season and/or soil moisture. The albedo of sea ice, with and without snow should be determined.

B. Forecasts - Use of snow cover data for extended forecasting shoule be investigated since at this stage no survey was performed of data needs.

III. <u>Energy Balance Models</u>

A. Data - Critical data input required for energy balance studies are:

1. Fractional snow cover and albedo. The present snow cover maps are adequate in describing snow area coverage but at present they describe albedo only qualitatively, not in accurate percentage values. Albedo differences of a few percent can cause large errors in snow melt rates and in resulting model assessments of the albedo feedback on climate.

2. The albedo of snow fields should be specified in at least two wavelength bands (visible and near IR). This is because the albedo is much lower in the near IR, and because the near IR albedo is determined mainly by age, whereas the visible albedo is sensitive instead to depth and impurity content. In order to convert satellite clear-sky radiance measurements into albedo, a bi-directional reflectance function for snow is necessary. Both theoretical work and measurements at the surface and top of atmosphere will help develop this function. It is particularly important to report realistic albedo for sea ice, where values can vary in considerably larger range than over snow.

3. Auxiliary data sets which would make this collection much more useful include the snow and ice-free albedo for the underlying surface, surface temperature, and cloudiness. Combined impacts of snow and ice with cloud cover can dramatically affect the planetary albedo. The sensitivity of climate to snow or ice cover is thus increased by clouds.

B. Research - the following studies are recommended using the snow and ice data in energy balance/climate models:

1. determination of the strength of the snow and ice albedo feedback, which is very important in determining climate senssitivity (for example, to CO_2 changes),

2. investigation of ice-age initiation and model simulations of the Milankovitch hypothesis,

3. quantitative assessment of the role of the snow in the mean seasonal cycle,

4. parameterizations of snow cover and sea ice properties for use in the models.

Need of International Cooperation: Working Group IV

Edited by D. Wiesnet, B. Goodison, and G. Kukla

1. Intensive international cooperation in the study of snow and ice is needed. The newly emerging data bases on the seasonal snow and ice covers, which to a large degree are derived from satellite imagery, should be internationally standardized or at least made mutually compatible. Efficient international exchange of raw data can greatly increase the quality of individual snow and ice cover series.

2. International exchange of the processed data is expected to speed up the search for the causes of climate variability through diagnostic studies and climate modeling. This is especially important in the case of seasonal snow and ice covers. Numerous recent studies indicate that snow and ice may play an important and perhaps even critical role in the mechanism of climate changes.

3. The awareness of the climate change issue increased considerably in recent years all over the world. The newly formed U.S. National Climate Program has a counterpart in the Canadian Climate Program.

   The World Climate Research Program of the International Council of Scientific Unions and the World Meteorological Organization are the most suitable existing platforms through which international cooperation in snow and ice studies could be channeled. The geobase-oriented information systems of such established organizations are capable of a quick collection and dissemination of snow-related data, and are well suited for launching a major international Snow Watch program.

4. Closer international cooperation should be especially strongly encouraged in the following fields:

   a. monitoring of snow cover and collection of related data;

   b. standardization of charting methodology and of data interpretation techniques;

   c. studies of snow/climate relations including modeling.

5. It is preferable to channel international cooperative activity through existing appropriate channels, namely through WMO (World Climate Program and World Weather Watch) and/or through the IUGG Commission on Snow and Ice.

6. Archiving and dissemination of the data could be done through World Data Centers for Glaciology. Free exchange of raw data and of analytical results to interested researchers around the world should be secured.

7. National meteorological data-gathering and archiving networks should take necessary steps to generate snow cover series sufficient for detection of trends.

8. Snow-and ice-related terminology, measurement units, charting symbols. etc., should be standardized to facilitate easier comparisons of individual data sets. This can be done in a fashion similar to a corresponding taks of the International Commission on Cloud Climatology.

9. Future contact of the SNOW WATCH participants should be maintained, either with the help of the National Science Foundation or WDC-A.

10. Scientific exchange programs between the climatologic, meteorologic, and hydrologic communities in government, industry, and universities worldwide should be strongly encouraged. Necessary financial resources should be secured.

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Snow in Climate Diagnosis and Modeling
Introduction

The immense glaciers which covered much of North America and Europe only 15,000 years ago developed from unmelted snow. Not surprisingly, perturbations of seasonal snow and ice fields are suspected to have played a principal role in the mechanism of the glacial/interglacial cycle (Kellogg, 1974; Suarez and Held, 1976; Kukla et al., 1981). According to climate models, snow and ice fields are highly sensitive elements of the sun-earth-atmosphere system (Sellers, 1969; Budyko, 1969; Manabe and Wetherald, 1975).

It is also generally recognized that snow and ice covers have a profound impact on microclimate and weather on a synoptic scale (Radok, 1979; Namias, 1980; Kukla et al., 1981). Evidence is accumulating on an anomalously deep snow cover in Tibet being followed by an anomalously late onset of the Indian monsoon (Reiter and Reiter, 1981; Chen and Yan, 1978). Additional aspects of the problem are discussed in this volume by Namias (p. 13), Robock (p. 41), Kukla (p. 27), and Roads (p. 55).

Still, in short-term weather forecasting, the snow cover distribution is seldom taken into account. It was shown that accuracy in short term forecasts does not generally improve with the inclusion of snow. Only in exceptional situations was it recommended to include the snow cover distribution in the computerized weather prediction program of the U.S. National Weather Service (Wagner, 1973). What is the answer to the dilemma? Is snow cover a passive product of a particular circulation pattern, or does weather develop in response to the distribution of snow on the ground?

Improved general circulation models should soon be able to solve the problem, with Hahn (p.45 this volume) showing the way. However, it is also obvious that better observational data are needed. The disagreement between the model results and observations may be due not only to the model errors but also to the poor quality of snow charts in autumn (see also Kukla and Robinson, p.103 this volume).

G. Kukla

A. Hecht

D. Wiesnet

Editors

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Snow Covers in Climate and Long-Range Forecasting

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ABSTRACT

Snow cover variations are important for diagnosis and forecasting on monthly, seasonal, and interannual time scales.

The variable extent of snow cover fields affects advancing polar air masses and introduces variable horizontal temperature gradients, which in turn may influence cyclogenesis and also may reinforce blocking. As a result, weather and climate patterns are modified considerably on both local and continental scales.

Patterns associated with light and heavy snow years[1]

An attempt was made to ivestigate the snow characteristics of winters in the northeastern United States. Two primary sources of data were used in the investigation: 1) snowfall totals for many stations in the northeastern United States from 1932 through 1959, and 2) seasonally averaged or mean maps at the 700 mb (about 10,000 foot) level. The latter charts were prepared from 1932, considering winter as the three months December, January, and February. Winter snowfall statistics were also worked up for these periods.

The northeastern cities whose records were conveniently available for the purposes of this study are shown in figure 1 together with the normal annual snowfall.

The mean flow charts for years of heavy and light snows were examined. The charts associated with the six highest and six lowest ranks of table 1 suggest fundamental types of anomalous flow which indicate the abnormality of the snow regime.

The winters 1957-58 and 1944-45, which rank 2 and 3, respectively, are quite typical for patterns making heavy snowstorms possible. The outstanding features of these charts (figures 2 and 3) are: 1) strong positive anomalies in the 700 mb contour patterns over much of Canada and adjacent portions of the Atlantic, and 2) a stronger than normal trough over the eastern United States and a strong ridge over the Far West. These conditions represent weaker than normal westerly winds over much of the continent (low zonal index), the deployment of colder than normal air masses over the eastern United States, and the generation and steering of southern storms northeastward along the eastern seaboard. The accompanying departures of temperature are shown below the mean contour charts, and the prevailing (principal) storm tracks for the season are indicated by arrows superimposed on the contour charts. The accompanying departures of precipitation, to the right of the temperature anomalies, show that precipitation was not extremely heavy over most of the area so that much of it was in the form of snow rather than rain. This was due in large part to the cold air masses prevailingly deployed in the anomalous patterns of upper-air flow.

The relatively snowless years, table 1, show strikingly different patterns. One of the typical examples is afforded by the winter 1936-37, depicted by the charts reproduced in figure 4. The most noteworthy feature is the anomalously strong trough over the Far West flanked by strong ridges over the adjacent Atlantic and Pacific. This prevailing wind pattern results in warm temperatures over the Eastern United States and cold weather in the West--an ideal situation for strong development and northward movement of storms through the east-central portion of the country. These storms deposit copious amounts of precipitation (see percentage of normal precipitation chart in figure 4), but owing to the enhanced flow of warm air from the south (relative to normal), precipitation over the Northeast occurs mostly in the form of rain rather than snow. In other words, although these cases include strong storm-generating and developing mechanisms, the air masses injected into the storms are generally too warm to produce heavy snows in the Northeast.

Obviously, years with abnormally light snow may also occur when the total precipitation (both rain and snow) for the winter is low.

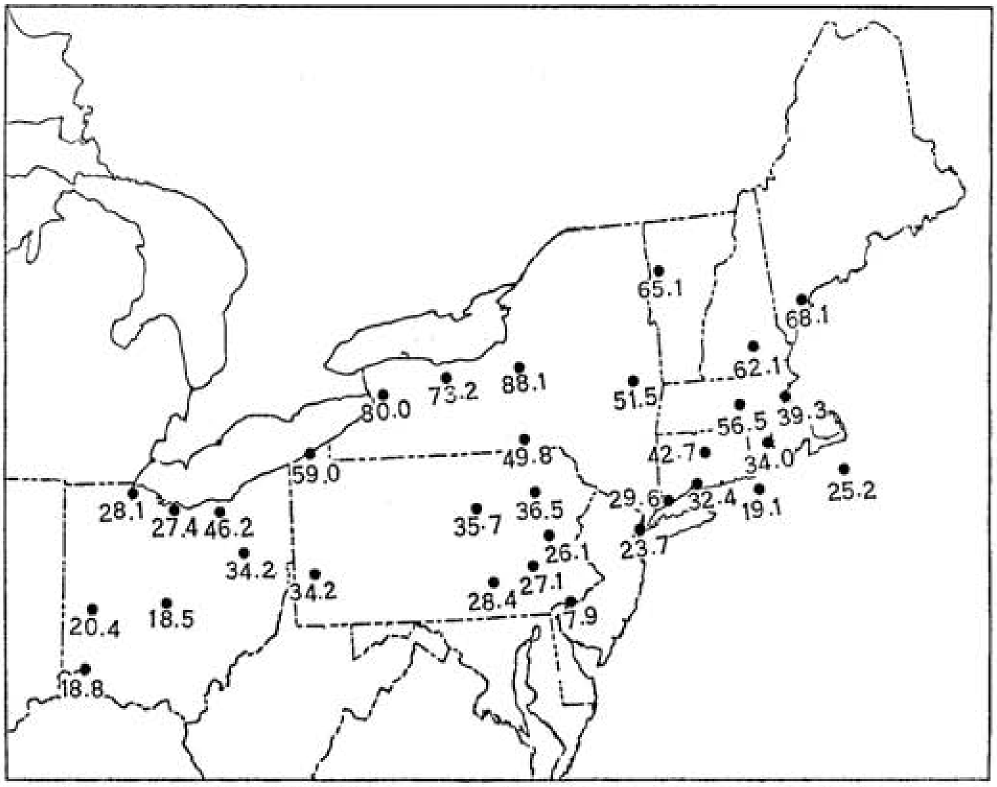

Figure 1. Stations used to prepare averages given in table 1 and their normal annual snowfall in inches.

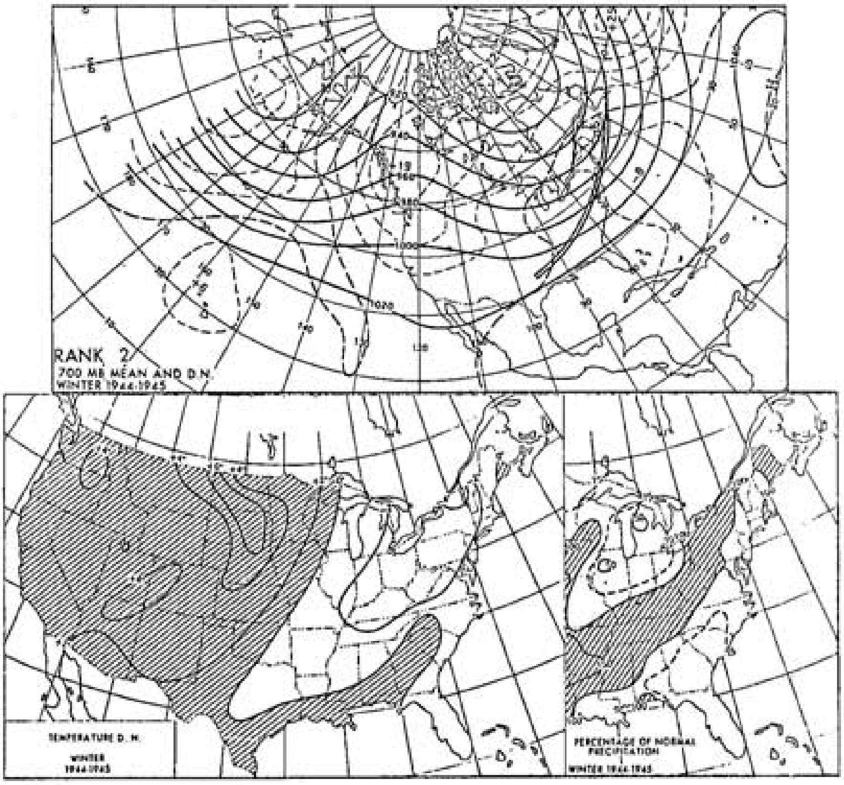

Figure 2. UPPER: Mean 700mb contours (solid lines labeled in tens of feet) for winter 1957-58, and isopleths of departure from normal (broken) drawn for each 50 feet and with maximum values labeled in centers. LOWER LEFT: Associated isopleths of departures from normal of temperature F°. LOWER RIGHT: Percentage of normal precipitation.

Table 1. Average snow recorded at 32 stations over northeastern United States for winters 1929 through 1959.

Rank	December		Depart from 30-yr Avg	January		Depart from 30-yr Avg	February		Depart from 30-yr Avg	Cold season total[1]		Depart from 30-yr Avg
	Year	Avg		Year	Avg		Year	Avg		Year	Avg	
1	45-46	17.4	+9.5	44-45	21.1	+10.8	33-34	20.1	+10.3	55-56[2]	58.3	+17.7
2	44-45	16.0	+8.1	47-48	19.6	+ 9.3	57-58	20.1	+10.3	57-58	56.4	+15.8
3	51-52	15.8	+7.9	34-35	16.4	+ 6.1	39-40	16.6	+ 6.8	44-45	55.3	+14.7
4	33-34	12.4	+4.5	35-36	15.9	+ 5.6	46-47	15.9	+ 6.1	47-48	53.5	+12.9
5	47-48	12.3	+4.4	56-57	14.5	+ 4.2	49-50	13.7	+ 3.9	33-34	51.4	+10.8
6	29-30	11.4	+3.5	57-58	14.4	+ 4.1	44-45	12.3	+ 2.5	51-52	49.3	+ 8.7
7	56-57	11.1	+3.2	53-54	14.4	+ 4.1	51-52	12.0	+ 2.2	33-36	48.7	+ 8.1
8	50-51	11.0	+3.1	38-39	13.7	+ 3.4	32-33	12.0	+ 2.2	58-59	47.8	+ 7.2
9	35-36	10.9	+3.0	40-41	13.6	+ 3.3	35-36	11.7	+ 1.9	56-57	46.3	+ 5.7
10	42-43	10.4	+2.5	42-43	13.6	+ 3.3	43-44	11.3	+ 1.5	38-39	45.9	+ 5.3
11	48-49	9.0	+1.1	58-59	12.3	+ 2.0	47-48	11.2	+ 1.4	50-51	44.2	+ 3.6
12	58-59	8.6	+0.7	50-51	11.0	+ 0.7	34-35	11.1	+ 1.3	40-41	44.1	+ 3.5
13	54-55	8.0	+0.1	37-38	10.9	+ 0.6	45-46	11.0	+ 1.2	39-40	42.6	+ 2.0
14	46-47	8.0	+0.1	55-56	10.2	- 0.1	55-56	10.2	+ 0.4	42-43	42.6	+ 2.0
15	55-56	7.6	-0.3	48-49	9.7	- 0.6	41-42	9.5	- 0.3	46-47	41.4	+ 0.8
16	30-31	7.0	-0.9	39-40	9.2	- 1.1	54-55	9.1	- 0.7	45-46	41.1	+ 0.5
17	32-33	6.7	-1.2	30-31	9.0	- 1.3	38-39	8.0	- 1.8	34-35	39.1	- 1.5
18	52-53	5.9	-2.0	51-52	8.6	- 1.7	31-32	7.6	- 2.2	49-50	37.4	- 3.2
19	37-38	5.5	-2.4	52-53	8.6	- 1.7	48-49	6.8	- 3.0	53-54	36.4	- 4.2
20	39-40	5.4	-2.5	41-42	8.1	- 2.2	58-59	6.8	- 3.0	48-49	33.9	- 6.7
21	57-58	5.1	-2.8	29-30	7.5	- 2.8	50-51	6.8	- 3.0	54-55	33.9	- 6.7
22	34-35	5.1	-2.8	45-46	7.4	-2.9	42-43	6.7	- 3.1	30-31	32.8	- 7.8
23	49-50	4.7	-3.2	46-47	7.2	- 3.1	30-31	6.4	- 3.4	43-44	32.5	- 8.1
24	38-39	4.4	-3.5	54-55	5.9	- 4.4	52-53	6.3	- 3.5	32-33	30.9	- 9.7
25	40-41	4.3	-3.6	49-50	5.3	- 5.0	40-41	6.2	- 3.6	41-42	30.4	-10.2
26	36-37	3.9	-4.0	36-37	5.1	- 5.2	53-54	5.9	- 3.9	29-30	30.1	-10.5
27	53-54	3.7	-4.2	43-44	4.7	- 5.6	37-38	5.2	- 4.6	37-38	29.7	-10.9
28	41-42	2.7	-5.2	33-34	3.8	- 6.5	29-30	5.1	- 4.7	36-37	27.7	-12.9
29	43-44	2.0	-5.9	31-32	3.6	- 6.7	56-57	4.6	- 5.2	52-53	27.5	-13.1
30	31-32	1.1	-6.8	32-33	2.5	- 7.8	36-37	3.8	- 6.0	31-32	26.2	-14.4

1. "Cold season" includes all months having snow.

2. For the heaviest snow year, 1955-56, the heaviest snow occurred in March, so it doesn't show in the December, January or February months.

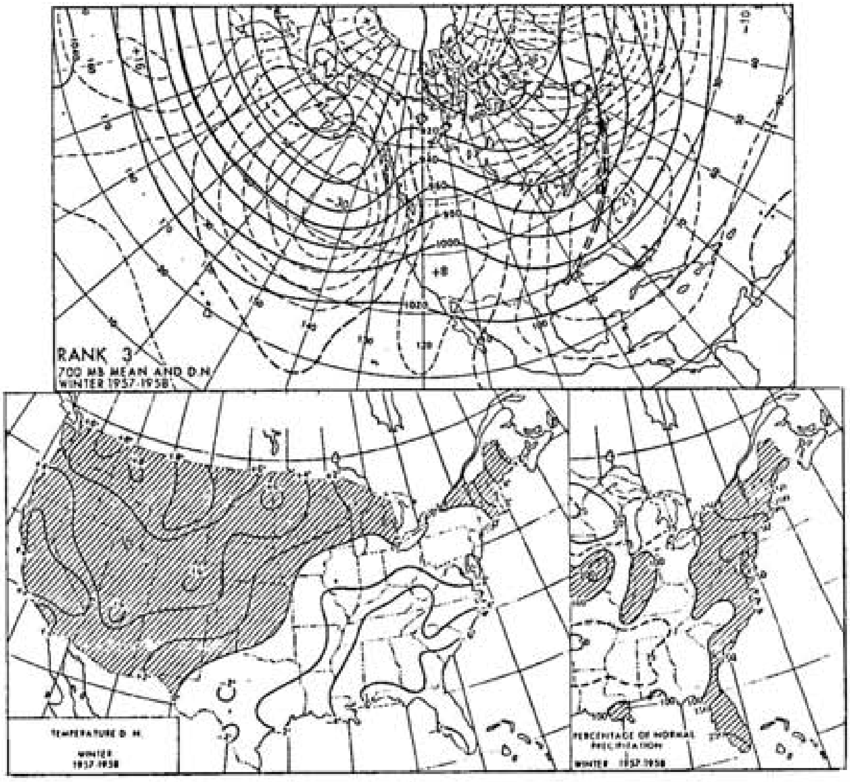

Figure 3. Charts for the winter of 1944-45 show 700mb contours, temperature departure from normal, and percentage of normal precipitation.

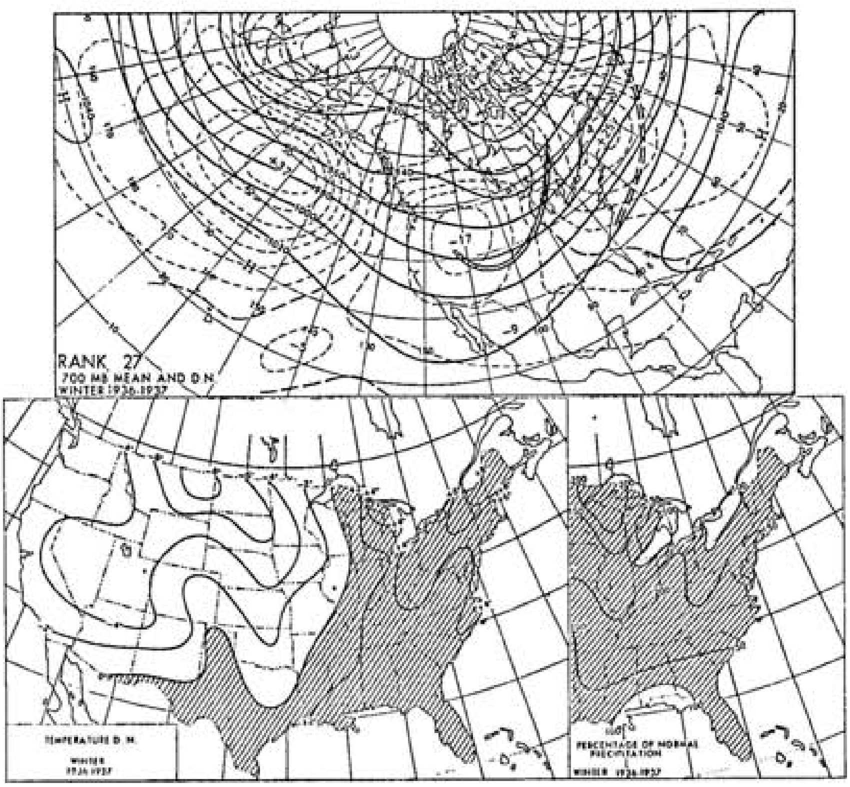

Figure 4. Charts for the winter of 1936-37 show 700mb contours, temperature departure from normal, and percentage of normal precipitation.

In the wet snow years, like those illustrated in figures 2 and 3, East Coast cyclones appear to be diverted northward rather than eastward or become stalled by great blocking anti-cyclones which are other manifestations of the positive anomalies in northeastern Canada.

A case where extensive snow cover played a vital role in affecting atmospheric circulation occurred over the Central United States from mid-February to mid-March 1960, when the southern boundary of snow was persistently found well south of its normal position (figure 5). The accompanying sea level mean circulation for this period shows a tremendous North American continental anticyclone, representing the net effect of repetitious outbreaks of cold Polar anticyclones following on the heels of rapidly developing East Coast cyclones. The paths of these storms, drawn heavier during their 24-hour period of greatest deepening (up to 35 mb in 24 hours) are shown in figure 6. The resulting thickness pattern, including its departure from normal, is reproduced in figure 7. From these figures alone it is not possible to separate the effect of cooling by snow from that which is due simply to the transport of polar air masses southward over the continent, for even in the event snow was not present, the central portion of the United States would have been colder than normal. However, from the computer estimates of the expected surface temperature derived from the 700 mb charts following the procedure of Klein, et al. (1959), it is probable that the snow cover actually did reduce temperatures in the Central United States as much as 8° to 10°F per day.

A rough computation may also be made to show that the magnitude of this influence is quite reasonable. At the latitude of the snow boundary shown in figure 8, about 300 Langleys (calories per cm^2) per day are normally received on horizontal ground from the sun and are potentially available to heat the air. In other words, this is the normal net insolation for this area during the mid-February to mid-March period (Fritz and MacDonald, 1949). If we assume an albedo of 0.8 with snow cover and 0.2 without, then only about 0.2x300=60 Langleys per day become available to heat the air when snow is present, as against 0.8x300=240 Langleys per day without snow. Since little melting would occur during most of the period because of the observed low temperatures, most of the energy absorbed by the surface was probably used to heat the overlying air.

Now if, with snow, all the absorbed solar energy was used to heat a 100 gram column of air about 1 km in depth, then

$$\frac{\Delta T}{\Delta t} = \frac{Q}{c_p M}$$

(where Q is the heat added; c_p, the specific heat of air; M the mass of air; and T the temperature change).

$$\frac{\Delta T}{\Delta t} = \frac{60}{0.24x100} \approx 2.5=C/day.$$

Without snow, on the other hand,

$$\frac{\Delta T}{\Delta t} = \frac{240}{0.24x100} = 10°C \text{ per day.}$$

Then the difference, which may be looked upon as due to the diminished heating of the lower air when snow is present, is about 7.5°C. If we double the air layer to 2 km, the difference is halved to about 3.5°C, or roughly 7°F, a figure comparable to the observed error of the statistical estimates along the snow boundary.

It seems likely that this extensive and abnormal snow blanket, besides refrigerating the air masses in transit, had other more subtle effects.

The zones of most intense cyclogenesis (figure 6) are found much farther south than normal along the eastern seaboard. Expressed in another way, the occlusion process of the storms was greatly speeded up relative to normal in storms of this type.

The deepening of East Coast cyclones is, to a considerable extent, baroclinically induced, so that barotropic numerical predictions frequently contain large positive errors in the coastal area.

In order to demonstrate the impact of the East Coast cyclogenesis during mid-February to mid-March on the North American general circulation, a correlation was made between each day's sea level pressure map and the 30 day mean of which it was a part. This was done for a grid of points extending from 50° to 110°W, and from 30° to 65° N.

The fluctuations in squared correlation show rise following the major periods of cyclogenesis. A super imposed epoch plot (figure 9) with 0 taken as the whole 24-hour period of greatest cyclogenesis shows a tendency for the correspondence to be relatively low preceding cyclogenesis and to rise to a plateau subsequently. In other words, it appears that the

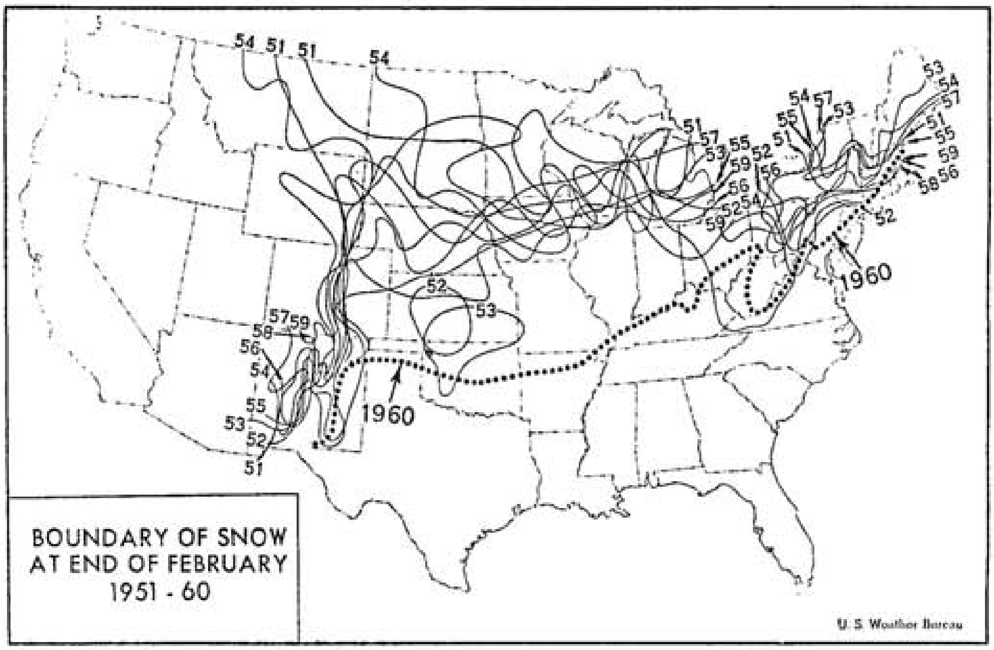

Figure 5. Southern boundary of snow at the end of February during each of the years 1951-1960.

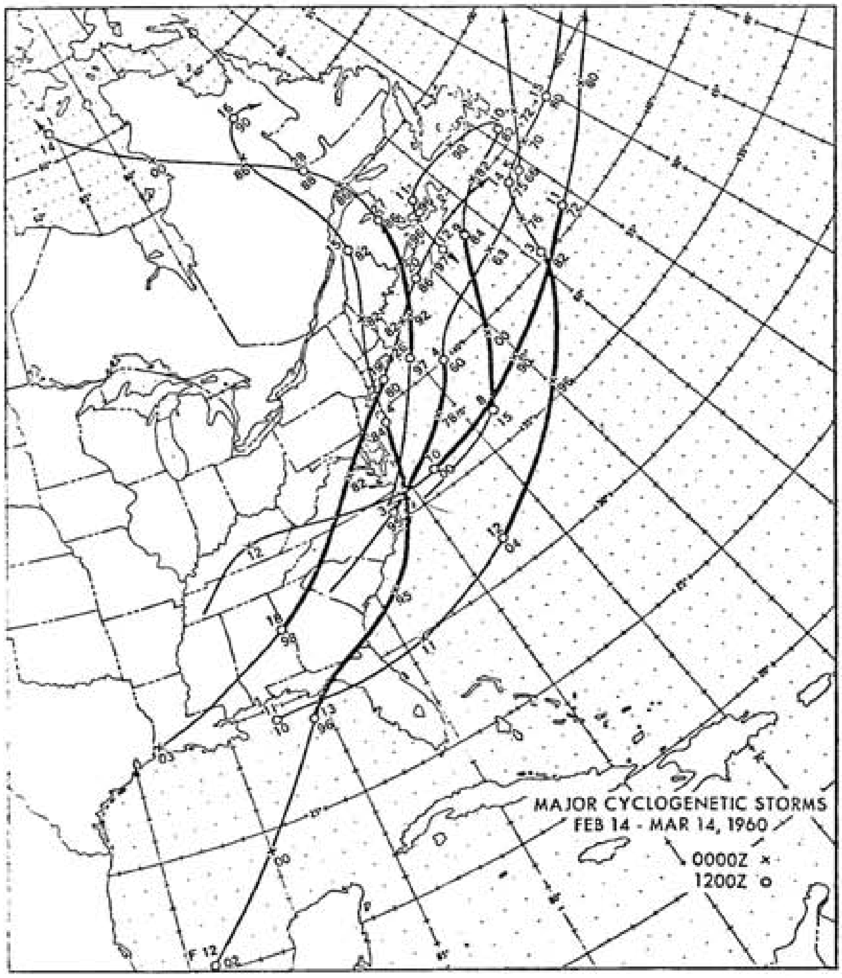

Figure 6. Paths of major cyclogenetic storms during the period mid-February to mid-March 1960. Figures beside the crosses (0000Z) and circles (1200Z) show the dates (upper) and intensity in mbs (lower), with hundreds omitted. The heavy segments of the paths are those of maximum 24-hour deepening.

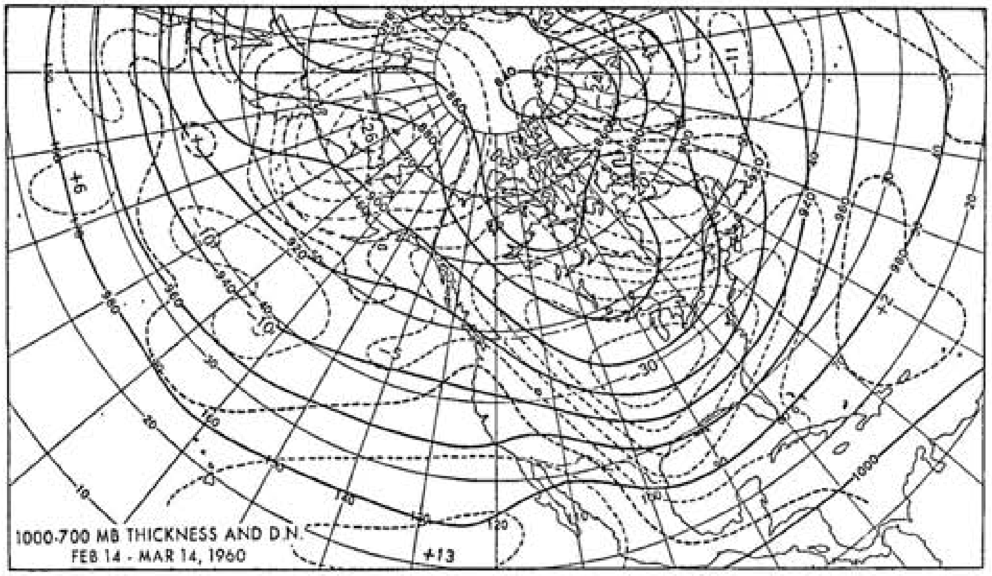

Figure 7. Mean thickness between 1000-700 mbs (solid), and departures from normal (broken), for the period mid-February to mid-March 1960.

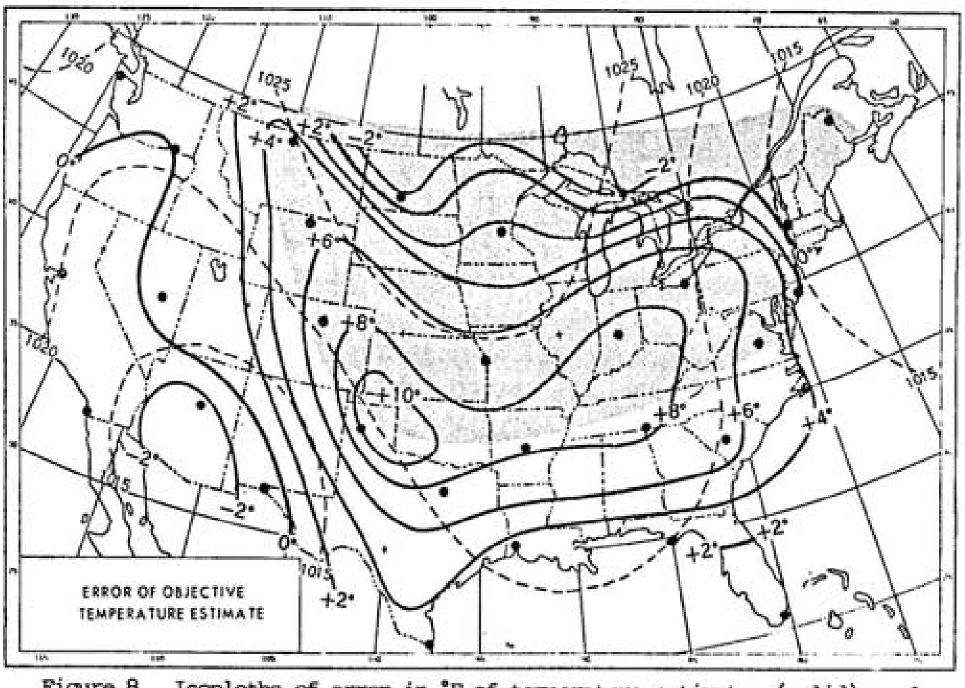

Figure 8. Isopleths of error in °F of temperature estimates (solid), and isobars of mean sea level pressure (broken) for the period mid-February to mid-March 1960. Shading indicates prevailing snow cover.

cyclogenesis is a sort of resuscitating injection for the prevailing quasi-stationary pattern of the 30-day period. We thus arrive at a "feed back" mechanism relating snow cover to atmospheric circulation. The feedback can be described as follows:

1. The general circulation for the period, an outgrowth of earlier abnormal forms during the winter, favored polar anticyclones and their deployment southward following intense east coast cyclones;

2. The advancing polar air masses were refrigerated in their southward transit by an abnormally extensive snow cover;

3. The low-level temperature contrast between these cold air masses and the warmer air masses overlying the Gulf of Mexico and the Atlantic coastal waters was thus increased over what it would otherwise have been;

4. East coast cyclones, feeding on baroclinicity enhanced by this extra contrast, occluded and developed rapidly;

5. The cyclogenesis helped to re-establish the Canadian anticyclone and consequently assisted in the ejection of fresh polar air masses southward into the United States.

This process, if highly dependent on the snow cover, would be terminated when that cover disappeared, as well as whenever other influence of the general circulation became overwhelming.

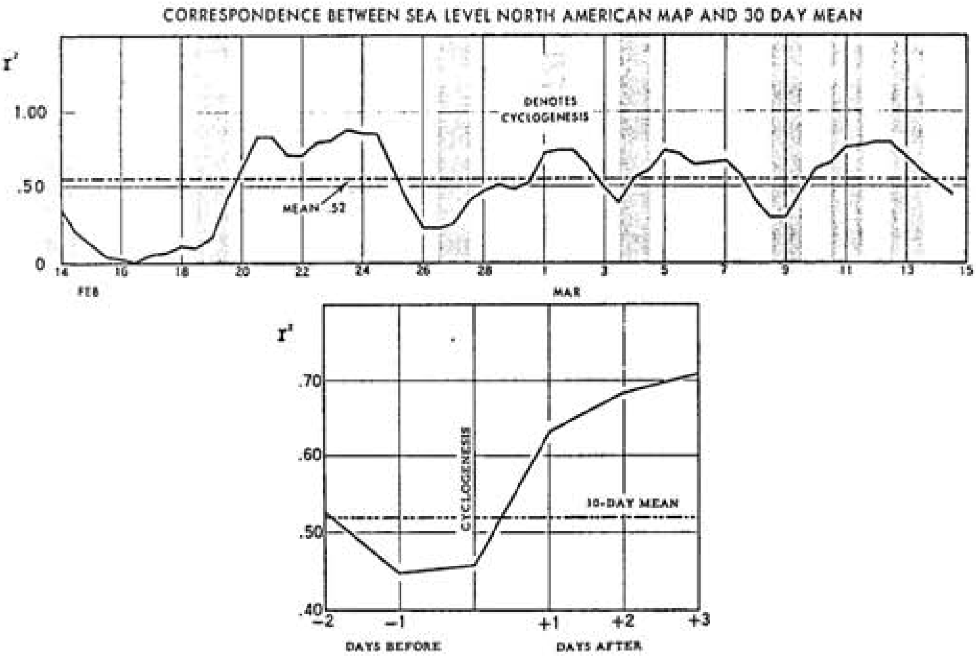

Figure 9. Square of correlation between daily and 30-day mean during mid-February to mid-March 1960 over North America and adjacent Atlantic (upper). LOWER: Mean of values from upper graph plotted as days preceding and following the most active 24 hours of cyclogenesis (not including those 24 hours).

Snowcover and blocking[2]

Aside from the sea surface temperature anomalies, it is probable that the nature of the land surface of northern Europe exerts an influence on the overlying atmospheric circulation. The most obvious case of this sort results from variable extensive snow fields and the numerous effects exerted by virtue of differences in albedo with or without snow, differences in condensation, in the heat used for melting, and so on. While these effects may appear to be local, they frequently take place over a large area, and what is perhaps more important, introduce variable horizontal temperature gradients which modify the normal flow and may also influence cyclogenesis and anticyclogenesis. Some very large-scale manifestations of important modifications in the overlying air temperature and of cyclogenesis along the southern boundary of an unusually southward-displaced snow cover over North America have been detailed earlier by the author (Namias, 1962).

Recurrent and strong blocking activity was observed over northern Europe for several seasons beginning in the latter half of 1958 and continuing through the fall of 1960. This led to major climatological fluctuation, particularly in pressure and precipitation over much of Scandinavia. Especially noteworthy was the gradual decline in annual precipitation along the west coast of Norway.

An attempt was made to explain the physical nature of the blocks and their maintenance. Two possible causes, both acting in concert with the atmospheric circulation, were suggested: sea-surface temperature anomalies, and cold-season snow cover over Scandinavia.

The first factor indicated that anomalous sea surface temperature gradients had been established (by the atmospheric circulation) south of Greenland and Iceland in such a way as to encourage differential heating to the overlying air.

The second factor, reduced cold-season snow cover, may have acted in the sense of permitting a strengthened monsoon circulation over Scandinavia during the subsequent warm seasons. This would also favor the development of upper-level anticyclones (blocks).

Snow During the Abnormal Winter of 1976-77[3]

The severe 1976-77 winter over eastern North America and the drought in the West are related to contemporary and antecedent atmospheric, oceanic, and cryospheric factors. Although greatly amplified, the atmospheric flow pattern was in phase with the normal winter pattern so that the seasonal forcing by mountains, coastlines, etc., did not oppose the anomalous pattern.

The highly abnormal North American winter of 1976-77 was characterized by a drought associated with a strong upper level ridge over the West and severe cold with attendant trough over the East (figure 10 and 11).

By mid-winter, the fronts connected with frigid arctic air produced snow rather than rain over much of the Midwest and East. While amounts were usually not heavy, snow persisted on the ground owing to persistent cold air outbreaks (figure 12). In the Great Lakes region, snows continued and often snow rather than rain occurred in connection with the Gulf and eastern seaboard storms (figure 13).

According to Matson and Wiesnet (1976), satellite-measured North American snow and ice cover was more extensive than during any of 10 past winters since these measurements began. The snow was both a result and cause of the intense cold over the East, for it led to high albedo and also served to refrigerate the arctic air. In addition, the excess cooling over land strengthened the baroclinicity along the eastern seaboard where the Gulf Stream kept temperatures relatively high. Thus, northeast storms developed, occluded rapidly, and helped displace the Icelandic low toward Newfoundland (see figure 10) (Dickson and Namias, 1976). Some disturbances embedded in the arctic jet stream also plunged south-eastward from northwest Canada and developed in the cold air as described by Reed (1977).

The anomalous weather can be explained as a result of several synergistic factors:

1. The quasi-stationary long-wave pattern that developed from the North Pacific eastward through North America was in phase with the climatological normal flow pattern, although greatly amplified. This helped "lock in" the anomalous pattern because seasonal forcing did not oppose the factors leading to the abnormal forcing.

2. The abnormal forcing appears to have been associated with an unprecedented vast area of cold surface water in the antecedent summer which changed to anomalously warm water from the west coast of North America to about 140°W partly as a result of the onset of a changed atmospheric flow pattern when the prevailing winds there blew much more from south to north than usual. This change resulted in reduced sensible and latent heat losses, reduced north to south water

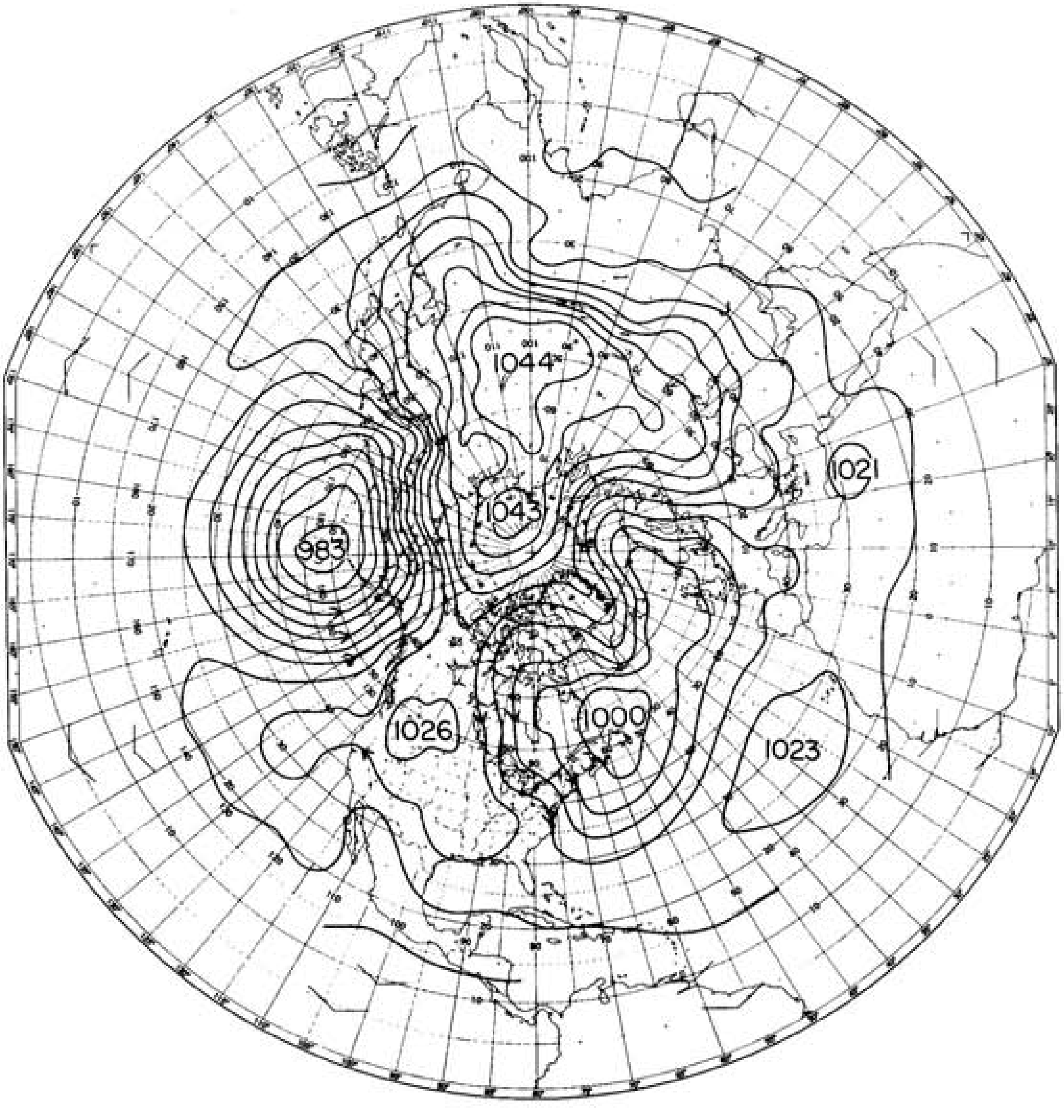

Figure 10. Mean sea level isobars (drawn for 5mb intervals) for January 1977.

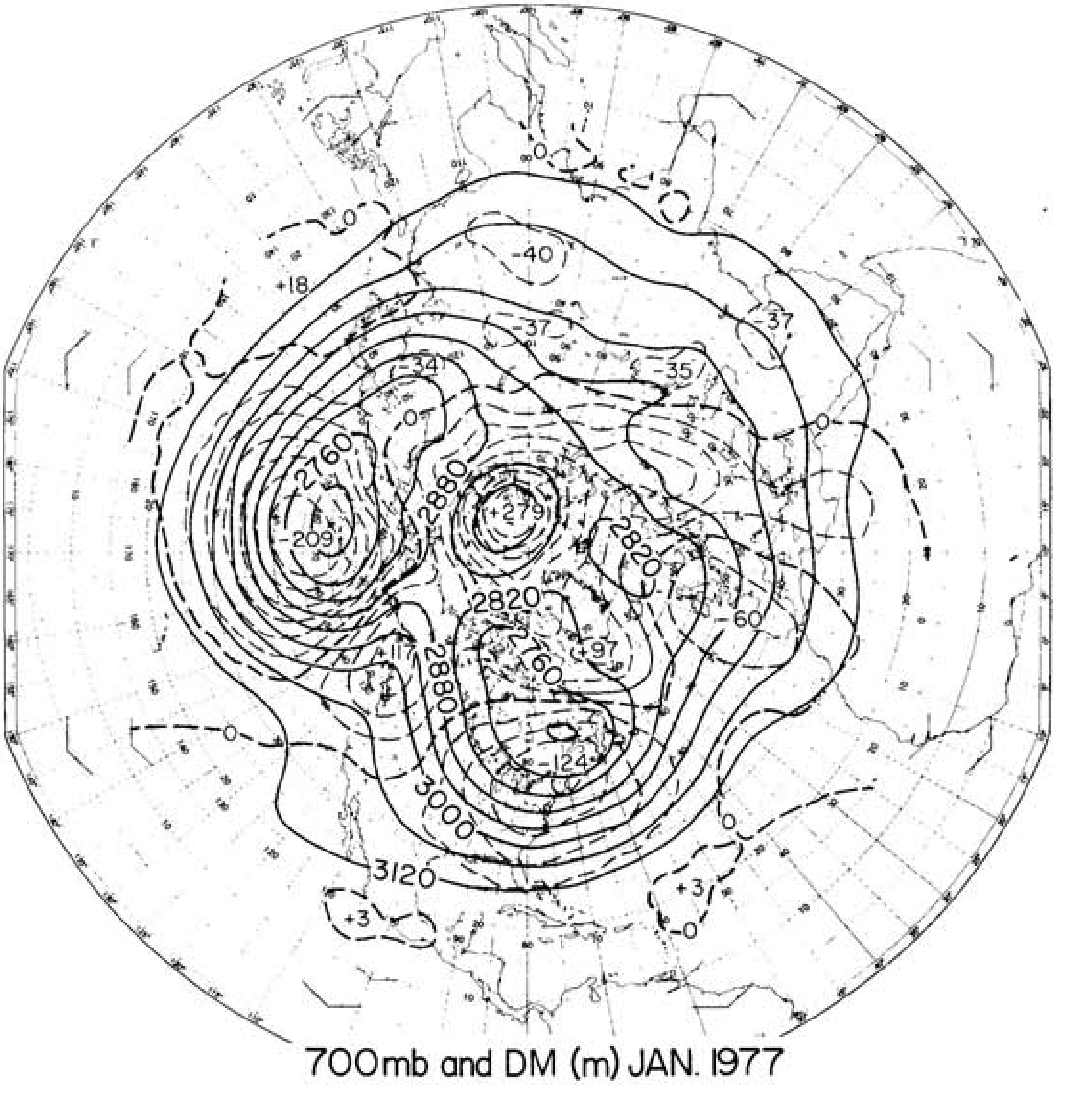

Figure 11. Mean height of the 700mb level (full) and departure from normal (dashed) in meters for January 1977. Note strong amplitude long wave affecting North America.

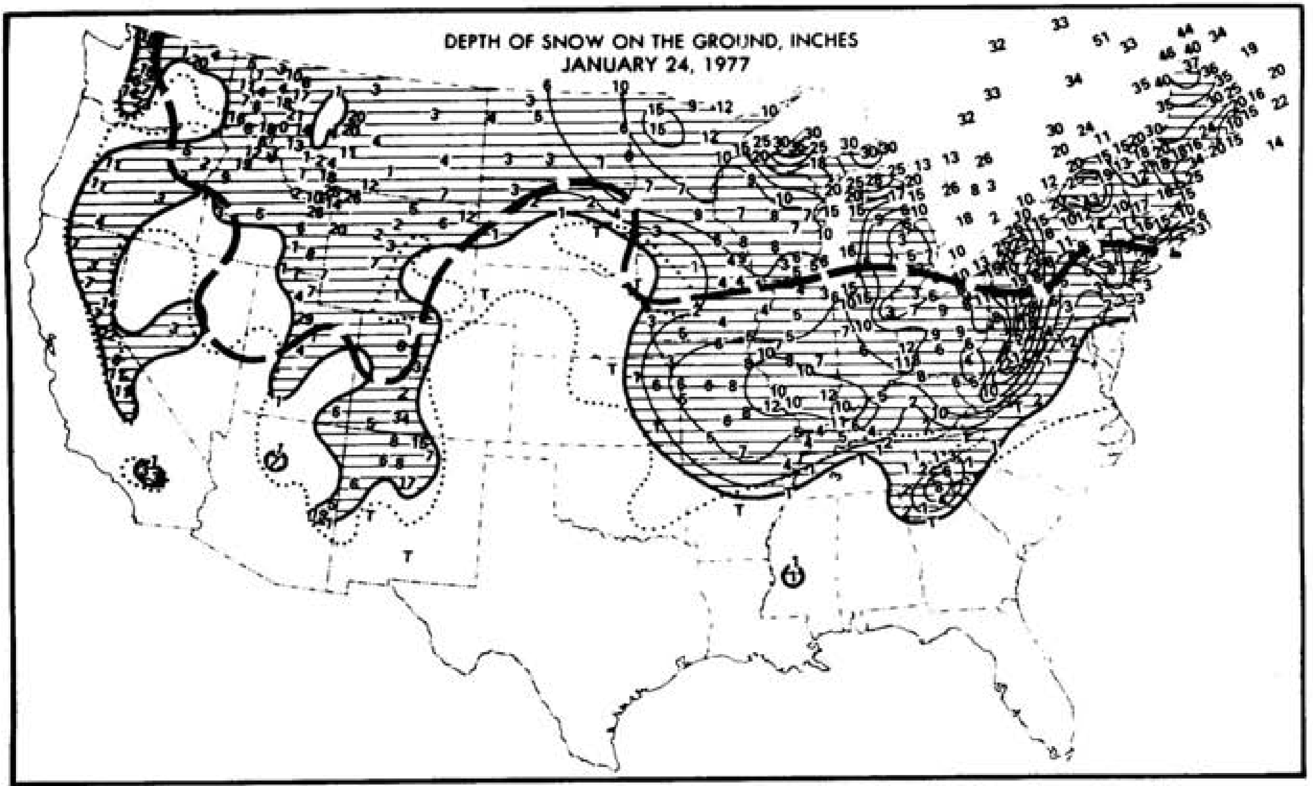

Figure 12. Depth of snow on the ground 24 January 1977 and median at this time from about 30 years.

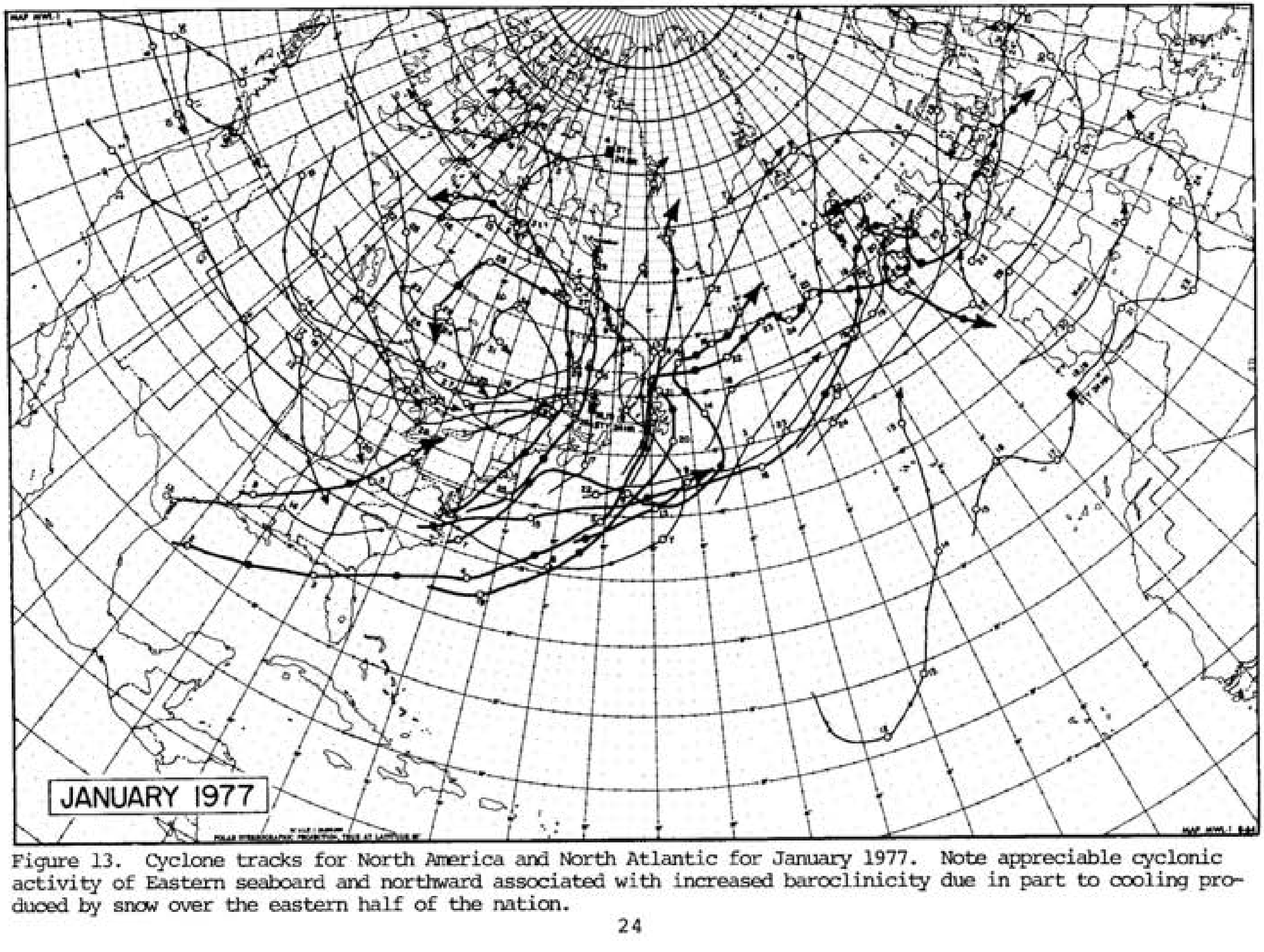

Figure 13. Cyclone tracks for North America and North Atlantic for January 1977. Note appreciable cyclonic activity of Eastern seaboard and northward associated with increased baroclinicity due in part to cooling produced by snow over the eastern half of the nation.

3. The summer to fall atmospheric change, wherein the west coast ridge and east coast trough began to develop, appears to have resulted in part from normal seasonal forcing influences operating on an abnormal wind pattern. In this case a strong trough off the west coast and a drought-producing ridge over the northern Plains, positioned stable during summer, retrograded to more compatible positions in fall. The detailed mechanics of this change are unclear, but statistical average climatic mid-tropospheric changes from summer to fall suggest the observed evolution.

4. The enhanced west-east sea surface temperature zonal gradient over the Pacific introduced increased baroclinicity in the overlying atmosphere, resulting in a zone of frontogenesis, cyclogenesis, and increased south-to north upper level flow east of 140°W. This flow helped steer storms northward to Alaska rather than allowing them to pursue a normal eastward course, and at the same time produced, through barotropic redistribution of vorticity, a meridionally extensive ridge over the west coast of North America, and a trough in the east. These features were manifested by abnormal warmth in Alaska and cold in the eastern half of the United States.

5. Persistently recurrent arctic outbreaks displaced the polar front far to the south along the Gulf coast, and often led to snow far south of normal as well as heavy snows leeward of the Great Lakes. The snow in turn helped refrigerate the arctic air in its southward transit, partly through an increased albedo. The snow was therefore not frequently removed from the surface and also was maintained by the frequent arctic air surges and replenished by storms moving along the southern eastern seaboards.

6. Because of the enhanced temperature contrast off the eastern seaboard between refrigerated arctic air and the warm Gulf Stream, northeast storms occluded and deepened rapidly, resulting in the Icelandic low being displaced to Newfoundland the surface and to southeastern Canada aloft. This Canadian low seems to have created and maintained the arctic block which fed back to assist in suppressing the Canadian low.

Snow in Numerical Forecast[2]

All forecasters are aware of the importance of snow in affecting local surface temperature, but it is doubtful if this factor is given major consideration in the formulation of broad-scale circulation forecasts. It is often neglected as a direct factor or not well parameterized in numerical forecasting models which consider no heat sources and sinks. The cumulative effects of snow, especially if it exists over a large area where snow is uncommon, must become more and more important as the time interval of the prediction increases.

Aside from the long-range implications of this interactive type of phenomenon, one must consider the possibility that such processes must also be included in any really successsful short-range numerical forecasting model. After all, mean algebraic errors of 440 feet in 48 hours (in barotropic predictions) and individual errors of over 1200 feet in 36 hours observed during some of these east coast storms seem to be large enough to suggest that the lack of incorporation of heating effects might be a substantial source of error even in baroclinic models-- errors for which no convincing explanation has been forthcoming.

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Note: Individual sections were summarized from the following publications:

[1]Namias, J. (1960) Snowfall over eastern United States: factors leading to its monthly and seasonal variations. Weatherwise, V.13(6), p.238-247.

[2]Namias, J. (1964) Seasonal persistence and recurrence of European blocking during 1958-1960. Tellus, v.16, p.394-406.

[3]Namias, J. (1978) Multiple causes of the North American abnormal winter 1976-77. Monthly Weather Review, V.106(3), p.279-295.

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Snow Covers and Climate

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ABSTRACT

High reflectivity, high emissivity, low water vapor pressure, and low conductivity make snow an importnt element of the climate system whose formation and dissipation closely depends on the amount and angular distribution of incoming radiation.

Snow Impact on Microclimate

Snow-covered land or snow-covered sea ice exhibit major differences from snow-free ground and ice-free ocean.

These differenes are:

1. Low heat conductivity. Fresh dry snow (density 0.1 - 0.2 g cm^{-3}) is the best insulator among common natural surfaces. Its effective conductivity (including heat transfer by water vapor diffusion) is between 0.00015 - 0.00040 cal cm^{-1} $sec^{-1}\cdot C^{-1}$ (Mellor, 1964). A fresh snow cover 30-50 cm thick maintains soil in an unfrozen state up to several weeks even when surface air temperatures fall well below zero. Ground insulation is enhanced by an air-filled layer of compressed grass, weeds, or dry leaves, commonly packed at the snow/soil interface. Heat losses from ocean to atmosphere drop considerably when dark new ice is blanketed by snow. Conductivity increases and insulating capacity of snow deteriorates as it ages and its density increases. Values by an order of magnitude higher, between approximately 0.0012 and 0.0022 cal $cm^{-1}sec^{-1}\cdot C^{-1}$, were reported in compacted snow with density of 0.5 g cm^{-3} (See overview by Mellor, 1964).

2. High reflectivity in the visible bands. Fresh snow reflects about 95 percent of shortwave radiation in wavelengths from 0.3 to about 0.9 μm (see figure 1), including visible bands potentially useful in photosynthesis. The remainder penetrates into the snow pack, and in the case of a thin pack reaches the underlying surface. Reflectivity drops sharply in the near infrared (NIR) and in the far infrared (LW) bands, which are absorbed in the uppermost, so-called active layer of snow. Differential spectral absorptivity has important implications for the dissipation mechanism of snowpacks.

   Spectral albedo of snow was studied in the laboratory by O'Brien and Munis (1975); in the field by Kuhn and Siogas (1978), and Grenfell and Maykut (1977, and unpublished); and computed by Choudhury (1978), Choudhury and Chang (1979), and Wiscombe and Warren (1980). Reflectivity of aging snow decreases with an increase of grain size in the snow active layer, with concentration of impurities at the surface such as soil debris, plant litter, or soot (see Warren and Wiscombe, 1980), with the exposure of protruding vegetation, rocks, etc., with the thinning of a snow cover deposited on a dark surface, and probably with the occurrence of liquid water in the snow.

3. High thermal emissivity. The thermal emissivity of snow approaches unity, and drops slightly with increasing grain size. Most sources give the emissivity of the snow as about 0.98-0.99. The longwave atmospheric counter-radiation received by snow is reradiated back to space. Wexler (1936) found the radiative loss from the top of snow to be about 0.1 cal $cm^{-2}min^{-1}$, and only slightly dependent on the air temperature. The snow surface cools much faster than the overlying air and inversions develop (Weller and Holmgren, 1974). They are especially pronounced at night when the surface becomes several degrees cooler than the air aloft.

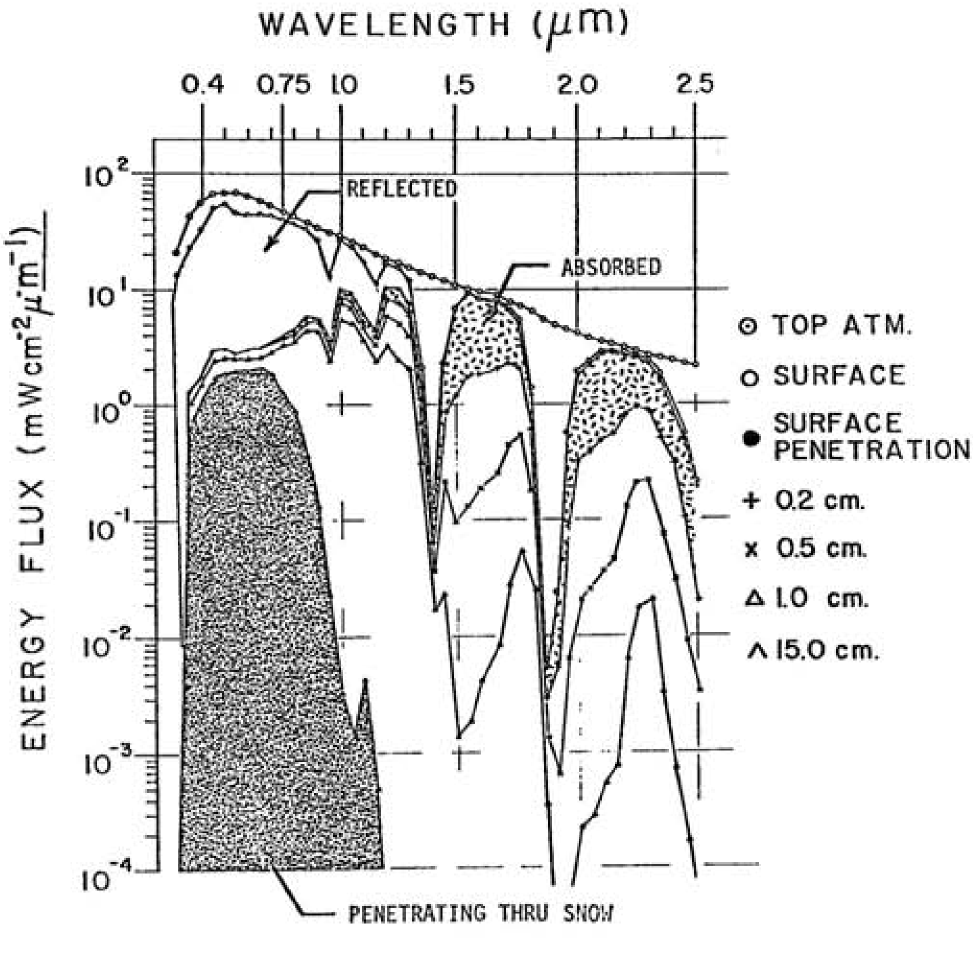

Figure 1. Shortwave radiation flux in a 15cm thick snowpack on land in a clear, dry atmosphere and with solar elevation of 23°. Model computation of Choudhury and Kukla (1979). Dark stipple; penetrating to the underlying surface; light stipple: absorbed in the uppermost 2mm of the snow.

4. Low surface moisture. The vapor pressure of snow can only reach that of water at 0°C, which is 6.1 mb, a relatively low value. The pressure is still considerably lower with cold snow. In this way, snow fields act as a sink of atmospheric moisture (Miller, 1973; Radok and Lile, 1977; Lax and Schwerdtfeger, 1976; Linkletter and Warburton, 1976).

The Snow Melt

Specific heat of snow is approximately 0.5 cal g^{-1}. The phase transformation of snow to water requires approximately 80 cal g^{-1}. The heat consumed in vaporization of snow is 676 cal g^{-1}. Snow dissipation may happen in several ways:

1. Premelt metamorphism and sublimation. In this phase the snow layer is metamorphosed by internal recrystallization. Vapor in the pores serves in the mass and energy exchange. The higher the temperature gradient, the higher and faster is the metamorphosis. The temperature gradient across a 50 cm-thick snow layer in interior Alaska is often 30°C or more. Premelt metamorphism commonly occurs in subfreezing weather when no liquid water develops in the pack. Loose, coarse-grained aggregate called depth hoar is the result of dry metamorphism (Akitaya, 1967). As the grain size and density of the pack increase, so does the amount of light penetrating to the snow base. Subsurface melt can then be initiated at the soil/snow interface.

2. Subsurface melt (solar melt) occurs near the top and at the base of a thin snowpack as a result of penetrating shortwave radiation. It is frequently observed in subfreezing weather. Whereas near the top, the melt is driven mainly by the absorbed near-infrared radiation, the bottom heating is produced largely by the absorption of visible light in grass and in the soil.

   The base melt and the subsequent dissipation of the pack starts on slopes with southern and southwestern exposure (in the Northern Hemisphere), as well as on top of buried stones, stumps, furrow crests, etc. Gradually considerable areas of dark soil, rocks or vegetation, etc. become exposed by this process in clear subfreezing weather. Impact of such snow-free surfaces on the heating of the atmosphere is substantial (Holmgren et al., 1975).

3. Thermal melt. This commonly studied form of snow dissipation occurs under a layer of warm air and frequently under low clouds. A large part of the energy needed for the melt is supplied by atmospheric longwave radiation and by convection. Liquid water is released within the entire thickness of the pack which can later collapse into a water-logged slush.

4. Dissipation of snow in fog or rain. This is the fastest mode of snow removal, common at the start and at the end of the snow season. When warm, water-saturated air is advected over a snow field whose vapor pressure is $\lesseqgtr$6.1 mb, a downward-oriented vapor pressure gradient results, and condensation occurs at the snow surface. The melt is accelerated if in addition liquid water is supplied by rain. This type of melt is a dominant form of snow dissipation in the forests.

   It is well known to meteorologists that the first major snowfalls of the season tend to occur or start at night (Ageta et al., 1979). It can be stated that snow cover formation, apart from the Arctic, is a nighttime process whereas snow cover dissipation is a daytime feature.

The influence of the underlying surface and of the structure of the vegetation canopy on snowmelt is dominant. In general, in the Northern Hemisphere, well-drained rocky or sparsely vegetated slopes of southern exposures are first to lose the snow cover. Fields and meadows along the southern forest margins, wind-deflated hilltops, plowed fields with deep furrows, and tall grasslands come next. Poorly drained flat short grasslands and untended fields covered with flattened plant litter, etc. follow. Snow stays longest in closed forests, in shaded gullies, in drifts on north-oriented slopes, and where deposited on top of ice. For the central Arctic, a dense low stratus cloud with a base at a few hundred feet forms over the snow covered pack ice in summer, and absorbs the incoming shortwave radiation, warms up to 1-2°C and radiates heat toward the snow surface. In addition, multiple reflection in visible bands occurs betweeen the snow and the base of the clouds with resulting increase of energy reaching the snow/ice interface and being available for the base melt. The snow cover deteriorates, develops meltwater puddles, and these eventually siphon through the ice into the ocean (Untersteiner 1961; Herman and Goody, 1976; Herman, 1977; Stanford, 1977).

Snow Covers and the Synoptic Weather

In short term weather forecasting, the snow cover distribution is seldom taken into account. It was shown that the accuracy of the short term forecast does not generally improve with the inclusion of snow. Only in exceptional situations was it recently recommended to include snow cover distribution in the computerized weather prediction program of the U.S.

National Weather Service (Wagner, 1973). Snow cover is also not differentiated in operational weather charts. It is well known, however, that in the long run, extensive snowfields do have a significant cooling effect on the overlying air mass.

Figure 2 shows the relationship between air surface temperatures and snow cover at three stations in North Dakota, USA. The stations are located in the central flats of the North American continent in moderately undulated uniform terrain dominated by open space. Data for January, February, and the first half of March of a five-year-long interval between 1974 and 1978 were analyzed.

Both the average maximum and minimum surface air temperature were lower by about 10°C with the snow on the ground than without it. Out of 587 station-days with more than 5 cm of snow on the ground only at six times (1 percent) did the temperature surpass +7°C. This happened during the melt, within the last three days of the snow presence. The daily minima never rose to +1°C. On the other hand, during the 224 station-days with snow-free ground, the temperature maxima were above 7°C 83 times (37 percent), above 10°C 41 times (18 percent), and above 15°C 11 times (5 percent). The daily minima were above 1°C six times.

In the forested mountains, snow survives much higher ambient air temperatures (Yamada, et al., 1981.) Thus, for example, at Blue Canyon, California, the originally 70 cm thick snow cover of 7 May 1975 disappeared only after ten days of continuous, above-freezing weather with daily temperature minima between 2.8°C and 13.3°C, and maxima between 13.9°C and 17.8°C.

The presence of a fresh snow cover on the normally snow deficient northern Great Plains of the United States caused a serious warm bias in computerized forecast of maximum and minimum temperatures released by the National Weather Service in early March 1977 (Dewey, 1977). The computer program is based, to a large degree, on regional multidecade climatology. The forecast errors were consistently larger for daily maxima than for minima and averaged 8.1°C in the case of daily maxima, and 4.8°C for minima at two stations in South Dakota with the thickest snow cover.

Dry continental air is not the only type which is cooled by snowfields. An intense cooling also affects warm moist air crossing a snow covered area. Sensible and latent heat as well as moisture are extracted in the process of turbulent mixing combined with longwave radiation exchanges between the cloud base and the snow. A case study of such a situation, when a warm air was advected into Michigan from Kentucky, was analyzed by Treidl (1970).

The impact of snow on synoptic scale is well illustrated by a simplified weather map of North America for 29 January 1980 (figure 3). Except in the vicinity of partially ice-free inland lakes, snow was falling along the snowline where the cyclonic track was deflected by an inland-located high-pressure block. The situation is frequently associated with southward anticyclonic outbreaks of cold polar air into the snow-free zone. Such outbreaks release cold air generated in the semi-persistent anticyclonic cells which form over the snowfields (figure 4). Canadian and Siberian anticyclones can serve as an example. New snow reinforces the cooling and drying power of the earlier cover and adds to the original area by a further southward accretion (Namias, 1975). This is just one of several mechanisms through which seasonal snowfields achieve their remarkable persistence (Namias, 1980).

The radiative cooling of the snowfields with resulting anticyclonic circulation lays the seeds for the early dissipation of inland snow in spring. This is because precipitation over the desertified interior is deeply reduced. Average thickness of snow in the continental interiors at the end of the season is only about 0.1 - 0.5 m. Mid-winter drifts redistribute the snow, expose the bare soil, or form weak spots with shallow coverage. When the direct solar radiation increases in spring, snow in the weak spots sublimates, evaporates, or melts. Vertical turbulence is greatly enhanced by non-uniform heating of the partially dissipated snow cover, and inversions break down during daytime. Horizontal eddies intensify as well; these in turn speed the evaporation and the extraction of water vapor by the lower troposphere. Nocturnal radiative cooling slows down. High pressure cells weaken and an advection of warm moist air from the snow free areas is facilitated. Similarly the dissipation of snow on top of the pack ice is enhanced by increased wind stress in late spring when unfrozen water is exposed in leads and polynyas.

<u>Snow Cover Related Feedbacks</u>

Numerous subtle feedbacks operate in the transition zone (Kellogg, 1974). Some of them are:

1. <u>Snow-albedo-temperature feedback</u> (Croll, 1890). A snow-covered surface absorbsless radiation and cools the surrounding air. More snow is then deposited and the snow covered area expands.

2. <u>Snow-high pressure cells-polar outbreaks</u>. Radiative cooling produces anticyclonic cells over the snowfields. Cold polar air is exported to lower latitudes. Snow precipitates along the polar fronts and snow cover expands. More extensive snow enables deeper southward penetration of the next outbreak.

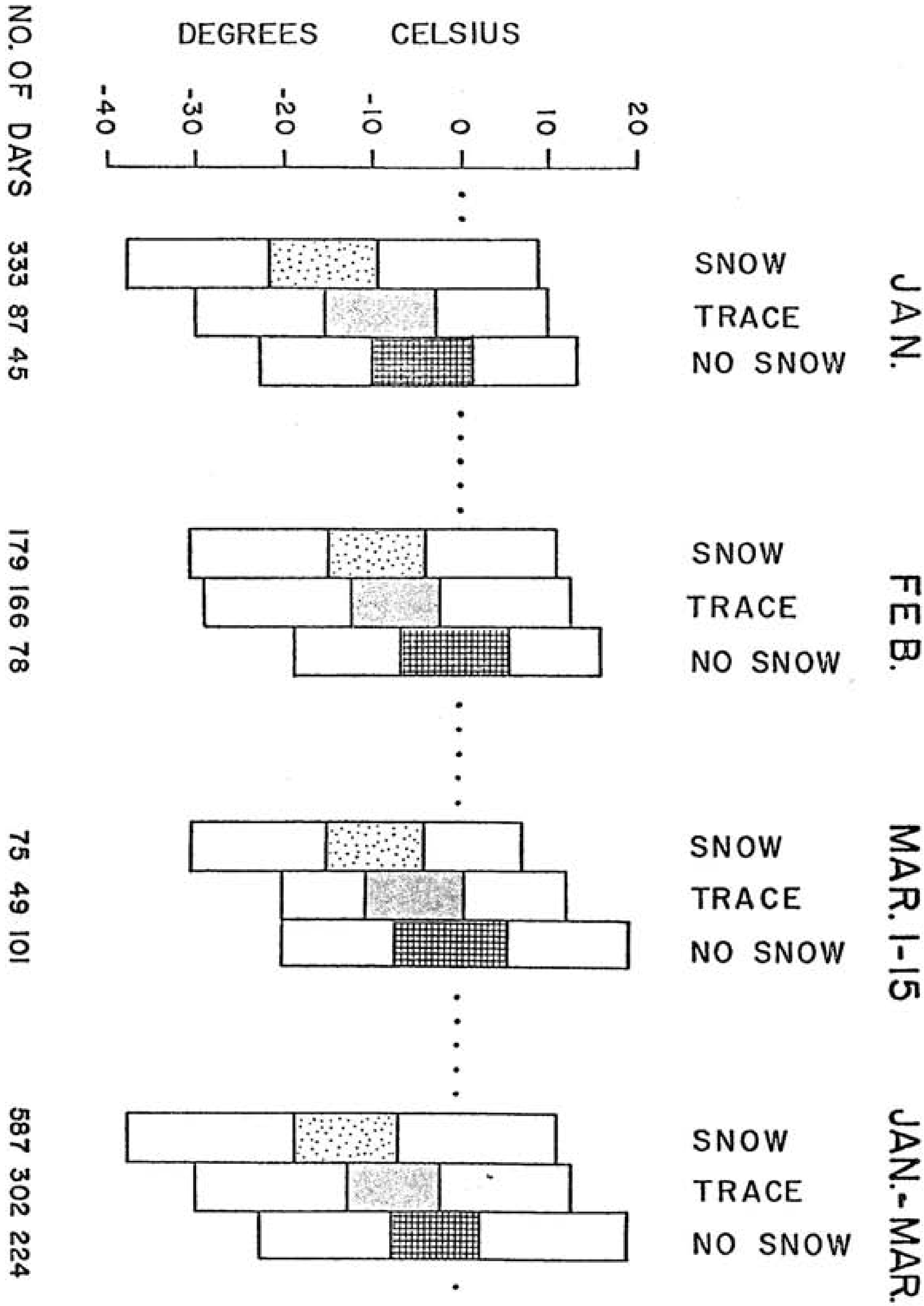

Figure 2. Average range of the winter air surface temperatures, Almont, Mott, and Williston, North Dakota, USA. Record covers 1113 days from 1 January through 15 May, between 1974 and 1978. Mean daily range shown by stippled inner column, absolute range by outer blank column. Temperatures over snow-free ground are higher by about 5-10 degrees C during each month as well as during the whole season.

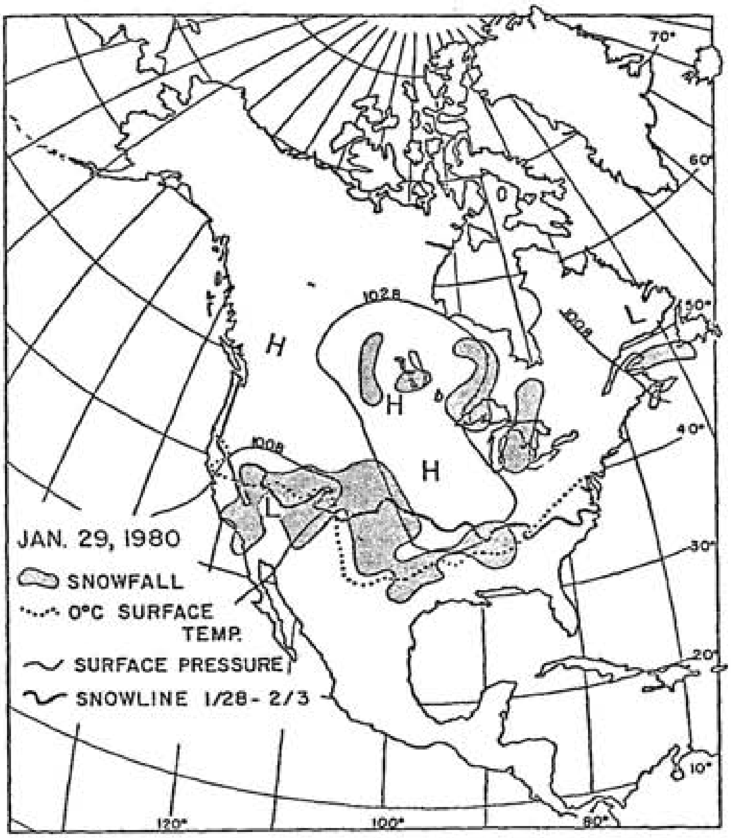

Figure 3. Snowfall occurrence along the snow cover margins and in the vicinity of ice-free inland lakes shown by a simplified 0700 EST surface weather map for 29 January 1980. H- high pressure centers, L- low pressure centers. 1028 and 1008mb isobars shown.

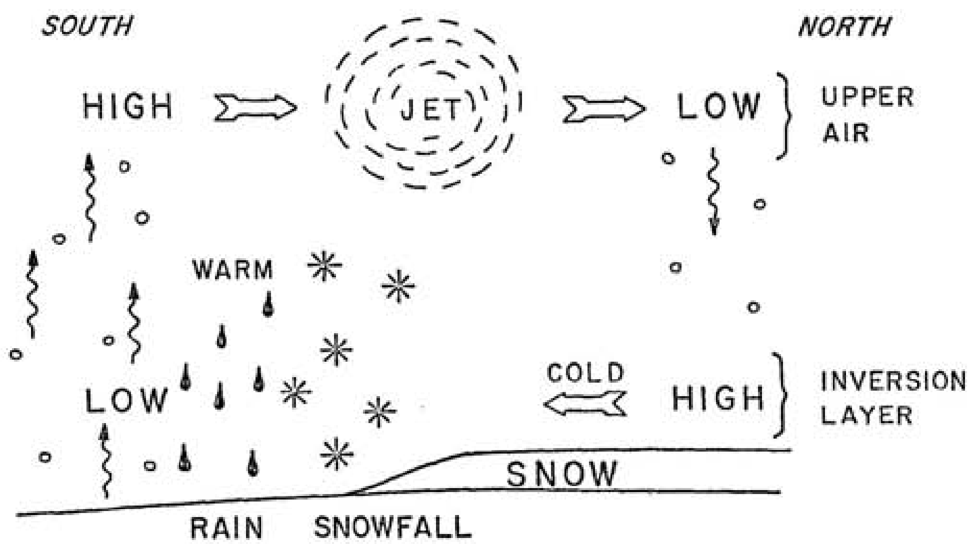

Figure 4. Schematic meridional transect over snow-covered land showing sinking motion of air and moisture, and buildup of high pressure over the snow fields, precipitation along the snow edge, upward motion of air and moisture in front of the snow line.

3. Snowmelt-evaporation-Arctic stratus. Increased evaporation from leads, from the open ocean, and from the snow surface in the Arctic increases atmospheric humidity. This turn leads to increased atmospheric counterradiation, speeded evaporation, and formation of clouds. Clouds warm by the absorbed solar radiation and by the upward reflected shortwave radiation from underlying snow.

4. Snowline elevation feedback. If the snow accumulates at an exceptionally high rate in the mountains or at high latitudes, the permanent snowline drops, a larger area is covered by snow, the region cools, more precipitation is deposited in a solid state, and snowfields further expand (Williams, 1978; 1979). Where precipitation is abundant radiation marginal, multiyear snow turns into ice which will flow into foothills, expand the snow and ice-covered zone and speed the feedback (Barry et al., 1975). The feedback can also be triggered by orogeny and crustal uplift.

Impact of Snow on the Climate of Middle Latitudes

What is the influence of snow covers on global climate? Clearly, the global impact results from the integration of individual local effects of snow on the weather throughout the year.

Snow introduces a step into the response of the earth's surface temperature to insolation forcing (figure 5). This is vividly illustrated in the continental interiors in spring. When snow disintegrates in early May in central Siberia, a cold winter regime is replaced by a hot summer regime within days. During such a transitional interval, the afternoon temperatures climb from around 5-10°C to 25-30°C.

The zone in which the transition from a snow covered state to a snow-free one takes place shifts with the season. Figure 6 shows a latitudinal position of this zone in the lowlands of interior America and Asia, as well as over the Antarctic during 1975. South of the zone, no snow was present (except for mountains). North of it, no snow free ground or melting snow was detected in satellite imagery. The transition zone is thus marked by the coexistence of frozen snow covers, melting snow, and snow-free ground or open ocean. The zone is loosely associated with the position of the polar front and makes its closest approach to the pole in July and August. The poleward retreat of the outer boundary in spring and early summer is slower than the equatorward advance in the fall.

The surface climate polewards of the transition zone is characterized by subfreezing, dry surface air, inversions aloft, by high pressure cells, dominant anticyclonic circulation, and by the high sensitivity of surface heat and moisture exchanges to direct solar radiation in clear weather. The heat reserves of the troposphere have little effect on surface albedo and on evaporation rates, which are both principally controlled by the shortwave radiation absorbed on the surface. Within the transition zone and south of it, the influence of atmospheric heat reserves and humidity on the surface heat exchange is substantial.

Snow Covers and Turbidity

Increased atmospheric turbidity results invariably in the reduction of shortwave radiation absorbed by the surface (Hummel, 1977). The net radiation may still increase (Shaw, 1975), as is the frequent case with low level turbidity (Schneider, 1972). However, in winter and early spring, the metamorphism, the surface albedo, and the evaporation from the snow surface are not directly dependent on the net radiation balance. The increased turbidity of polar air at any level at this time of the year is likely to delay the effect on snowmelt. The Arctic atmosphere is 10 to 100 times dirtier than the Antarctic atmosphere (Rahn et al., 1977). This is due to the high elevation of the Antarctic plateau, the higher level of volcanic activity in the Northern Hemisphere, the presence of deserts and semideserts upwind of the Arctic Basin, and sources of industrial pollution in North America and Europe (Rahn and Shaw, 1978). Contamination of the Arctic atmosphere is strongest in winter and in early spring when a persistent layer of Arctic haze forms (Rahn et al., 1977). Its frequency and concentration is strongest in March, April, and May. It practically disappears in July and August, forms again in September, and reaches high winter levels in November (Rahn and Shaw, 1978). The haze is a regional phenomenon independent of any local influence. It is dark gray in winter, and nearly colorless in spring, contains sooty carbon and pollution-derived sulfates and Pb^{210}, and occurs at any level of the troposphere, but most frequently in the lowest 2 km.

The depositional and thermal effects of Arctic aerosols on the Arctic environment and on hemispheric climate are unknown at present. While Rahn and Shaw expect the lower troposhpere to warm in spring by about 1°C as a result of direct radiation gain, the impact of the haze on cloudiness, on snow precipitation, stability of the inversions, and on the heating and evaporation rates remains unknown.

Increased turbidity was also observed in the Arctic stratosphere after violent volcanic eruptions such as that of Mount Agung, Indonesia, in 1963. It is unknown whether the snow and ice covers reacted to this increase and if so, in what way.

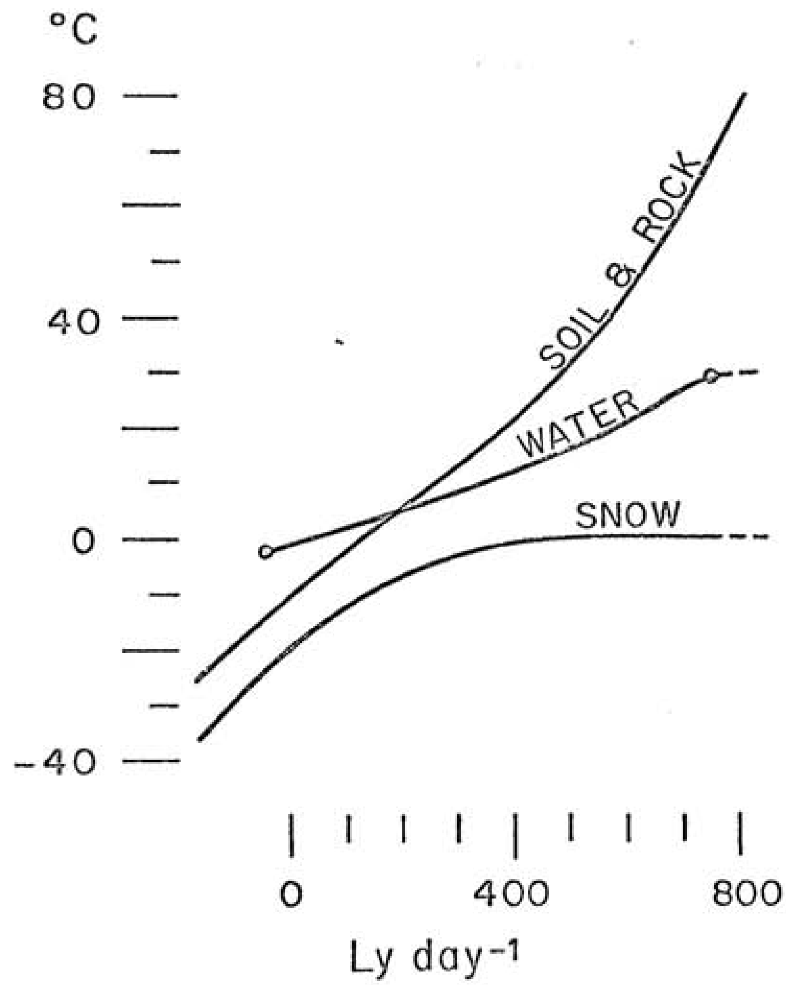

Figure 5. Schematic correlation of surface temperature of snow, water and dark soil or rock, with ground irradiance totals on clear days for lowlands in middle latitudes.

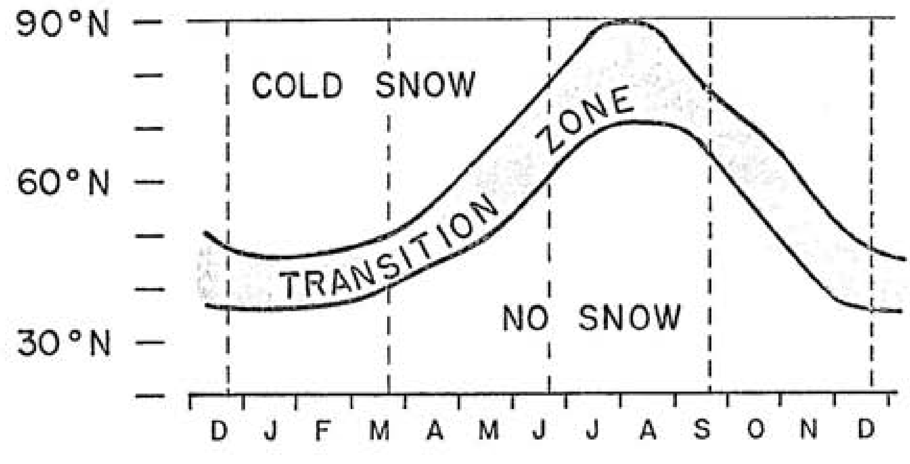

Figure 6. Seasonal shift of the transition zone in the lowlands of the Northern Hemisphere (between 70-100 W and 50-120 E) as observed during 1975. Northern boundary is delimited by the northernmost occurrence of snow-free ground, the southern boundary by the southernmost occurrence of snow fields. This is based on NOAA/NESS snow cover charts.

Snow Covers and Carbon Dioxide

Carbon dioxide in the atmosphere is rapidly increasing mainly because of the burning of fossil fuels. Projected doubling in the next few decades (Broecker et al., 1979) results in a predicted global warming of about 2°C in annual temperatures (Manabe and Wetherald, 1975). General circulation models foresee the largest effect in the high latitudes in summer (Madden and Ramanathan, 1980). The snow and ice season should be shortened and the atmospheric humidity should increase due to CO_2. Snow and atmospheric water provide the feedback elements which multiply the original inputs into the expected impact.

Choudhury and Kukla (1979) argue that the above models did not take into account the CO_2 related reduction of near infrared radiation reaching the active layer of snow and the exposed water in the leads. The near infrared is instrumental in the surface metamorphism of snow and in controlling the heating and evaporation rates in the water in leads. Thus, if not fully compensated by increased downward longwave flux, the decrease in incoming near infrared radiation amy actually cause the surface to cool. This process may be operative in autumn and in the spring when the air is cold and dry.

Carbon dioxide in the Arctic reaches the highest concentrations found anywhere with exceptions of industrial centers. Its concentration levels peak in April and May (Hanson et al., 1980). These are the months of the intense metamorphism of snow packs, of intensified subsurface melt, of high variation of surface albedo in the transition zone, and of intensified evaporation from polar water bodies. They also are the months of highest concentration of carbon dixoide and of Arctic aerosols.

Snow in Numerical Climate Models

The present level of sophistication of numerical climate models is not advanced enough to take a proper account of numerous subtle feedbacks controlling the dynamics of the cryosphere (Schneider and Dickinson, 1974; Smagorinsky, 1974). Most models simply prescribe snow where precipitation occurs in subzero temperatures, and rain or snowmelt, where air surface temperature rises above 0°C. The air temperatures are controlled by net radiation balance. This is far from the true dependence of snow on radiative forcing in the real world (Lettau and Lettau, 1975). It is just over a decade since snow came "out of hiding" and was included in climate models (Radok, 1978). Although Adem (1964) had already considered seasonal snow fluctuation in his numerical forecast model, it was the widely publicized work of Sellers (1969) and Budyko (1969), simple by today's standard, that convinced the research community of the importance of surface cryosphere in the climate system. Although based on highly simplified physical assumptions with regard to snow, some general results of climate models are of interest. Thus, for example, Wetherald and Manabe (1975) found in their model that a four percent drop in the solar constant would shift the zone of peak annual snowfall from the present 70°N to 55°N, and the peak snow accumulation from 75°N to 60°N.

Suarez and Held (1976; 1979), when studying the possible impact of the Milankovitch mechanism on the past energy budget found an extensive sensitivity of the land-based snow to solar constant. They also confirmed a strong latitudinal dependence in the sensitivity of surface temperatures to insolation reported by Wetherald and Manabe (1975). That the presence of snow, based either on land or on ice, makes the high latitudes exceptionally sensitive is evident from numerous other models (see Gates, 1975; Simmonds, 1979; Budd and Smith, 1981; Andrews and Mahaffy, 1976; Barry et al., 1975; Williams, 1975; Weller et al., 1972).

Kukla et al. (1981) correlated astronomic variables with independently-dated paleoclimatic evidence and found the interglacials to be marked by an exceptionally high obliquity. High obliquity results in more radiation supplied to the high latitudes at the expense of the low ones.

The sophistication of climate models is rapidly improving (Smagorinsky, 1974; Ghil, 1980). When the transition zone processes are more carefully studied, and their physics correctly incorporated, the climate models, including the general circulation models, will make a giant step forward. Such furture improvement will be made possible by incorporating numerous microscale models of snow transformation which are at hand, and can be exploited for improved parametrization of GCM (Goodwin and Outcalt, 1975; Wendler and Weller, 1974; Maykut and Church, 1973; Lettau, 1977; Riordan, 1976; Schaller and Kraus, 1977; Diamond, 1953; Allison, 1972).

Also, numerous experimental studies exist containing a wealth of potentially useful data (Mantis, 1951; Mellor, 1964; Billelo, 1967; Benson, 1969; Oort, 1975; Radok, 1979). Very interesting in this respect is the greatly increased sensitivity of surface air temperatures to the CO_2 doubling as found by Ramanthan et al (1981) in the transition zone during spring and summer. More field and satellite observations, nevertheless, will still be needed to upgrade the knowledge on the processes in the transition zone, where snow and ice provide a sensitive link with external as well as internal climate forcings.

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The Use of Snow and Ice Data in Energy Balance Climate Modeling

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Introduction

Snow and sea ice are very important components of the earth's climate system. Because of their high albedo and their radiative and thermal properties, they interact in several simultaneous and complex ways with other components of the system, resulting in feedbacks which are possibly the most important ones in determining the overall sensitivity of the climate. This is because snow has a high surface albedo compared to the underlying snow-free surface, and has different emissivity characteristics for longwave radiation. In addition, the moisture flux between the surface and the air is also influenced by the presence of snow. The thermal inertia of a snow-covered surface is not very different, however, from that of a snow-free one. Sea ice also has a high surface albedo. In addition, its presence has a strong effect on the vertical moisture flux and the thermal inertia of the ocean. Its longwave properties are also different from those of water.

All of the above effects of snow and ice have not yet been incorporated into energy balance climate models, but the role of the snow- and ice-albedo feedback has recieved much attention. This work began when, in 1969, Budyko and Sellers simultaneously published energy balance models which incorporated the snow- and ice-albedo feedback and had an extremely large sensitivity. They both found that in their models a reduction of the solar constant of 2 percent or less would result in an ice-covered earth with a mean surface temperature 100°C less then the present climate. This result has stimulated much research since it was published to try to understand the reasons for it, and to discover whether it was a real property of the climate system, or an artifact of the models. Although it was first suggested that the extremely simplified treatment of atmospheric and oceanic dynamics in these models was responsible, it now seems that the handling of the radiative energy balance, particularly the shortwave radiation, is the cause.

Using recently available snow and ice data, as well as satellite-derived measurements of the planetary radiative balance, it has been possible to develop much better parameterizations of the effects of snow and ice on the planetary albedo. These have resulted in model sensitivity which is much lower than was originally found by Budyko (1969) and Sellers (1969). In addition, it seems that the annual average assumption of these early models also contributes to an enhanced sensitivity when compared to a more realistic seasonal model.

It should also be pointed out that any energy balance model which does not explicitly model ice sheets on land and deep ocean circulations cannot realistically model the climate system for time scales longer than 100 years or for climates very different from the present, and so the ice-covered earth solution should not be taken seriously. The sensitivity of the climate system about the present climate, however, is a very important problem, and these models can be very useful in helping us to understand this.

It is useful to describe the sensitivity of the climate system in terms of the parameter β, first suggested by Schneider and Mass (1975) and further discussed by Cess (1976), where

$$\beta = S_0 \frac{dT}{dS} = \frac{F}{dF/dT + (S_0/4)\ (d\alpha/dT)}.$$

S is the solar constant, S_0 is the present value, T is the global mean surface temperature, F is the outgoing longwave flux, and α is the global mean planetary albedo. β then represents the change in global mean surface temperature times 100 resulting from a 1 percent change in the solar constant. Because of the interactive nature of the climate system, the sensitivity to solar constant changes is representative of the sensitivity of the system to other global forcings, such as changes in carbon dioxide.

The next section will briefly describe the Budyko-Sellers results and their albedo parameterizations. Then a new albedo parameterization based on observed snow and ice amounts which I have applied to a seasonal climate model based on that of Sellers (1973, 1974) will be described. Finally, the results of my experiments with the improved model will be presented, to illustrate the reduced sensitivity.

Budyko (1969) and Sellers (1969)

Budyko and Sellers both used very simple parameterizations for the planetary albedo based on the amount of snow and ice at the surface. They both parameterized snow and ice amount as simple functions of surface temperature, with Budyko using a step function at T = -10°C, and Sellers having a linear variation from snow to no snow for T = -10°C to T = 0°C. Sellers used what turned out to be an extremely large value of planetary albedo above a snow-or ice-covered surface, 0.85, and 0.250-0.444 for no snow. Budyko did not allow intermediate albedo values, using 0.62 for snow and 0.32 for no snow, which created a large albedo contrast at the snow line.

This large contrast in planetary albedo between a snow and no snow condition resulted in a very strong T-albedo feedback. The sensitivities of both models was β = 400-500°C.

A Better Planetary Albedo Parameterization

In order to understand the effects of snow and ice cover on the sensitivity of the climate systems, it is necessary to understand explicitly how snow and ice cover affect planetary albedo. I recently (Robock, 1980) calculated how snow and ice cover affect surface albedo. Using satellite data, I produced monthly average maps of Northern Hemisphere snow cover. In addition, I also explicitly calculated the surface albedo as a function of surface type, and considered the effects of meltwater on the surface, solar zenith angle, and cloudiness on the snow and ice albedos. Also using data on the seasonal cycle of sea ice, I calculated the detailed seasonal cycle of surface albedo.

More recently, I have parameterized the snow and ice covers as functions of surface temperature based on the data in Robock (1980). I have also used the planetary albedo model of Thompson (1979) to calculate the planetary albedo using the above surface albedo. Thompson explicitly considers solar zenith angle effects and cloudiness effects. In the above manner, it is now possible to calculate planetary albedo and to isolate the effects of snow and ice cover on it through their effects on surface albedo.

Model Experiments

I have been conducting experiments using the detailed seasonal climate model of Sellers (1973, 1974). The original version of the model, with simple and inaccurate surface and planetary albedo parameterizations had a sensitivity almost the same as the original Budyko and Sellers models. I have found that using the above detailed albedo parameterizations, the model sensitivity is lowered to about β = 200°C. Also the response is symmetric about the present solar constant, that is the decrease in temperature with a decrease in solar constant of 1 percent is the same as the increase in temperature with an increase in solar constant of 1 percent. Using an annual average solar forcing rather than the seasonal cycle causes the response to be the same when the solar constant is increased, but amplified when the solar constant is decreased. Thus the annual average assumption of the early models amplifies the sensitivity. When I do not include the solar zenith angle effects on cloud albedo, the sensitivity stays about the same, thus demonstrating that the snow- and ice-albedo feedback does indeed contribute significantly to the seasonal cycle of planetary albedo and to increased climate sensitivity, in contrast to the claims of Lian and Cess (1977). With snow and ice fixed and not allowed to respond to the changing temperature, β = 135°C.

Conclusions

Preliminary satellite data on snow and ice cover have allowed us, through energy balance climate models, to investigate the details of the climate system and its behavior. More detailed data, including that on the variability of snow and ice will be very useful in extending these experiments and furthering our understanding of climate change.

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Summary Requirements of GCMs for Observed Snow and Ice Cover Data

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For over 25 years, efforts have been made at the Geophysical Fluid Dynamics Laboratory to construct general circulation models (GCMs) for use in both forecasting and climate modeling projects. During this period of time, great strides have been made in the improvement of the accuracy of numerical forecasts as well as the quality of climate model simulations. In order to do this work, accurate snow and ice observations are needed to provide boundary conditions for atmospheric GCMs, initialize forecast models, and to validate forecast and climate model simulations.

Generally speaking, the needed global distributions of snow-and ice-cover data have been unavailable, incomplete, or hard to work with (small map sections; not digitized) so that the data are virtually unavailable. However, recent efforts by Wiesnet and Matson (1976) in compiling snow cover areal statistics and by Robock (1980) in his compilation of climatological mean snow margins have greatly helped to bridge the data gap between observers and GCM users. The figures in this paper include examples of how these new satellite-derived data sets can be used to validate climate GCM results. The model results displayed in these comparisons are those of a global spectral GCM with rhomboidal truncation at wave number 15. This model was time-integrated for 15 model years. For other descriptions of this model and its results, see Manabe et al. (1979) and Hahn and Manabe (1979).

The seasonal evolution of computed (by the GCM) and observed monthly mean snow cover is shown averaged over the Northern Hemisphere (figure 1), over Eurasia (figure 2), and North America (figure 3). From these figures, it can be said that the model tends to overestimate snow cover in the winter seasons, and this is somewhat more serious over Eurasia than North America.

Figure 4 shows the seasonal evolution of computed and observed standard deviation of monthly mean snow cover for the Northern Hemisphere; figure 5 Eurasia; figure 6 North America. Observations indicate that the interannual variability of monthly mean snow cover is largest in the months of October and November over the Eurasian continents. This feature is not duplicated by the model.

Figure 7 contains the mean climatological snow margin as compiled by Robock (1980) and as simulated by the model. These results indicate that the model is very successful in simulating the mean snow margin over North America but fails significantly over Eurasia.

For this report, the model success, or lack thereof, is insignificant relative to the importance of the existence of the observed data sets. Without the new observational data sets, the ability to evaluate the success of the model (with regard to its simulation of the snow cover distribution) would be severely limited. Accurate mapping of satellite snow cover should be continued in order to extend the short observational record in order to improve the quality of the aforementioned set for climate GCM verification.

Observed snow cover maps obtained from satellite images also serve to provide data for the initialization of forecasting GCMs. Unfortunately, preliminary attempts made by Gordon (unpublished) using observed snow cover data for this purpose resulted in January forecasts which were not noticeably improved. However, these results should be regarded as only a first attempt to identify the role of observed snow cover data in numerial forecasting. Additional studies using other GCMs in different seasons would help to achieve a greater understanding regarding this problem.

Still unmentioned is the notion of snow depth. Unfortunately, an atlas of observed monthly mean snow depth has yet to be constructed. Hopefully, a global atlas of this type will soon be made available so that GCM snow depth fields can easily be validated against observations.

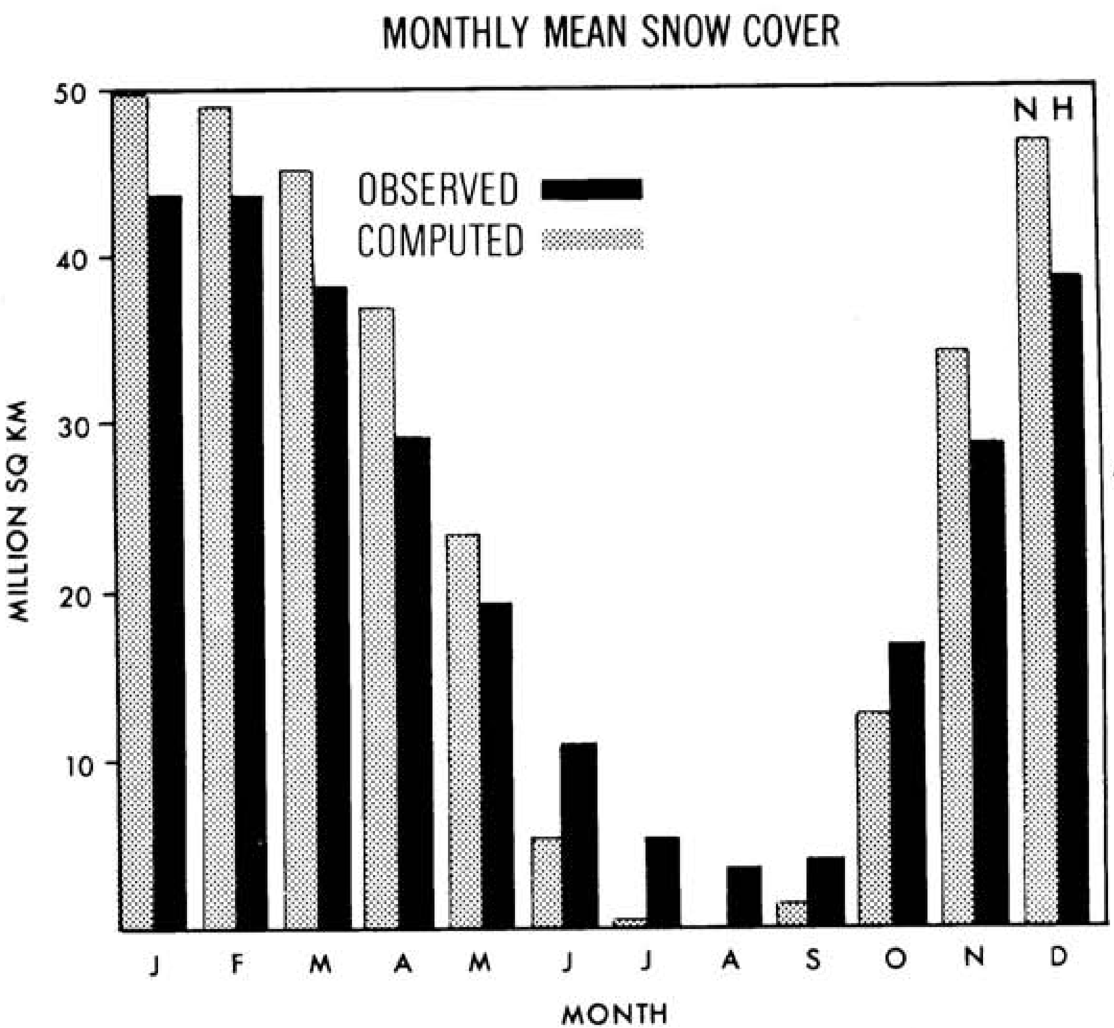

Figure 1. Monthly mean snow cover for the Northern Hemisphere as observed (Matson, personal communication) and as computed by the GCM.

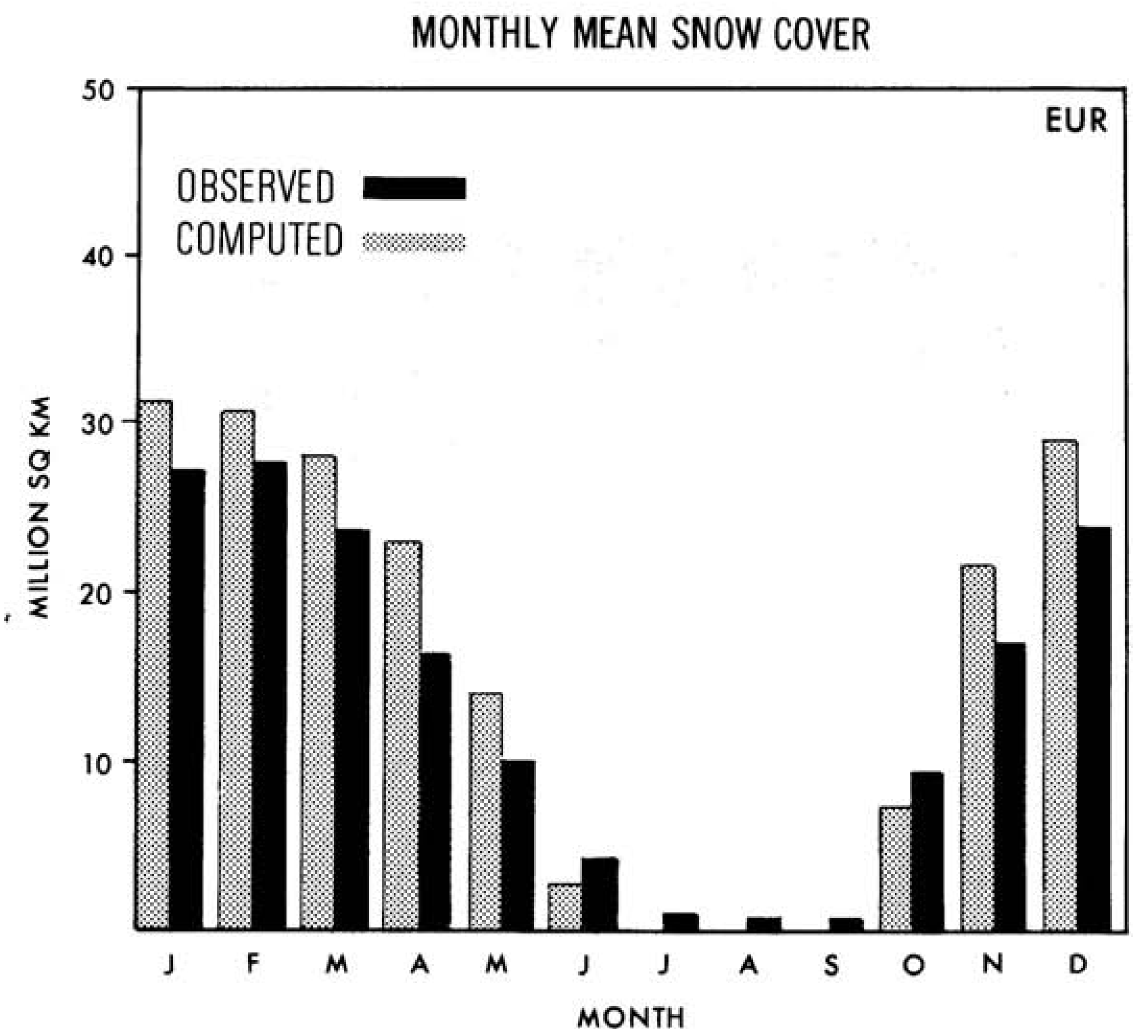

Figure 2. Monthly mean snow cover for Eurasia as observed (Matson, personal communication) and as computed by the GCM.

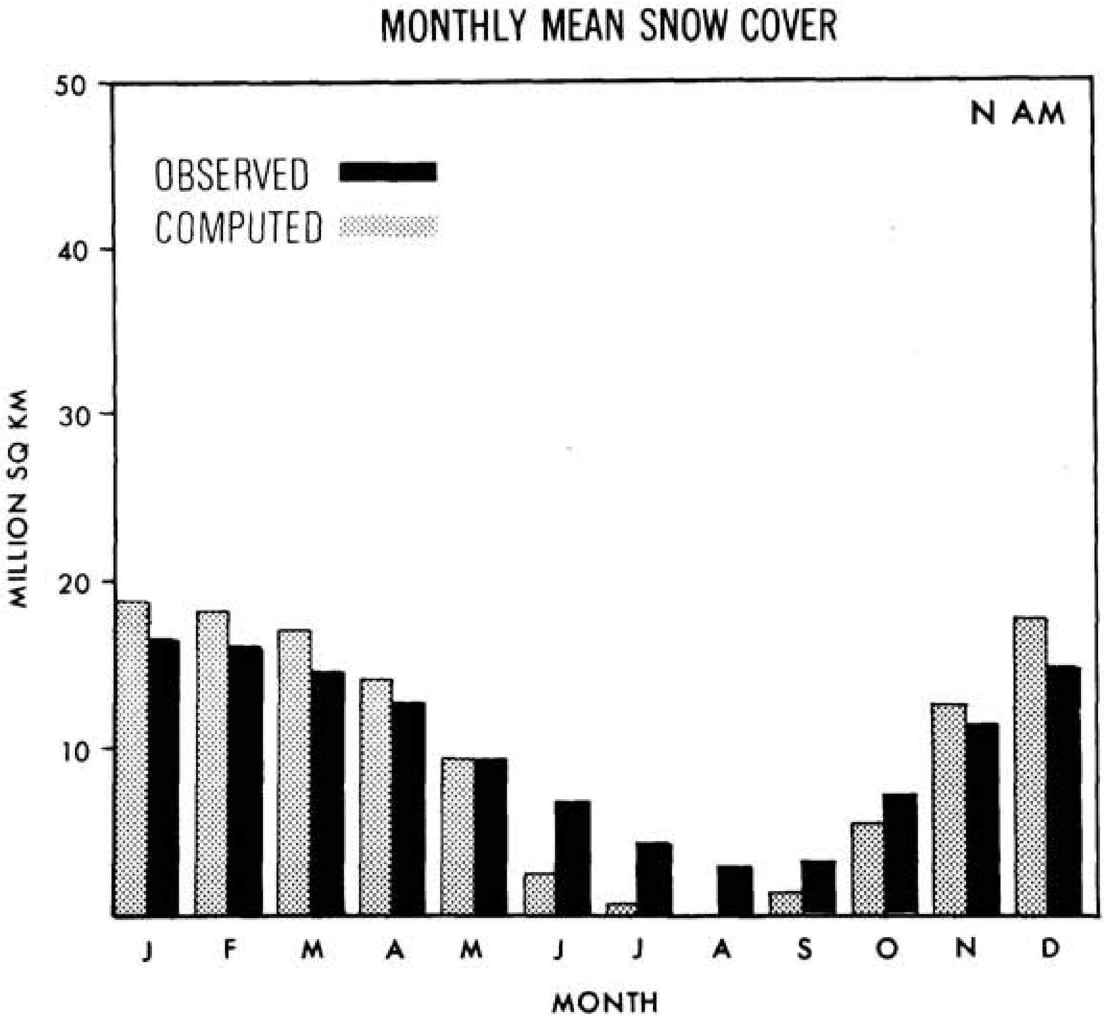

Figure 3. Monthly mean snow cover for North America as observed (Matson, personal communication) and as computed by the GCM.

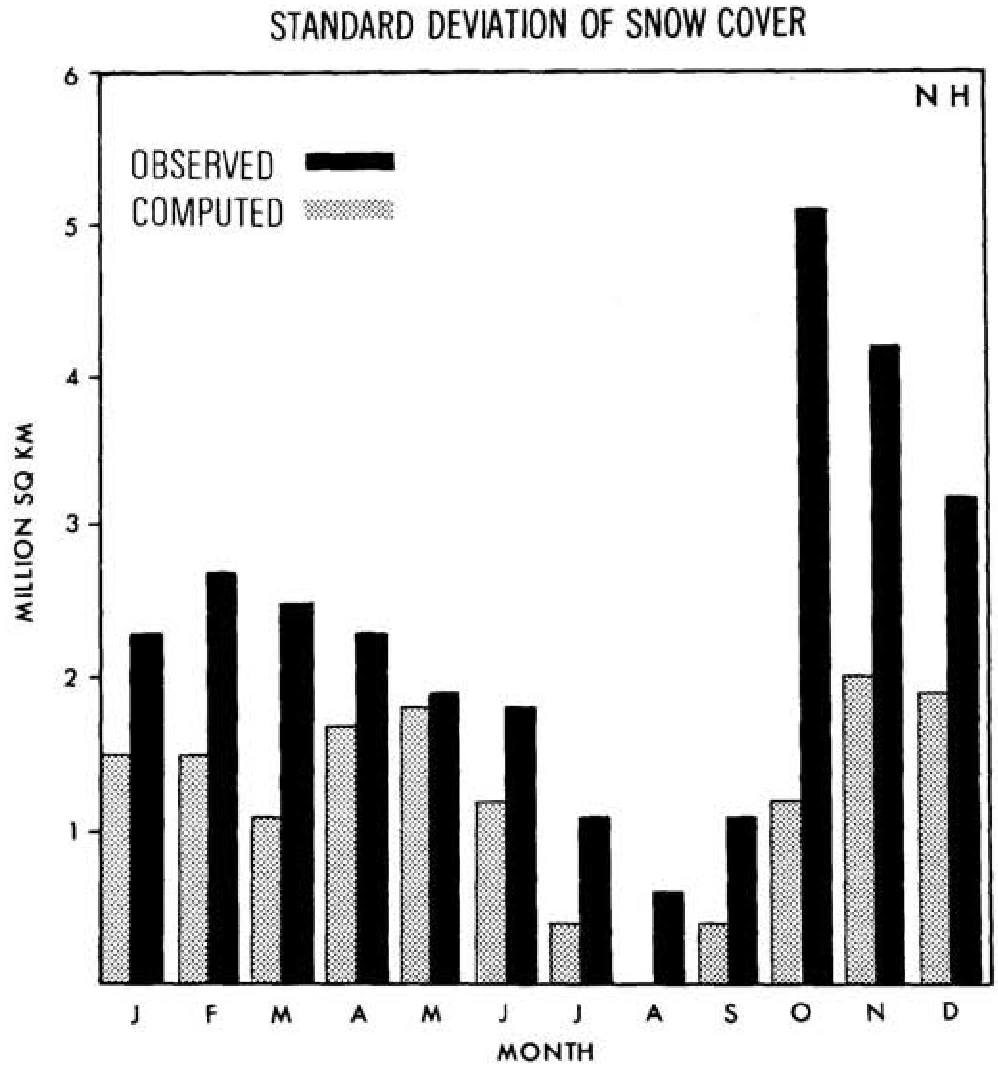

Figure 4. Standard deviation of monthly mean snow cover of the Northern Hemisphere as observed (Matson, personal communication) and as computed by GCM.

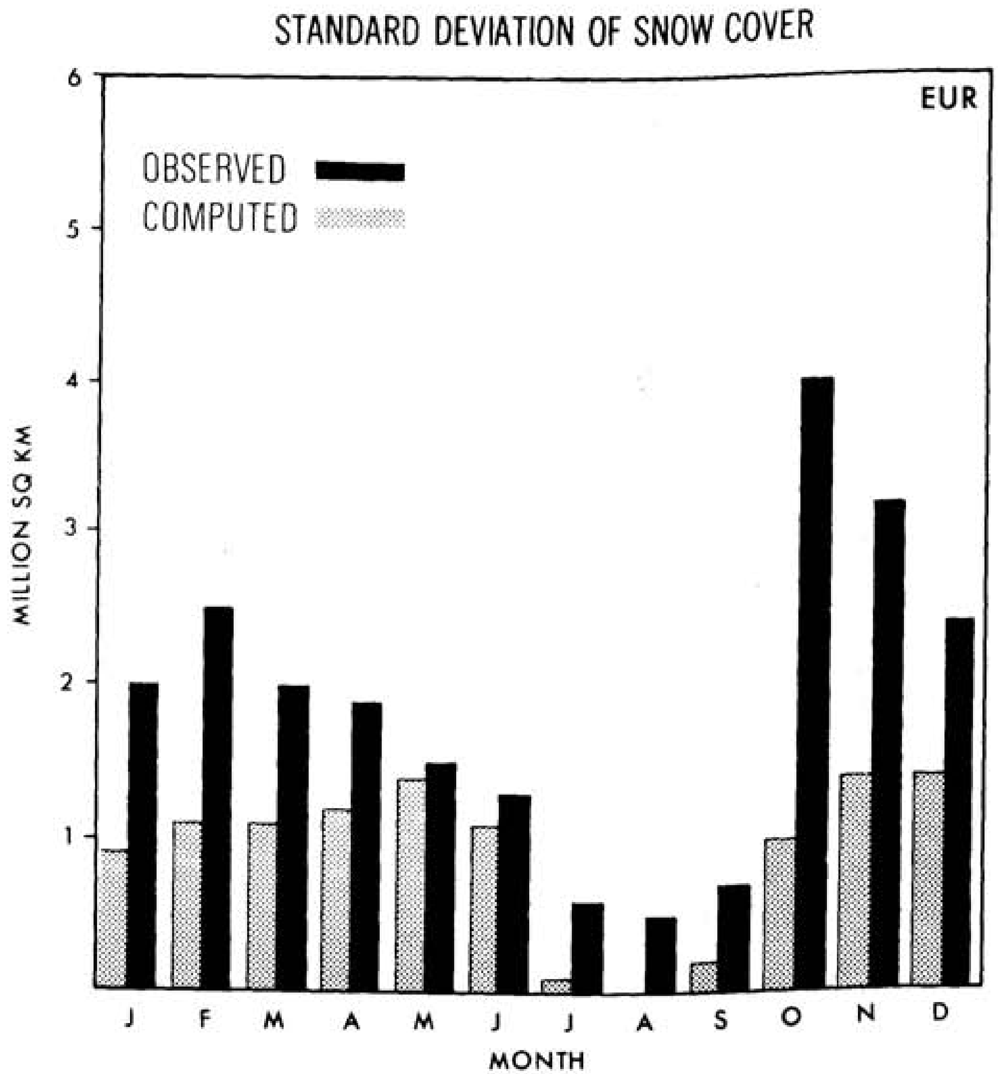

Figure 5. Standard deviation of monthly mean snow cover of Eurasia as observed (Matson, personal communication) and as computed by the GCM.

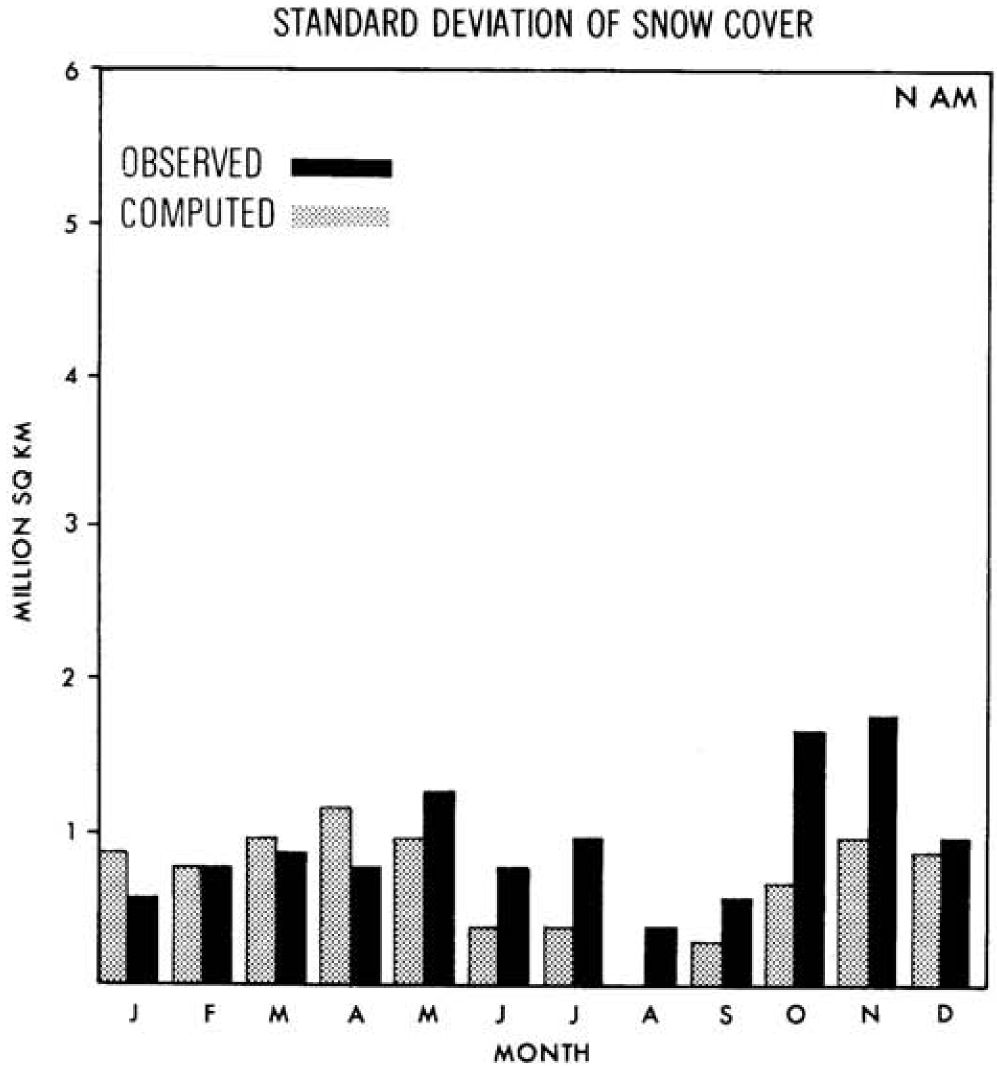

Figure 6. Standard deviation of monthly mean snow cover of North America as observed (Matson, personal communication) and as computed by the GCM.

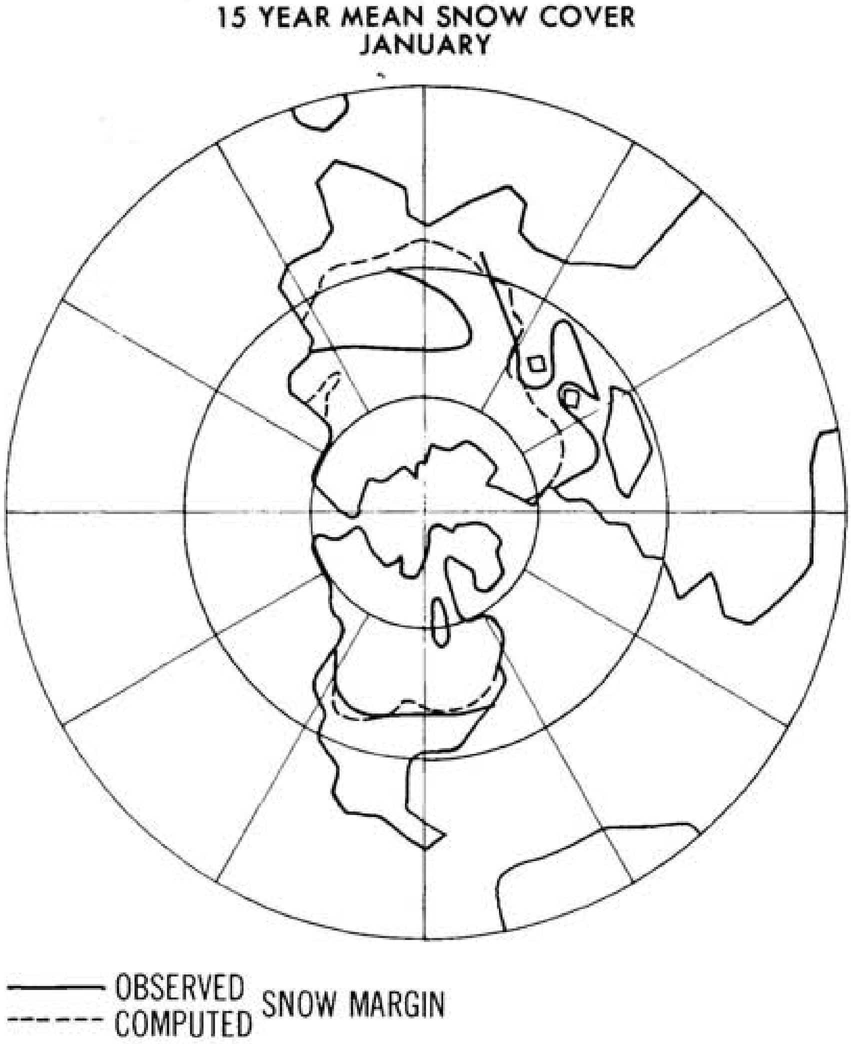

Figure 7. Climatological mean snow margin in January as observed (Robock, 1980) and as simulated by the GCM.

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Linear and Nonlinear Aspects of Snow Albedo Feedbacks in Atmospheric Models *
(Extended Abstract)

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Namias' hypothesis, that anomalous snow cover on the eastern side of the North American continent can generate an anomalous east coast low pressure system and an anomalous inland high pressure system, is consistent with the time-averaged anomalous response from a non-linear, primitive-equation, channel model with an idealized, flat, land-sea arrangement. An attempt to understand and describe this anomalous response in the nonlinear model as a linear response to anomalous diabatic heating was largely unsuccessful, primarily because the anomalous eddy fluxes were also important. This unsuccessful attempt to describe the nonlinear model's time averages by linear theory then motivated several comparisons between linear and nonlinear severely truncated quasi-geostrophic models. It was also found in these models that the eddy fluxes were extremely important for forcing or dissipating the stationary eddies.

Long-lasting and large-scale anomalies in the earth's boundary conditions have been hypothesized to force anomalous responses in the atmopshere's stationary eddies. One popular hypothesis has involved the influence of anomalous snow cover, because it has been documented by Kukla and Kukla (1974) and Wiesnet and Matson (1976) that the snow cover of the Northern Hemisphere varies from year to year. The resulting change in the planetary albedo can be large, depending upon the depth of the snow cover and especially upon geographical location and duration (see Kung, et al., 1964).

The anomalous response in the atmospheric geopotential field to anomalous snowfall has been discussed by Namias (1962), Dickson and Namias (1976) and Namias (1978). Briefly, Namias (1962) proposed that anomalous snow cover, generated on the east coast of North America, would force an inland high pressure system and an east coast low pressure system that would then be favorable for producing still more snow cover. It is by no means certain, however, that this proposed anomalous forcing mechanism forces the observed anomalous planetary wave structre. One might argue that the anomalous planetary wave, that might be due to some other mechanism, gives rise to the anomalous snow cover which is simply a response coincidental with the flow pattern. For example, it was first argued by Davis (1976), that if the atmosphere responds to an anomalous sea-surface temperature, then it responds at the lower-levels such that cold air is advected into the heating regions. In analogy, an increase in the anomalous snow cover on the east coast should favor at the lower atmospheric level and anomalous east coast high and an anomalous inland low. Linear theory offers some reasons for believing that this is the case since such circulations have been found in linear models (see Roads, 1980 and Egger, 1977). If one believes these linear models and since Namias' observations are exactly opposite to this, it might be suggested that these model failures are indicating that the anomalous planetary wave is determining the anomalous snow cover instead of the anomalous snow cover determining the anomalous planetary wave.

With this in mind, a nonlinear time-dependent primitive equation model was run and then compared to the response obtained in a linear model using the time-averaged zonal variables and diabatic heating field from the nonlinear model. Anomalous snow cover was generated in the nonlinear time-dependent model by increasing the snow albedo; as shall be shown, this gave rise to increased snow cover over the east coast, colder surface temperatures, cooling over the continents, warming over the oceans, and an anomalous planetary wave consistent with Namias' observations. Thus the results of the nonlinear model run were consistent with Namias' hypothesis that anomalous snow cover could generate an anomalous east coast low and inland high.

*Abstract of an article submitted for publication in Journal of Geophysical Research.

Suprisingly, however, the linear model's response to the anomalous heating field was a very poor description of the anomalous planetary wave. That is, the linear response to the anomalous diabatic heating field was much too large in amplitude albeit in phase with the anomalous response in the nonlinear model. The linear response to the anomalous eddy fluxes was also quite large but out of phase, and it was only with the combination of the anomalous forcings that the linear model could provide an adequate description of the anomalous response in the nonlinear model.

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Snow and Ice Cover Charts
Introduction

This section provides information on the U.S. operational products showing snow fields on a hemispheric scale on a weekly basis. They are the:

1. Northern Hemisphere weekly snow and ice charts by NOAA/NESS (see Smigielski, p.59 this volume),

2. Weekly charts of snow depth and age by the U.S. Air Force Global Weather Central (see R. Woronicz, p. 63 this volume) and,

3. Weekly sea ice charts by Navy-NOAA Ice Central (see Godin, p.71 this volume).

The NOAA set is based on satellite imagery and shows the relative reflectivity of snow as observed on the last clear day. Snow under persistent clouds is not charted.

The U.S. Air Force charts are based on ground reports of snow thickness. Satellite input and climatology are secondary sources. The charts do show snow under clouds. Reflectivity of the snow cover is not differentiated.

The Navy and Navy/NOAA weekly sea ice charts are based on satellite imagery and conventional reports. They show the extent, concentration, and age of the sea ice. They do not show snow on top of the ice or snow and ice thickness.

Also described in this section are the climatic snow cover charts produced at Lamont Observatory from the combination of satellite data and surface reports (see Kukla et al., p. 87 this volume).

Barry Goodison (p. 93) reports on the snow and ice charting in Canada and Inge Haupt (p. 97) informs on the sea ice satellite charting done by her group in Germany.

Finally, a brief report is presented on the accuracy of the NOAA, USAF, and Navy snow and ice operational charts for climate studies (Kukla and Robinson, p.103 this volume).

The Editors

Kukla, G; Hecht, A.; Wiesnet, D. eds. (1981) SNOW WATCH 1980. Proceedings of the Workshop held 1-2 October 1980 in Washington, D.C. Boulder, Colorado, World Data Center A for Glaciology (Snow and Ice), Glaciological Data, Report GD-11, p. 59 -62 .

Northern Hemisphere Snow and Ice Charts of NOAA/NESS

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Introduction

Since 1966, the Synoptic Analysis Branch (SAB) of the National Earth Satellite Service (NESS) has prepared a weekly snow and ice boundary chart for the Northern Hemisphere (figure 1). This chart is prepared on a 1:50,000,000 polar-stereographic base map centered on the North Pole.

Data Sources

The primary source of information used in the preparation of this chart are satellite images from the visible scanning radiometers of the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellite systems. Secondary input comes from the visible scanning radiometers of the Geostationary Satellite (GOES) systems over the North American continent south of 60°N, and occasionally from the Defense Meteorological Satellite Program (DMSP) systems. The specifications of currently used satellite sensors are shown below:

Satellite	Camera and Sensor	Resolution (KM)	Wavelength (μm)
NOAA-5 TIROS-N	Scanning Radiometer	3.7	0.5-0.7
NOAA-6 TIROS-N	VHRR*	1.0-4.0	0.58-0.68 0.725-1.10
GOES-1	VISSR**	1.0-7.4	0.5-0.7
GOES-2	VISSR	1.0-7.4	0.5-0.7

*VHRR - Very high resolution radiometer
**VISSR - Visible scanning radiometer

Presently the polar-orbiting satellites cross the equator southbound at approximately 0800 Local standard time (l.s.t.) and 1500 l.s.t.

Procedure

Each Tuesday the analyst, a satellite meteorologist, makes a pencil trace of the previous week's chart, which is one or two days old. Daily he collects all the NOAA visible data received in the past day (12 or 13 orbits) and compares snow and ice cover on the pictures to snow cover on the chart, and makes appropriate changes. Over North America, additional higher resolution data are used. Therefore, each segment of the chart shows the last cloud-free surface observation of the world. If an area is cloud covered for several days, the analysis of snow cover for that area will be several days old. If the area remaines cloudy for an entire week, the previous week's analyst compares his chart to the synoptic surface reports and Fleet Weather Facility weekly ice chart to recheck for errors or confirm drastic changes in snow or ice cover, such as a new snowfall or rapid snow melt. On Monday morning the chart is finalized and sent out. In the course of a week, one or two analysts, working shifts, will participate in producing the chart.

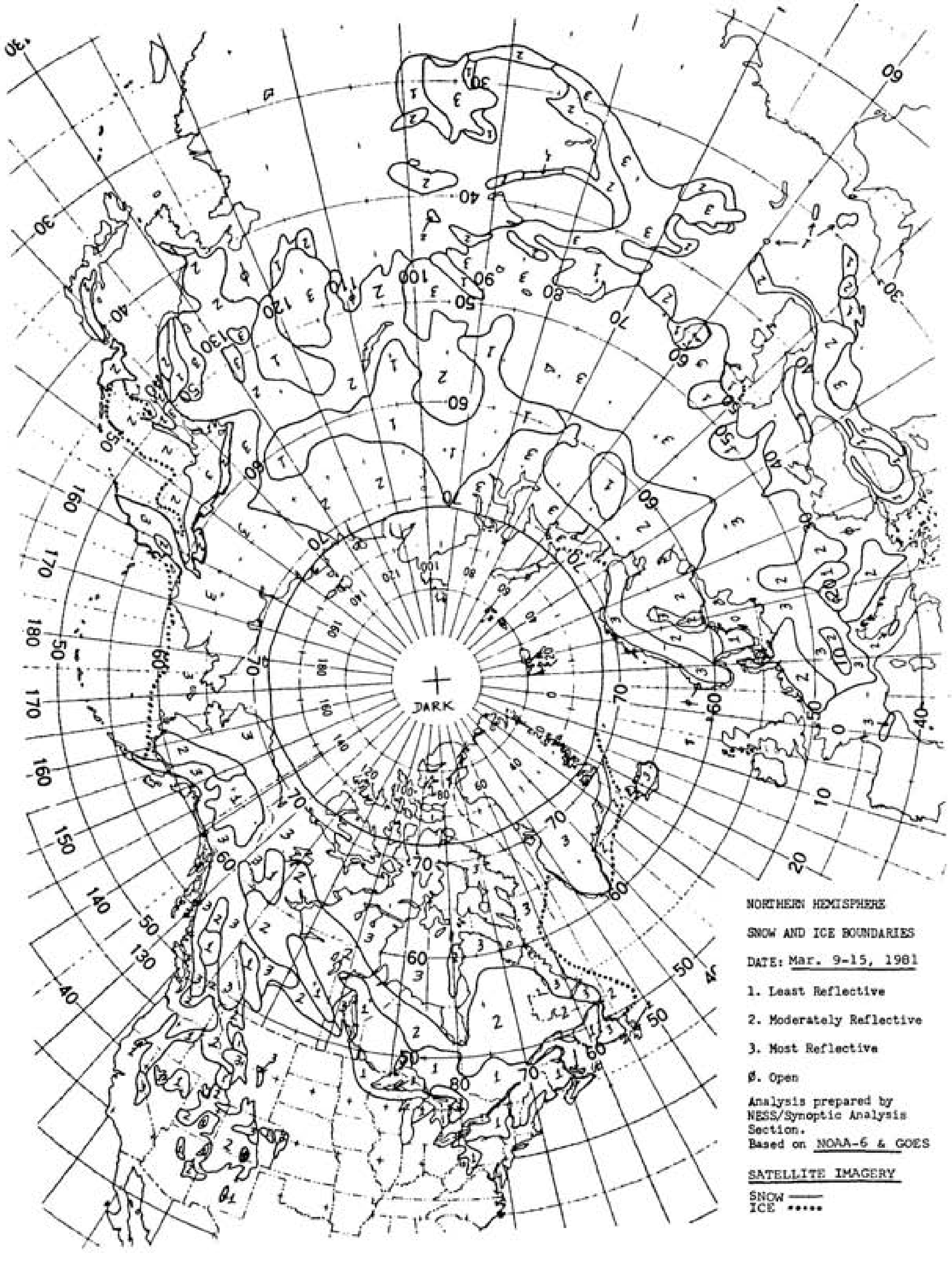

Figure 1. An example of the NESS weekly snow and ice boundary chart for the Northern Hemisphere.

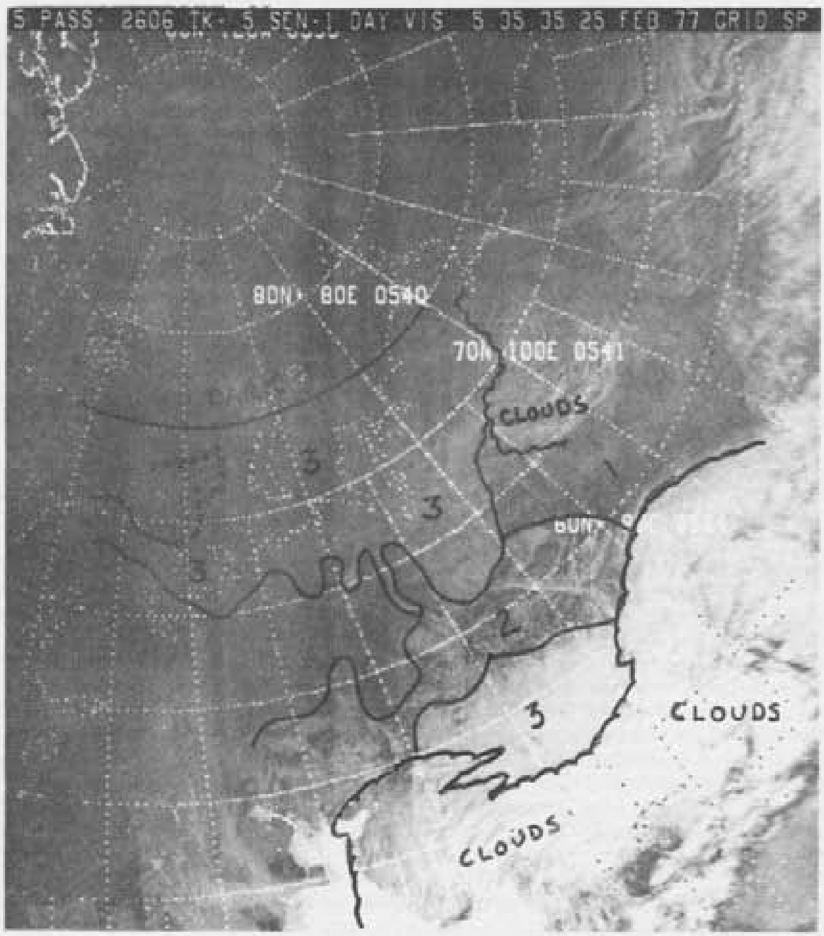

Figure 2. Reflectivities in changing sunlight.

Figure 3. Designating snow in mountain areas.

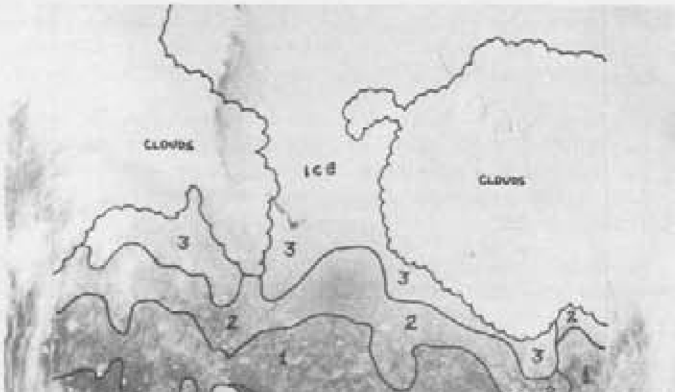

Figure 4. Reflectivity versus ground cover in eastern Canada. Note low reflectivity of densely forested zones with snow on the ground.

Terms and definitions

Solid lines on the chart indicate boundaries between different observed surface brightness of the snow fields. Small circles outline the ice boundary. The snow covered surface is divided into three categories, indicative of relative brightness of snow or ice covers. The categories are:

1. Lowest reflectivity (darkest)

2. Moderate reflectivity

3. Highest reflectivity (brightest).

These categories are subjective and are chosen by the analyst who observes the following guidelines designed to preserve as much continuity as possible:

1. To merit category 1-3, there must be visible snow. Any area of the chart not labeled with one of the categories is snow (or ice) free. An snow-free area largely surrounded by snow or ice is labeled 0 or OPEN.

2. Changes from the previous day's chart are mapped rather than starting anew. This helps preserve continuity between different analysts.

3. The designated reflectivity class of a given area is the average relative reflectivity within that boundary, i.e., a category 2 could be a composite of small areas in category 3 and category 1, or the entire area could have a homogenous moderate reflectivity of category 2.

4. Reflectivity categories are assessed relative to the surroundings at a particular time of the year and latitude (figure 2). The Greenland ice cap is labeled category 3 in both summer and winter, although it is much brighter in summer (owing to greater insolation). In December it may be barely visible (due to winter darkness), but it is still much brighter than its surroundings.

5. In wintertime, much of the far northern latitudes are in total darkness or near darkness. Consequently, the visible scanner of the satellite does not receive reflected light, and the areas around the pole are marked as "DARK" and left uncharted. For instance, at the winter solstice, the snow and ice chart is labeled as "DARK" north of about 55°N.

6. When snow-covered mountain tops are seen within large open areas that average less than category 1, the whole area in question is labeled SCTD MTN SNOW (scattered mountain snow, (figure 3).

7. When the distinction in reflectivity between small areas of land and water is great, such as in Arctic Canada in early summer, the entire area is labeled "3 over water, 1 over land."

8. The chart contains no information on snow depth. Lakes or plains with a thin fresh snow cover show up brightly while snow cover in an evergreen forest shows up dimly, if at all (figure 4).

Problem areas

Problems encountered in the production of the charts stem from the variable quality of satellite input, subjective classification of relative reflectivity, timing of the plotted information, and from the changing skill of the interpreting analysts. In summary they are:

1. satellite imagery
    a. variability in orbit times,
    b. sensor differences,

2. varying experience of the analysts,

3. reflectivity values: subjectivity in assigning numbers,

4. lack of information on the time of observation: - last date of observation not included,

5. lack of information on snow under persistent clouds.

Kukla, G; Hecht, A.; Wiesnet, D. eds. (1981) SNOW WATCH 1980. Proceedings of the Workshop held 1-2 October 1980 in Washington, D.C. Boulder, Colorado, World Data Center A for Glaciology (Snow and Ice), Glaciological Data, Report GD-11, p. 63 - 69.

The U.S. Air Force Snow Cover Charts

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A brief description is given here of the Air Force SNODEP model, perhaps the only completely automated snow cover analysis model in the world. It is run once daily at Air Force Global Weather Central (AFGWC) to produce a gridded analysis of snow depth and age. The grid is superimposed on a polar-stereographic map projection so that the grid point spacing is about 25nm (46.3km) at 60°N and S. SNODEP is global in scope, providing analyses in both the Northern and Southern Hemispheres.

The model produces its analyses using WMO weather observations which are received during the 24-hour period ending at 1200 hours G.m.t. each day. Snow depth reports are the primary source of snow information. These reports are spread into an array of four by four surrounding grid points (i.e., a 100 (185.2km) by 100nm square) to produce a snow depth analysis. Current weather information (WMO code 4677) and air temperature are used to estimate snowfall and snowmelt. Six-hour snow accumulation data are also used, when available, to adjust snow depth analyses. Since most snow depth observations are taken at 1200 G.m.t., no adjustments are made to these observations. Adjustments are made to snow depth observations which are taken at other than 1200 G.m.t. These adjustments are based on current weather and temperature data or six-hour accumulation information received subsequent to the snow depth observations. For reporting stations which do not make snow depth observations, SNODEP makes adjustments to the previous day's analysis to make the snow depth analysis. All in all observations from approximately 5000 stations in the Northern Hemisphere and 100 in the Southern Hemisphere are used in preparing these analyses.

Climatic values are used to model snow depth at grid points which do not have supporting stations reports. These climatic values are stored in the SNODEP data base and they are updated on the first day of each month. The model adjusts the snow depth analyses towards the climatic values by 10 percent of the difference between the previous day's analysis and the current climatic value at each grid point. Climatic values also influence the value of actual snow depth reports which are spread to grid points. To model terrain and other local effects, SNODEP scales the snow depth reports up or down to match gradients and in the gridded climatic data base. The range of influence is limited to a maximum of 2.0 and a minimum of 0.5.

Ice cover information is obtained from the Navy ice charts once each week and entered into the SNODEP data base manually.

Snow age is counted once the snow depth exceeds or equals one inch. The age is updated daily until the depth diminishes to less then one inch. The maximum age that can be sorted at grid points where climatic values are used is 20 days. The maximum value elsewhere is 365 days. Age is reinitiated for fresh snowfall.

Weather satelllite data are used to control the quality of the final analysis. Part of this quality control is totally automated. SNODEP uses cloud analyses from the 3DNEPH model and visual satellite data to identify grid points which do not have any snow cover. Snow cover is then removed from these grid points as required. The final step involves the review by forecasters at AFGWC. They make manual changes to the analyses whenever satellite pictures or weather charts show obvious errors in the analyses.

The major limitations or weaknesses of the model include errors resulting from the spread of snow depth reports over great distances and the use of climatic values in data-sparse areas. Some snow depth observations (i.e., WMO code 3700 groups) have poor precision in reporting the depth of deep snow. This directly affects the quality of our final analyses. In order to circumvent some of this lack of precision, we discard any WMO code 3700 depth report greater than 8 inches and use current weather information to modify the previous analyses. Finally, snow age in data-sparse areas is purely artificial and generally non-meteorological in nature.

The analysis covers most parts of the continents in both hemispheres. Input data used in the chart construction are:

1. land, sea and ice geography with U.S. Navy weekly ice fields (see Godin, p. 71 this volume);

2. monthly climatology;

3. surface observations on the current snow and ice depth;

4. snow/no snow flags; and

5. DMSP visible background brightness.

Quality control includes manual modifications.

The digitized chart printout is in polar-stereographic projection. It comes out in two variants:

1. the current snow and ice depth, and

2. the age of surface snow and ice.

Problems

Main weaknesses in the program are seen in the following areas:

1. poor WMO Code 3700 reporting practices;

2. sparse surface observations;

3. need to use of climatological values due to 1. and 2.;

4. need of a data-spreading technique to cover areas with poor information.

The Snow/Cloud Discriminator Experiment

This experiement was conducted at AFGWC to test the feasibility of using satellite-derived imagery in the near-infrared portion of the spectrum, together with visual imagery, to discriminate cloud-covered from snow-covered scenes. A special satellite sensor was developed by Westinghouse Electric Corporation as part of this experiment. This sensor, called SSC, was a "push broom" scanning radiometer which consisted of a linear array of 48 germanium photo-voltaic detectors. These detectors were located at the image plane of a wide-angle lens and they provided a cross-track scan of about 400nm from the sub-satellite point (figure 1). The instrument collected reflected solar energy in a narrow band entered near 1.6 micromenters (1.51-1.63 μm). Electronic gain control was provided to adjust the sensitivity of the detectors in response to changes in scene illumination caused by changes in the solar zenith angle throughout the orbital path. The sensor was carried aboard the Defense Meteorological Satellite Program (DMSP) spacedraft flight four (F4) which was launched in June 1979.

AFGWC began processing digital SSC data in July 1979 and quickly found that liquid-water clouds were causing the sensor to saturate. We also discovered that arid and semi-arid terrain features also caused saturation (figure 2). At that time AFGWC developed a new gain control profile to reduce the threshold for saturation from approximately 30 percent to about 60 percent of the incident solar energy (i.e., assuming a Lambertian surface). This profile was uploaded near the end of October 1979. As a result, the areal extent or saturation from clear arid and semi-arid scenes was reduced in size but not eliminated. Liquid-water clouds were also causing the sensor to saturate in most cases. Cirrus clouds, however, appeared to have considerably lower reflectivities than liquid water clouds. We found that cirrus clouds reflected from 16 to 30 percent of the incident solar energy. Snow-covered scenes reflected between 8 and 16 percent of the near-infrared energy. Imagery taken from the SSC showed that there was good contrast between cloud-covered and snow-covered scenes (figure 3).

AFGWC also prepared a minimum brightness data base using SSC data which were collected during October, November, and December 1979. When we displayed these results we found excellent agreement between areas which were apparently snow-covered (i.e., dark in appearance) and similar features found in matching NOAA/NESS Snow and Ice Boundary Charts. We then used manually prepared snow and cloud analyses in conjunction with matching DMSP visual and SSC imagery to develop cloud/no cloud and snow/no snow analysis techniques. We automated the technique and tested it against the manually prepared analyses, using the analyses as "truth". Our results showed that the technique was 90.1 percent reliable in making cloud/no cloud decisions (table 1). We conservatively estimate that if the resolution of the SCC picture elements (pixels) was improved to match the near constant 3nm (5.56km) resolution of

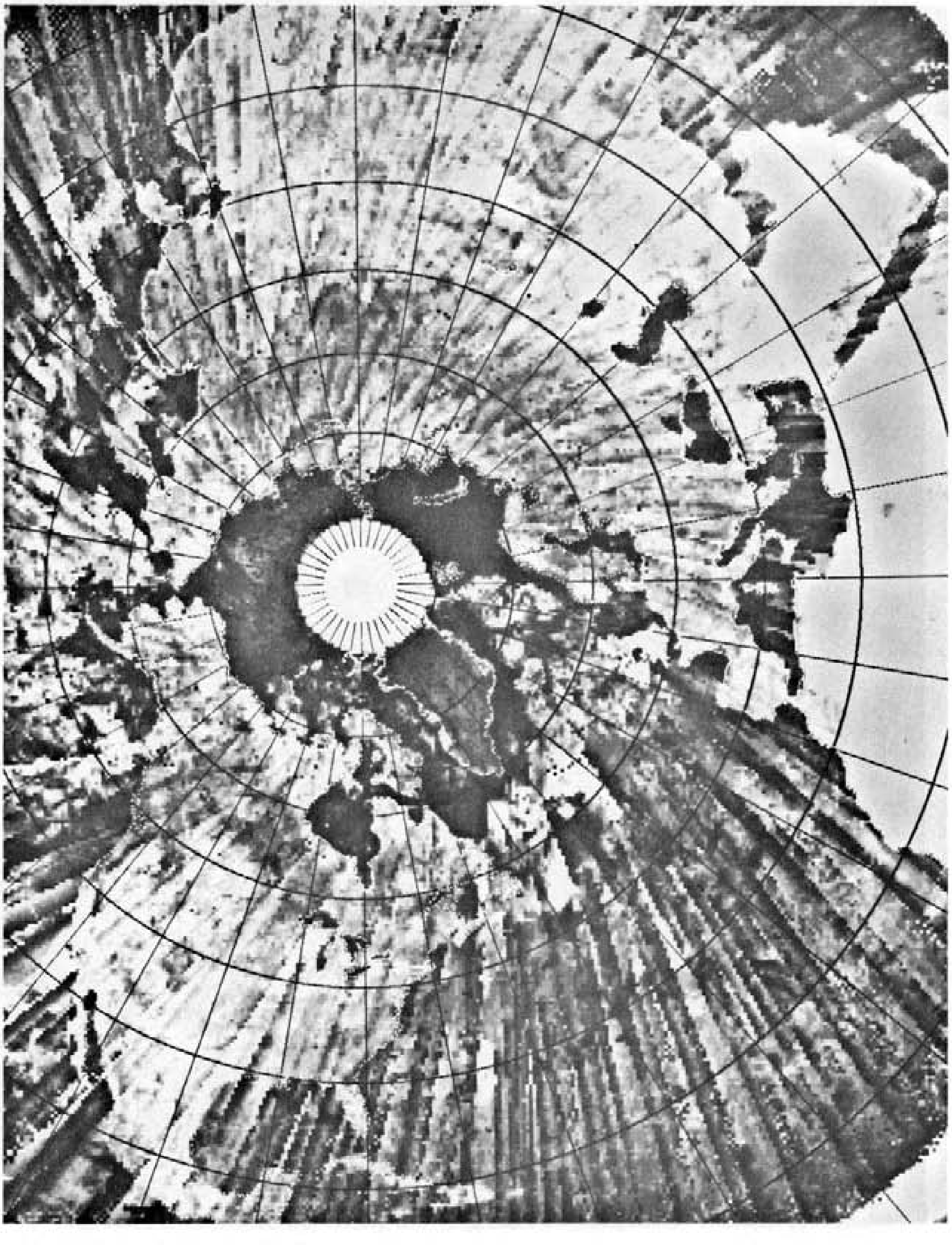

Figure 1. A display of SSC minimum brightness based on SSC data collected during July and August 1979. Brightness is represented by 16 greyshade values ranging from black to white. The sensor was set to saturate whenever scene reflectances exceeded approximately 30 percent. The white disk at the pole is merely a data void area. Notice that semi-arid and arid terrain features caused the sensor to saturate. Snow-covered Greenland is much darker in comparison to the semi-arid regions by virtue of the low reflectivity of snow in the near infrared.

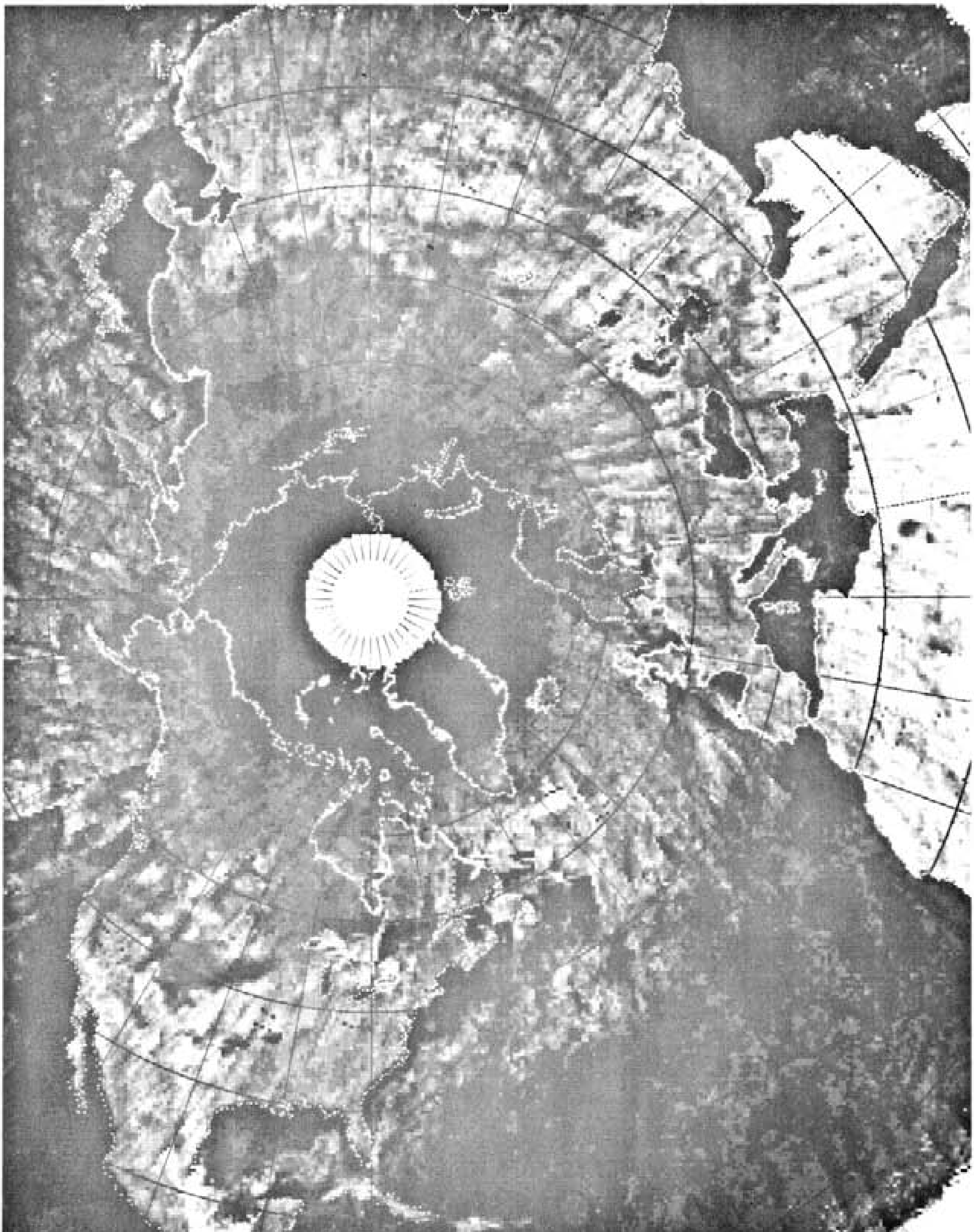

Figure 2. A display of SSC minimum brightness based on SSC data collected during October, November, and December 1979. Brightness is represented by 16 greyshade values ranging from black to white. The sensor was set to saturate whenever scene reflectances exceeded approximately 60 percent. The white disk at the pole is merely a data void area. Notice that semi-arid and arid terrain features caused the sensor to saturate.

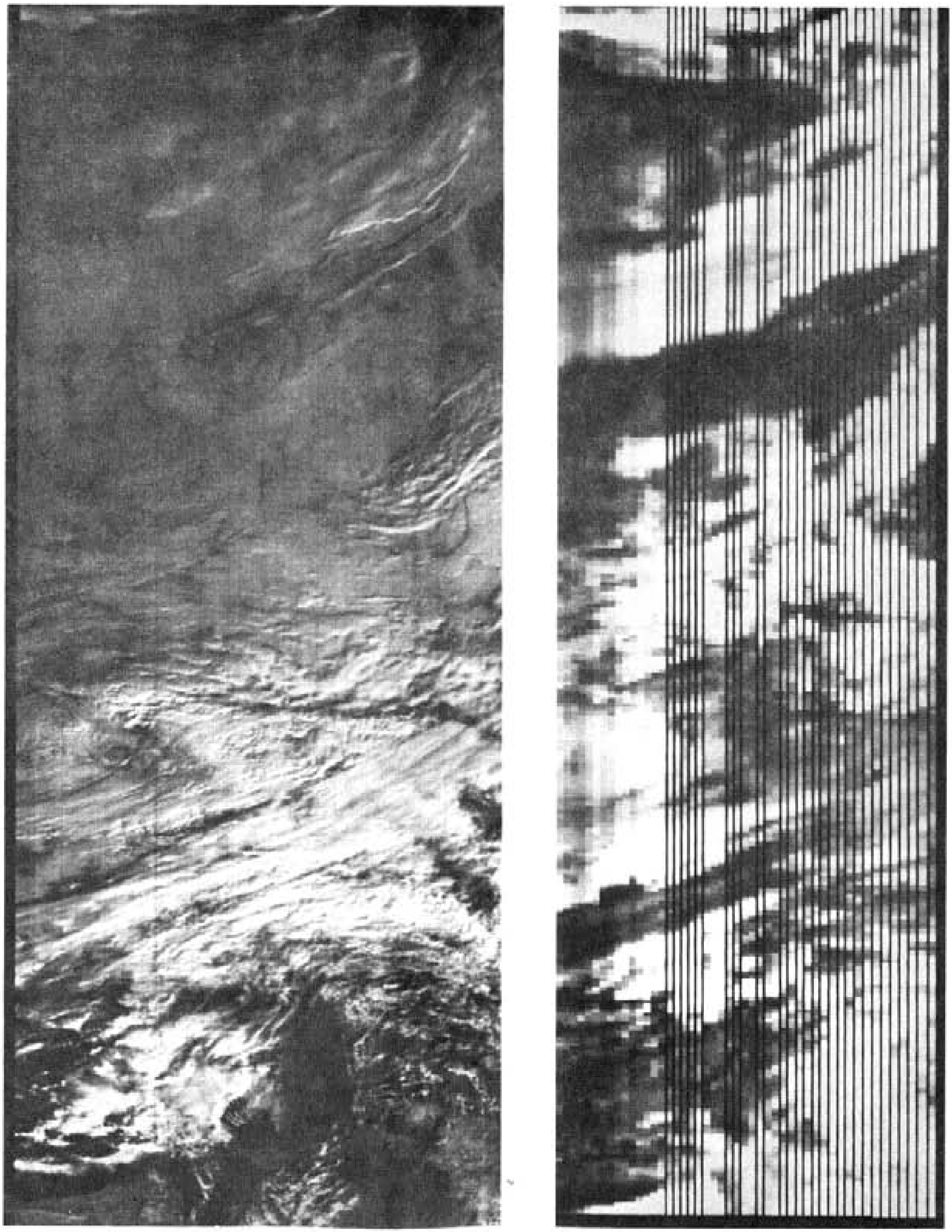

Figure 3. A display of matching DMSP visual (0.3nm resolution) and SSC data left and right respectively. These data were collected over Eurasia on 25 December 1979 during orbital revolution 2860. A narrow band of stratus clouds is located in the upper quarter of the visual display. Next to these clouds is an area of cloud-free, snow-covered terrain. DMSP thermal data (not shown) indicate that the cloud top temperature is warmer than the adjoining snow-covered terrain. Current 3DNEPH satellite data processing techniques would have failed to detect these stratus clouds. Notice, however, how well these clouds stand out against the dark snow background in the SSC display. Cirrus clouds are less bright than liquid water clouds in the SSC display. The lower portion of the displays covers part of the Middle East. Notice that cloud-free, arid terrain features caused the SSC sensor to saturate.

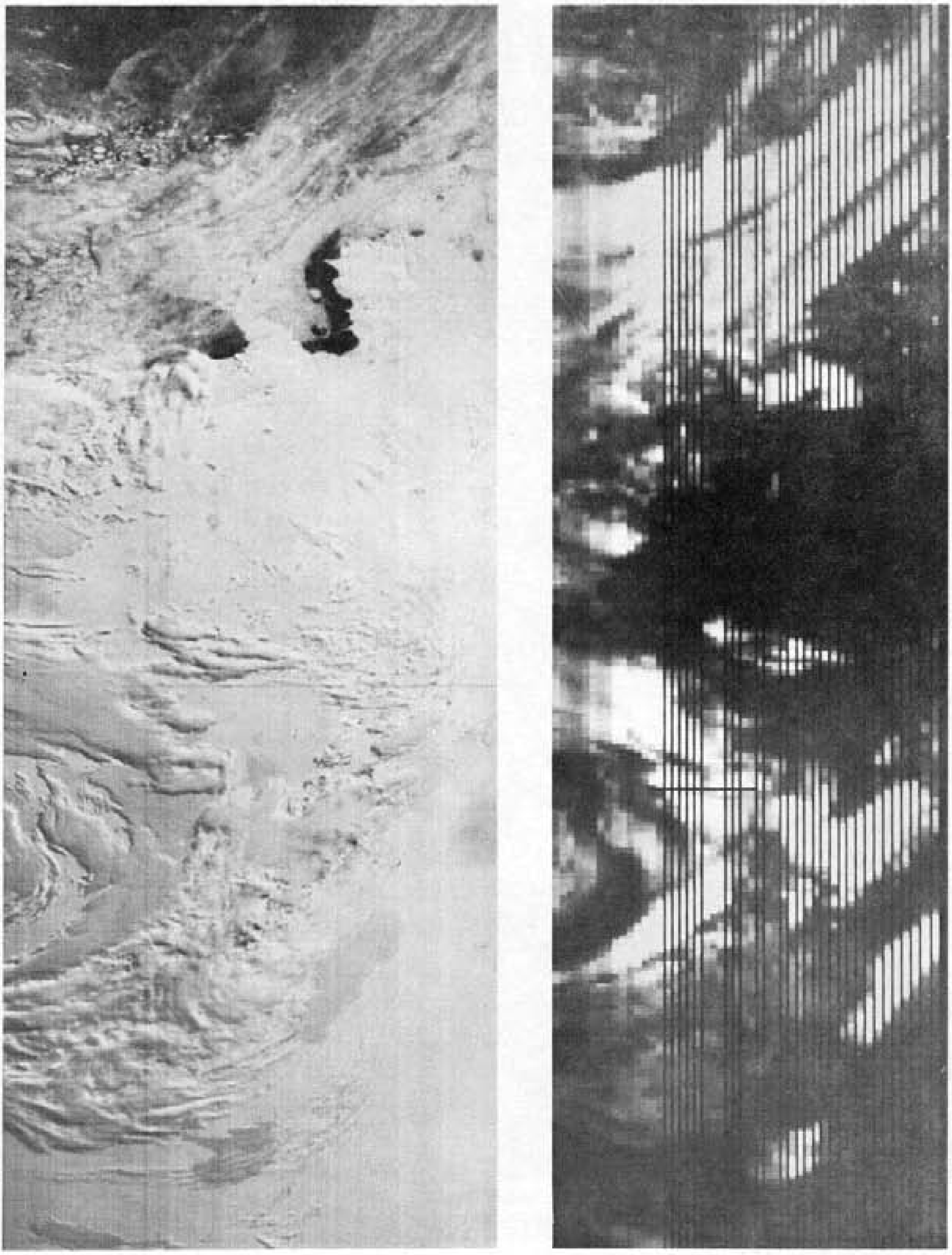

Figure 4. A display of matching DMSP visual (0.3nm resolution) and SSC data left and right respectively. These data were collected over Antarctica on 12 December 1979 during orbital revolution 2680. Notice the excellent contrast between bright clouds and dark snow in the SSC display compared to the relatively poor contrast between bright snow and clouds in the visual display.

Table 1. Reliability statistics of the Snow/Cloud Discriminator Experiment.

1.6 μm discrimination:

Manual Charting:	Cloud and Snow Free CF	SNOW SN	CLOUD CLD
Cloud and Snow Free: CF	92.4%	1.3%	6.3%
Snow SN	10.3%	81.9%	7.8%
Cloud CLD	4.6%	6.1%	89.3%

OVERALL RELIABILITY = 90.1%

the visble band pixels, the reliability of the technique would be better than 95 percent. The reliability of snow/no snow decisions was 81.9 percent. Some 10.3 percent of the decisions erroneously labeled snow scenes as clear, snow-free scenes. The remaining 7.8 percent of the decisions described snow pixels as cloud-covered (figure 4). Subsequent discussions with George Kukla lead us to believe that some of the error in making snow/no snow decisions can be attributed to dark, cloud-free scenes which contain snow, yet appear to be sufficiently dark in the visual spectrum to be labeled snow-free. This is especially true in areas where coniferous forest cover underlying snow.

The following features are considered advantages of the discrimination technique:

1. stable detector,
2. good signal to noise ratio,
3. no need of conventional data,
4. good reliability,
5. spinoffs,

The limitations are:

1. low resolution,
2. data dropouts,
3. time discontinuities,
4. interchannel variability,
5. limited dynamic range,

Product Form and Availability

Maps are plotted on a gridded data base with a polar-stereographic projection which is true at 60°. The product is digitized and is available on computer listings and tape (7 track, 800 bpi).

The charts are available for distribution at the National Climatic Center in Asheville, North Carolina.

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Sea Ice Charts of the Navy/NOAA Joint Ice Center

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Introduction

Since 1973, the Naval Polar Oceanography Center, formerly the Fleet Weather Facility, Suitland, Maryland, has produced global sea ice analysis products for Department of Defense and civilian users. Over the years the ice products have had a wide range of utility from guiding ships through ice-infested waters to numerical heat budget model inputs. In 1977 alone, over 800 naval ice messages to ship and shore facilities were transmitted, 200 users received weekly mailings, and ice facsimile products were transmitted weekly.

The Joint Ice Center (JIC), organized in 1976 is composed of Navy and NOAA personnel and is tasked with providing for the ice information requirements of the Department of Defense and NOAA. In response to those requirements, the JIC continues to produce a number of global, regional, and specially tailored analyses and forecasts.

The JIC is staffed primarily by Navy personnel. The Ice Analysis and Ice Prediction Divisions are directly responsible for preparing the ice analyses and forecasts. The Ice Analysis Division consists of a Navy civilian supervisor, three or four ice analysts and two technicians. One of those analysts is a National Earth Satellite Service scientist. The Ice Prediction Division consists of a National Weather Service supervisor and two Navy personnel.

JIC produces weekly Arctic and Antarctic ice analyses and forecasts.

Weekly Arctic Ice Analyses

I. General Information. Manually analyzed Eastern (figure 1) and Western (figure 2) Arctic Sea ice charts are produced weekly as a synthesis of ice data and satellite information of varying resolution and utility. Seven-day ice limit forecasts reflect anticipated trends.

II. Data Sources. Conventional data are accumulated, decoded, and evaluated for timeliness and reliability as received.

A. Shore station ice reports

1. USSR, Finland, and Sweden (Baltic and Gulf of Bothnia)
2. Norway (Jan Mayen, Bear Island, Hopen)
3. Greenland
4. Alaska
5. Canada

B. Ship reports

1. U.S. Coast Guard ice breakers
2. Military Sealift Command vessels
3. Icelandic Coast Guard
4. Merchant and fishing vessels

C. Aerial ice reconnaissance (method of observation)

1. U.S. Navy dedicated ice recons (visual, radar, radiation thermometer, laser profilometer)
2. U.S. Navy ice observer flights of opportunity (visual, radar)
3. National Weather Service (visual)

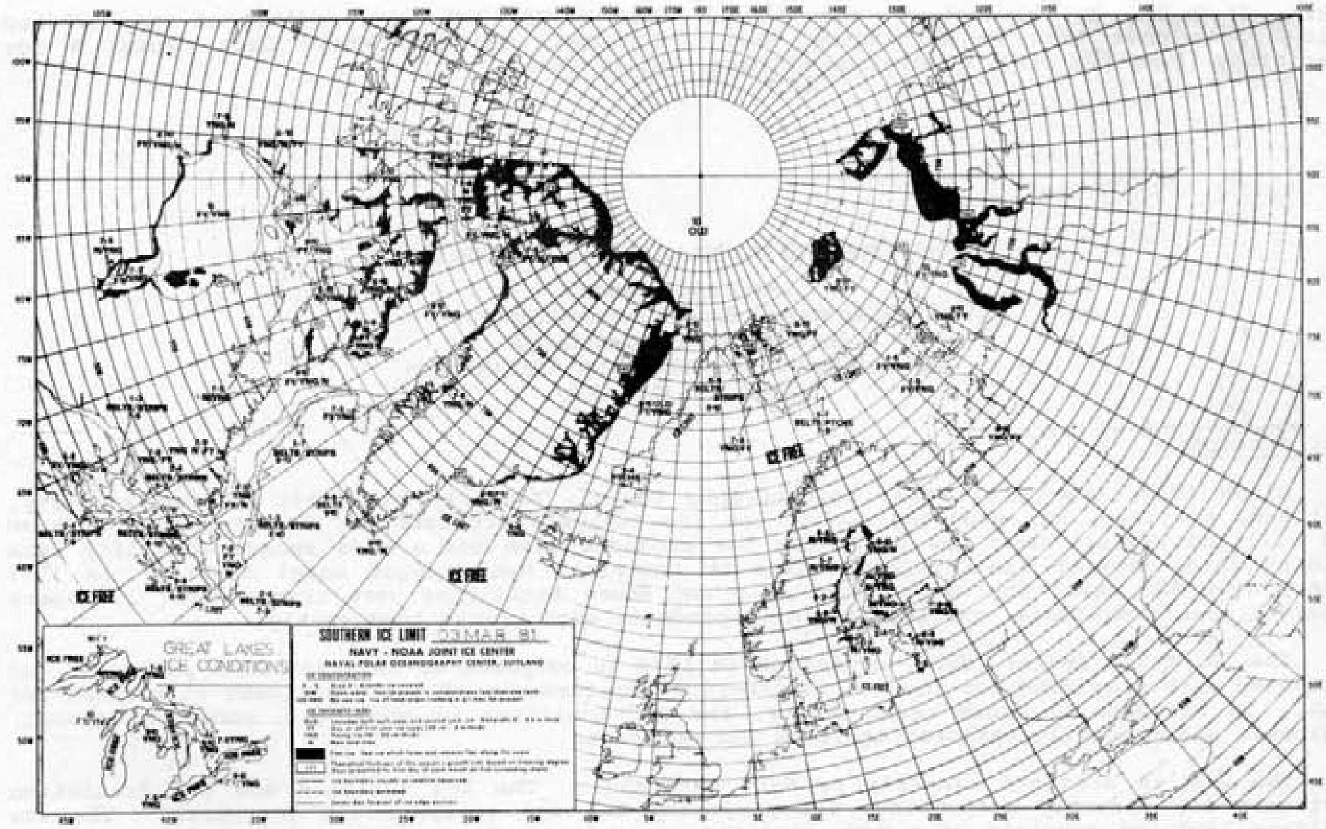

Figure 1. Eastern Arctic sea ice analysis chart.

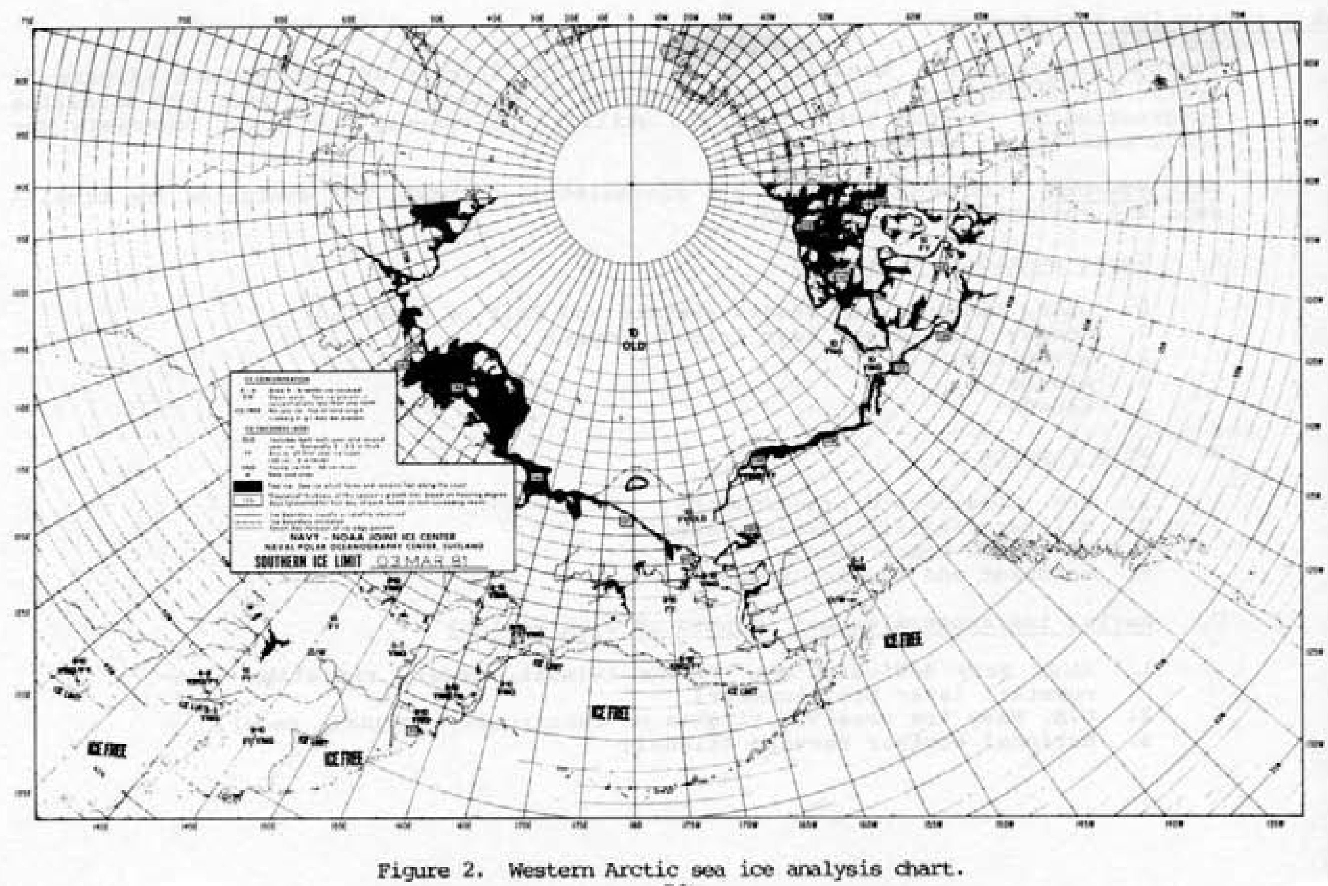

Figure 2. Western Arctic sea ice analysis chart.

4. U.S. Coast Guard International Ice Patrol (visual, radar)
5. Private industry (visual)
6. U.S. Navy patrol aircraft (radar)
7. Foreign sources: Canada (SLAR, visual), Denmark (visual), Norwegian patrol aircraft (visual, radar), Japan (visual, radar)

D. Ice analyses from other domestic and foreign centers

1. Canadian Ice Central, Ottawa (received daily by fascimile, via data coupler)
2. U.S. Weather Service Forecast Office, Cleveland (received by telecopier)

III. Analysis Tools

A. Eastern (85°E westward to 110°W) and Western (110°W to 85°E) Arctic work charts (H.O. 2560) of 1:11.11 million polar azimuthal equidistant projections.

B. Satellite imagery

1. NOAA series, AVHRR VISUAL Resolution - 1 km
   IR Resolution - 1 km
2. DMSP Hemispheric Mosaic
   VISUAL Resolution - 4-6 nm (7.4-11.1 km)
   IR - 4-6 nm (7.4.11.1 km)
3. NIMBUS V ESMR Resolution - 25 km
4. NIMBUS VII SMMR Resolution - 50 km

C. Automated diagnostic aids

1. 168-hour theoretical ice drift vectors located at 207 grid point locations in the Arctic.
2. Positive and negative degree-day accumulations and theoretical ice thicknesses at over 60 Arctic stations.
3. 15-day observed temperature trends for over 60 Arctic stations.
4. daily average temperatures and synoptic temperatures at over 60 Arctic stations.
5. daily Fleet Numerical Oceanography Center Northern Hemisphere sea surface temperature and atmospheric analyses fields.

D. Climatology

1. Compilation of weekly Naval Polar Oceanography Center Arctic ice analyses from 1972 through present.
2. Ice climatologies drawn from Naval Oceanographic Office publications.
3. Mean ocean current data from Hydrographic Office publications and others.

IV. Seven-Day Ice Limit Forecast. The forecast is intended to depict anticipated trends in ice limit positions. Available guidance is in the form of automated 144-hour wind/current ice vector forecasts at 207 Arctic grid-point locations and the application of persistence, extrapolative and climatological ice-movement rates. Diagnotic aids involving positive and negative degree-day accumulations and station temperature summaries are also considered.

Weekly Antarctic Ice Analysis

I. General. The weekly Antarctic Sea Ice Chart (figure 3) is produced almost exclusively from satellite information due to the sparsity of conventional data and the unavailability of automated diagnostic aids.

II. Data Sources.

A. Anatarctic shore station ice reports

1. United States
2. United Kingdom
3. Argentina

B. Ship reports

1. U.S. Coast Guard ice breakers
2. Military Sealift Command vessels
3. Research vessels (foreign and domestic)
4. Merchant and fishing vessels
5. Argentine Navy

C. Aerial ice reconnaissance (method of observation)

1. U.S. Navy ice observer flights of opportunity and dedicated recons (visual, radar)
2. U.S. Coast Guard (visual)
3. United Kingdom (visual)

III. Analysis Tools.

A. Southern Hemispheric work chart of approximately 1:15 million polar azimuthal equidistant projection.

B. Satellite Imagery. Same as in Arctic.

C. Climatology. Compilation of weekly Naval Polar Oceanography Center, Suitland, Antarctic Ice Analyses from 1973 to present.

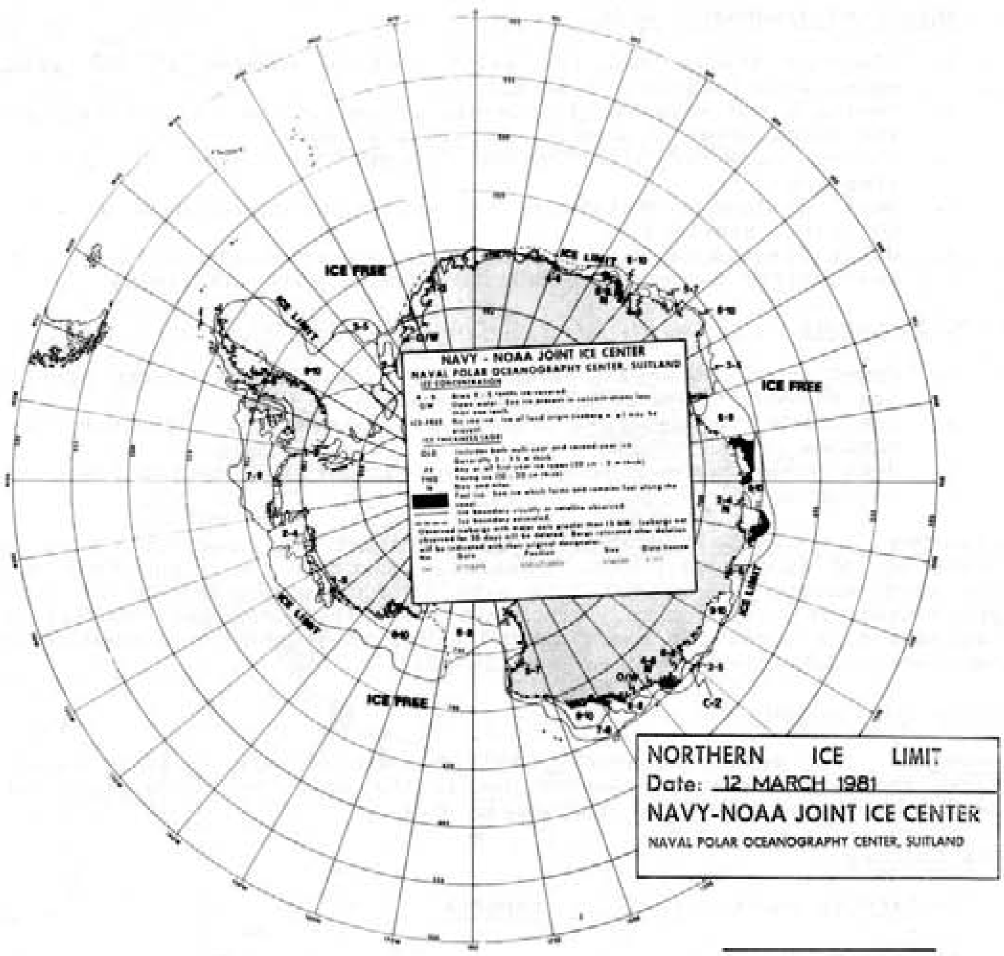

Figure 3. Antarctic sea ice analysis chart.

The Methodology of Ice Charting

The ice charts are constructed under operational time constraints and reanalysis with late data is not normally attempted. The information presented reflects an initial effort intended for operational use. The purpose of the analysis is to provide operators and researchers with reliable weekly hemispheric analyses derived principally from satellite imagery supplemented by conventional observations. In general:

1. Shore station, ship, and aerial reconnaissance ice observations are plotted and evaluated for timeliness.

2 Satellite imagery is analyzed for ice data content with the most recent and highest resolution imagery considered first. Comparisons are made with ice analyses from other centers (Arctic only). Synthesis of available conventional and satellite data yields the final analysis.

3. Where insufficient data are available to define the Arctic ice limit, the ice analysis is first made to follow continuity with the use of 168-hour ice drift vectors and other diagnostic aids (Arctic only). If data are not available during subsequent weeks, ice limits are gradually made to approach normal seasonal climatological positions.

To insure continuity and to develop regional expertise, the ice analysts are assigned specific geographical areas of responsibility. They routinely review and analyze all available conventional and satellite data for their region. The ice analyst must be able to resolve a number of highly technical and some "common sense" problems involving the interpretation of disparate forms of satellite data with whatever conventional data areavailable.

To help resolve interpretation problems, a procedure involving meteorological continuity checks has evolved. For example, each week before the Eastern and Wertern Arctic ice analyses are begun, personnel from the Ice Prediction Division brief the analysts as to the meterological conditions observed during the previous week. This briefing includes mean sea level pressure fields, surface temperature data, and freezing-day accumulations. After the ice analysis is completed, the forecaster in preparing for his 7-day ice forecast reviews the analyzed chart for continuity with the observed meteorological conditions over the past week. Any inconsistencies are then resolved by the individual analyst and forecaster or submitted to the division heads for final decision. This procedure has been beneficial in developing both a better understanding of the causal meteorologic/cryogenic relationships and quality controlling ice-limit extent.

Problem Areas

Some of the major problem areas we have identified in the production of ice charts are the following:

1. The state of the art concerning remote sensing of sea ice from satellites requires a multi-sensor approach. There is no existing sensor that provides all the required ice data. Passive microwave, visual, infrared, and active microwave are all valuable tools, but each has its unique limitations. Table 1. gives a partial description of advantages and disadvantages of the satellite data as made available to the JIC.

Table 1. Advantages and disadvantages of various forms of satellite data.

Sensor	Advantages	Disadvantages
Visual	- Observes young and older forms of ice though may not be able to discern among all of them - Can estimate concentrations - Has 1km resolution	- Cloud limited - Does not discern new ice - Night limited
Infrared	- Observes young and older forms of ice but may not be able to discriminate among all of them. - Can estimate ice concentrations - Has 1km resolution	- Cloud limited - Not useful in summer
Passive microwave	- Day/night - Penetrates clouds - Observes new and older forms of ice - Can estimate ice concetrations under certain conditions	- Has 25 km resolution - Ambiguities in interpretation of ice types and concetrations - Gridding - Small scale format - Summertime bias towards lower ice concetrations when ice is flooded

2. The rapid turnover of personnel requires a constant state of training.

3. The current ice program is extremely labor intensive. All of these disparate forms of data have to be reviewed subjectively and then analyzed onto a base work chart.

Looking to the future, the JIC is developing a techncial improvement plan that will address ways in which computer-assisted interactive technology will be used to significantly lessen today's labor-intensive, time-consuming methods. It is with this technology that we envision the development of new and more objective approaches to sea ice analysis.

Chart Content

The following features are depicted where available data allow:

1. Ice concentration

   a. Boundaries in units of tenths
   b. Open water (O/W), less than 1/10
   c. Ice free (IF), no ice present

2. Ages and stages. Data sparsity in the Antarctic limits delineation of New, Young, Old and Fast Ice regions.

   a. New (N)
   b. Young (YNG)
   c. First year (FY)
   d. Second, Multi-year (OLD)
   e. Fast ice (solid black)

3. Descriptives

   a. Patches (PTCHS)
   b. Fields (FLDS)
   c. Belts and strips

4. Ice limit and boundaries are represented by solid line.

5. Estimated ice limit is represented by dashed line.

6. 7-Day ice limit forecast is represented by dotted line. (Arctic only)

Samples of the charts are given in figures 1, 2, and 3.

The charts are distributed to interested researchers by mail. A compilation of weekly ice analyses are bound into a book format and are available from the National Technical Information Service (NTIS) in microfiche or hard copy form at the following address:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

The National Technical Information Service ships the desired publications and bills the organizations for them. Prepayment is preferred; additional charges are levied for billing. The order must specify title, ADA number and paper or microfiche format. Additional information regarding ordering procedures and costs may be obtained by telephoning the National Technical Information Service sales desk at 703-487-4650.

Kukla, G; Hecht, A.; Wiesnet, D. eds. (1981) SNOW WATCH 1980. Proceedings of the Workshop held 1-2 October 1980 in Washington, D.C. Boulder, Colorado, World Data Center A for Glaciology (Snow and Ice), Glaciological Data, Report GD-11, p.79 -85 .

Antarctic Sea Ice Cover from Satellite Passive Microwave

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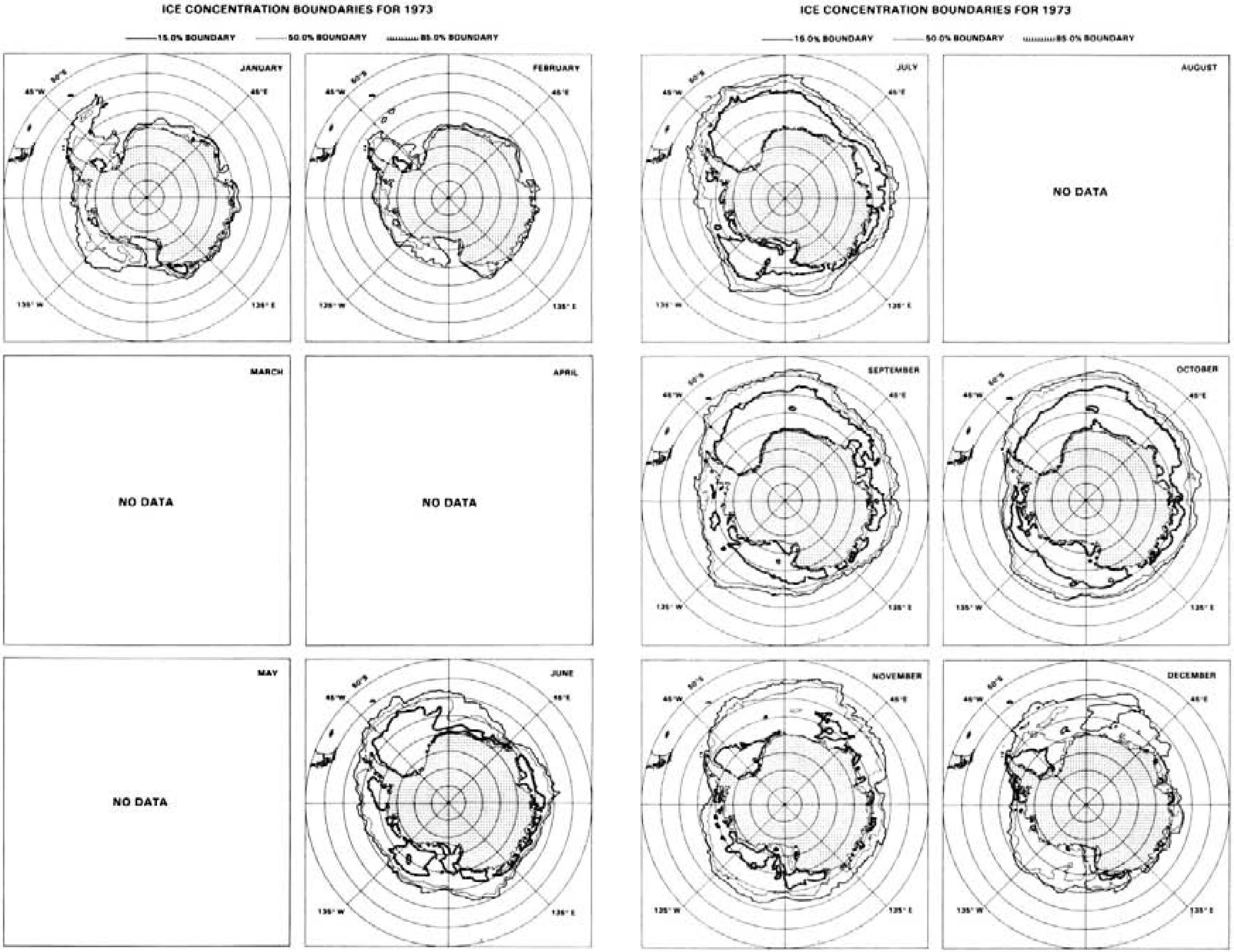
The Nimbus-5 satellite of the National Aeronautics and Space Administration was launched in November 1972, with an instrument on board, the Electrically Scanning Microwave Radiomenter (ESMR), easily able to distinguish ice-covered ocean from ice-free ocean. The ESMR records brightness temperatures at a wavelength of 1.55 cm, for which wavelength open water at the freezing point has an emissivity of about 0.40 and sea ice has an emissivity of 0.84 - 0.95. This wide contrast in emissivities allows a ready determination of the ice edge and an approximate calculation of sea ice concentrations within the pack. The instrument resolution is roughly 30 km, and the radiometric measurements have been averaged over 3-day periods in order to eliminate the diurnal cycle and many of the data gaps. As a result, a complete map of the Antarctic sea ice distribution has been produced for most 3-day intervals during 1973-1976, though there remain occasional large gaps, for instance for the entire region during all of March-May of 1973 and all of June-August of 1975. Normal degeneration of the instrument after 1976 prevented the collection of data of comparable quality for the later years. The estimated accuracy of the ice concentration values is ± 15 percent, and the location of the ice edge is taken at the 15 percent ice concentration line.

The 3-day images were combined to form monthly average maps, contour plots which are presented in figures 1 to 8. These show clearly the yearly cycle from minimum ice extent in February to maximum ice extent from August-September and the spatial distribution of ice 15-50 percent concentrated, 50-85 percent concentrated, and 85-100 percent concentrated.

In figure 9, the yearly cycle of the monthly areal extent of ice is plotted for each of the four years (1973-76). The top curves depict the areal extent of ice-laden waters, indicating a yearly range of 3-20 million km^2. In the middle curves, the actual surface area of ice, rather than the area of ice-laden waters, is plotted; and in the bottom curves the difference between the top two curves is plotted, i.e., the area of open water or leads within the ice pack. It should be observed that as the ice pack expands in fall and winter, the open water area within the pack expands as well, the reason being the greater expanse over which the open water can occur, not a decrease in mean concentration within the ice cover. In fact, figure 10 presents the mean concentrations within the pack and those show lower mean concentrations in January, February, and March and higher mean concentrations in the winter months. The total 4-year range in monthly mean concentrations (over the 30 km x 30 km grid elements with ice present) is only 50-80 percent, and the yearly cycle is far less distinct than that for the ice areas (figure 9).

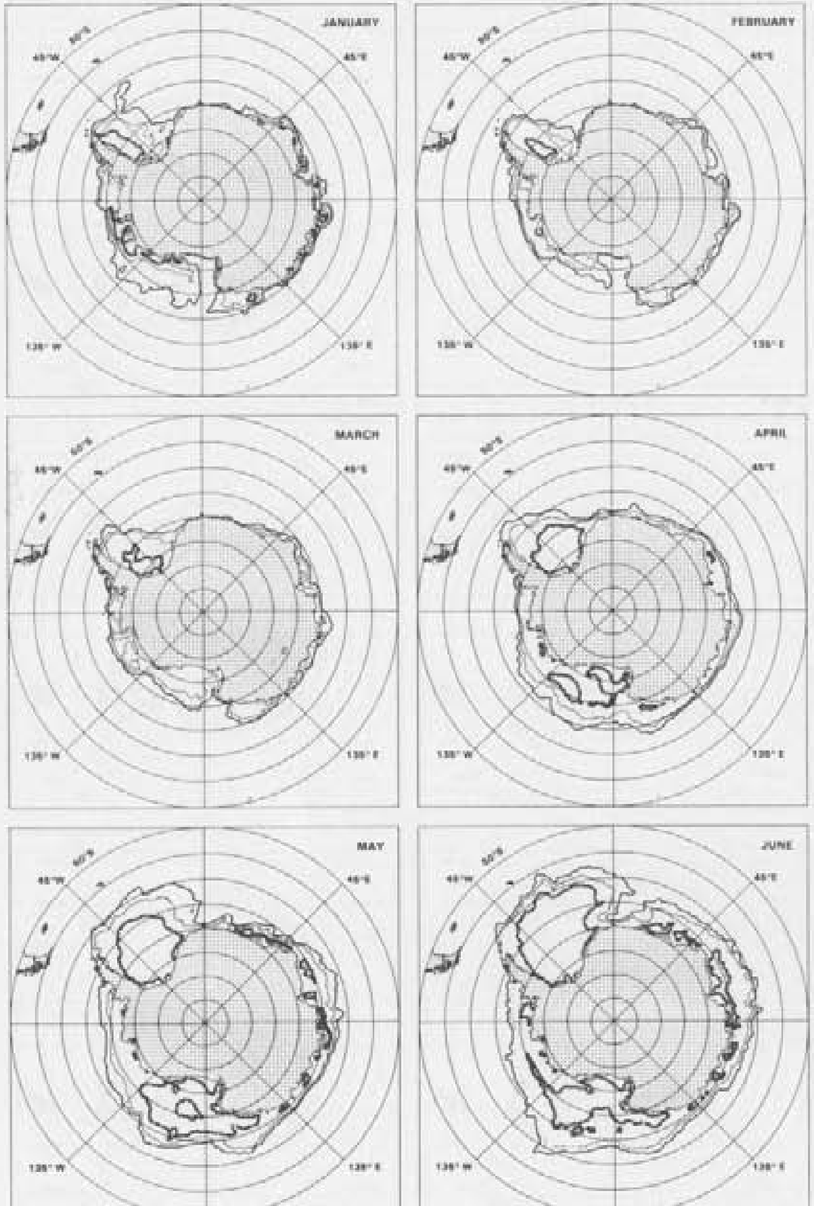
These ESMR sea ice data will be presented in greater depth and with more discussion in an upcoming atlas by the same authors.



Figures 1-8. Charts of average monthly sea ice extent and concentration based on microwave data for January 1973 through December 1976.

ICE CONCENTRATION BOUNDARIES FOR 1974

—— 15.0% BOUNDARY —— 50.0% BOUNDARY ········ 85.0% BOUNDARY



ICE CONCENTRATION BOUNDARIES FOR 1974

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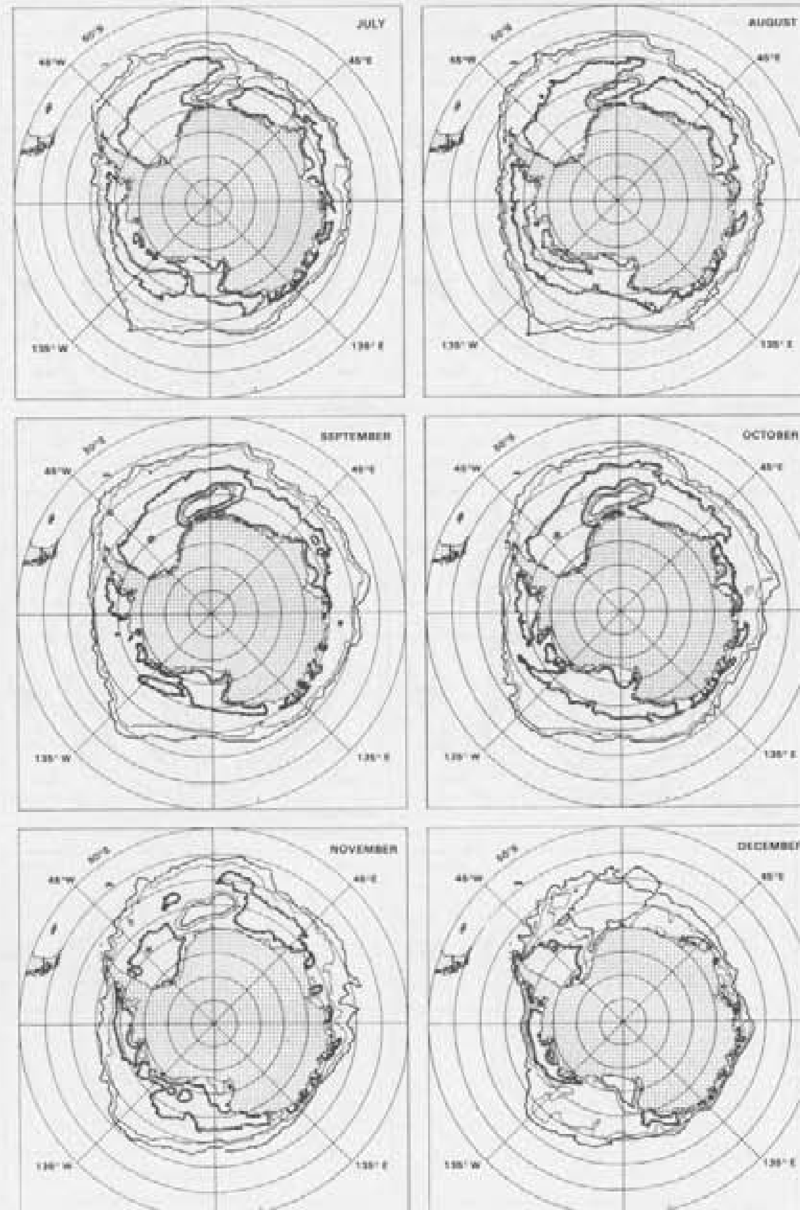

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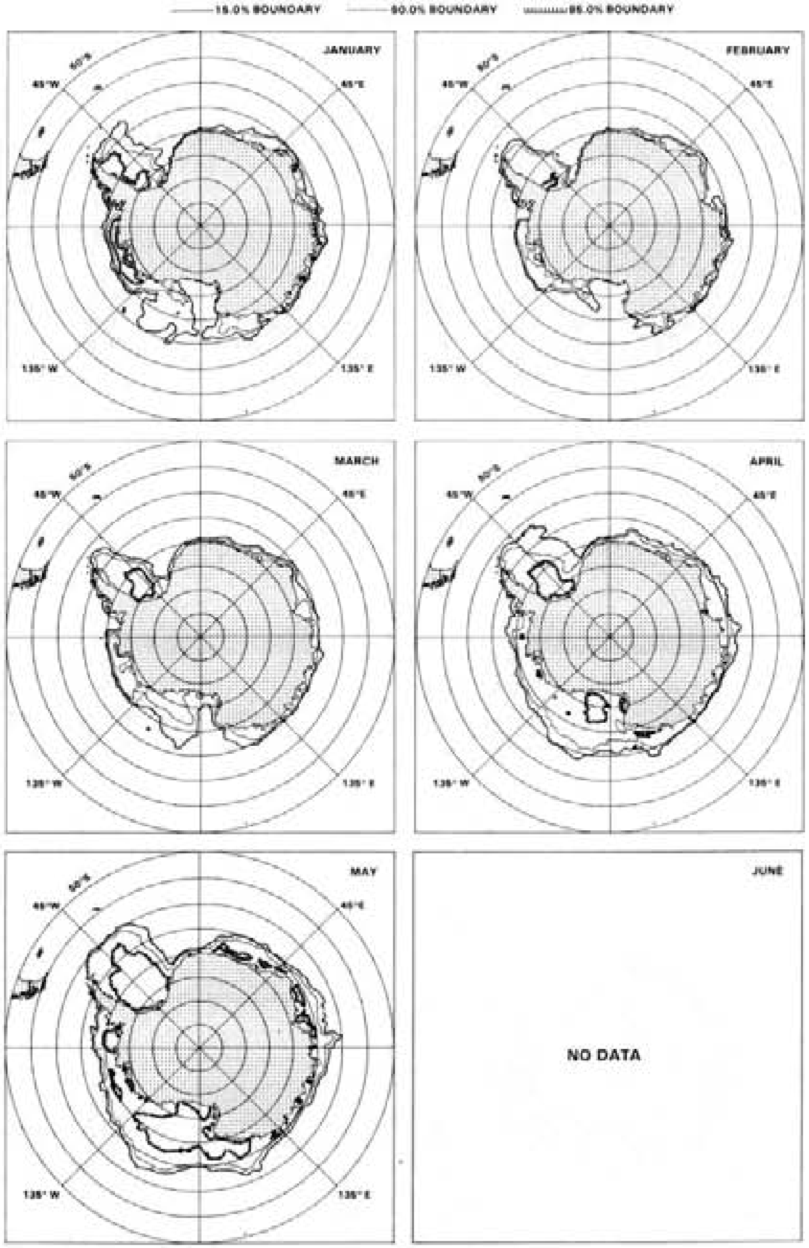
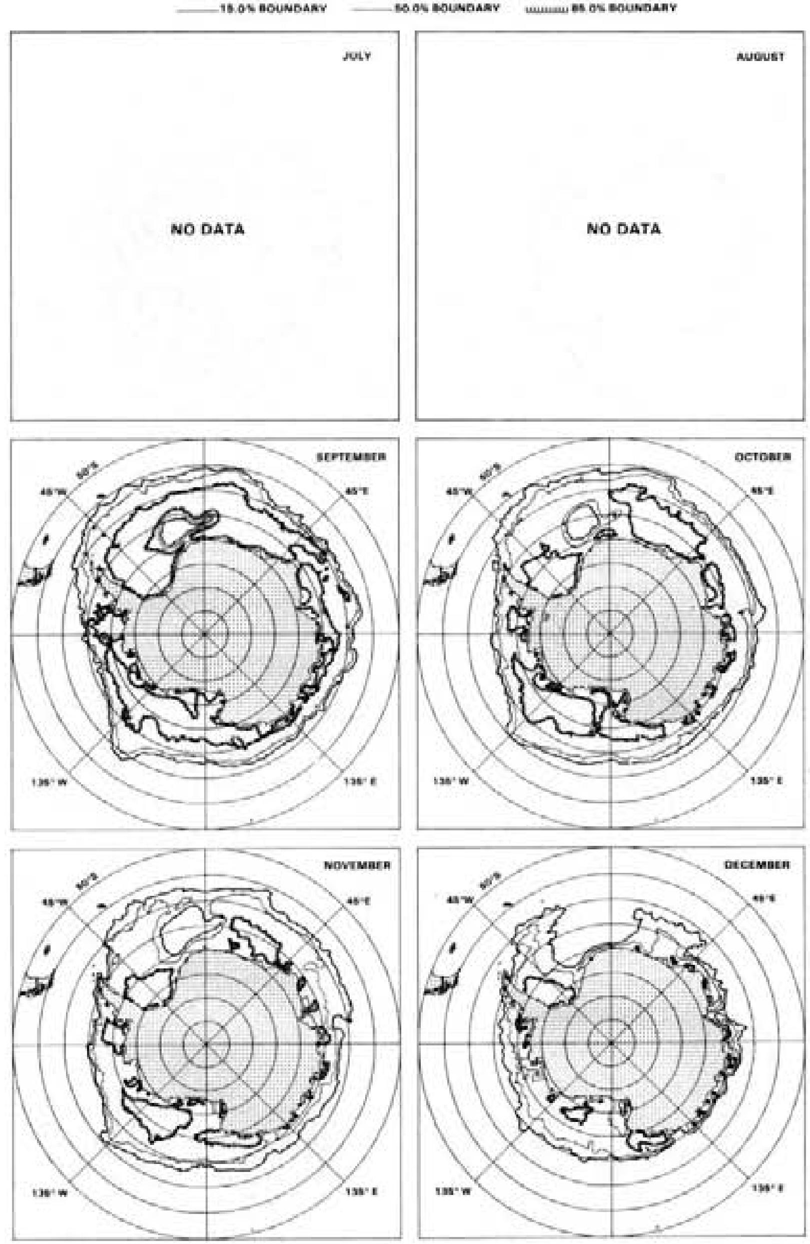
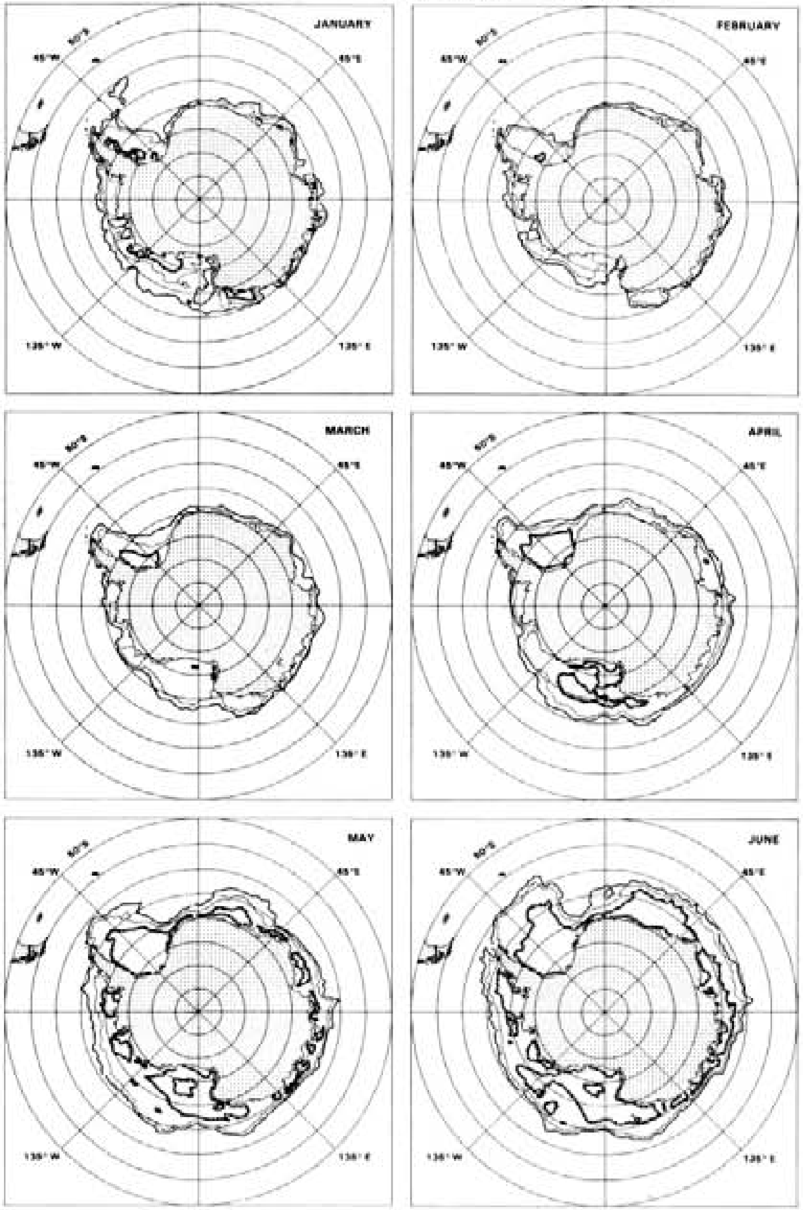


ICE CONCENTRATION BOUNDARIES FOR 1975



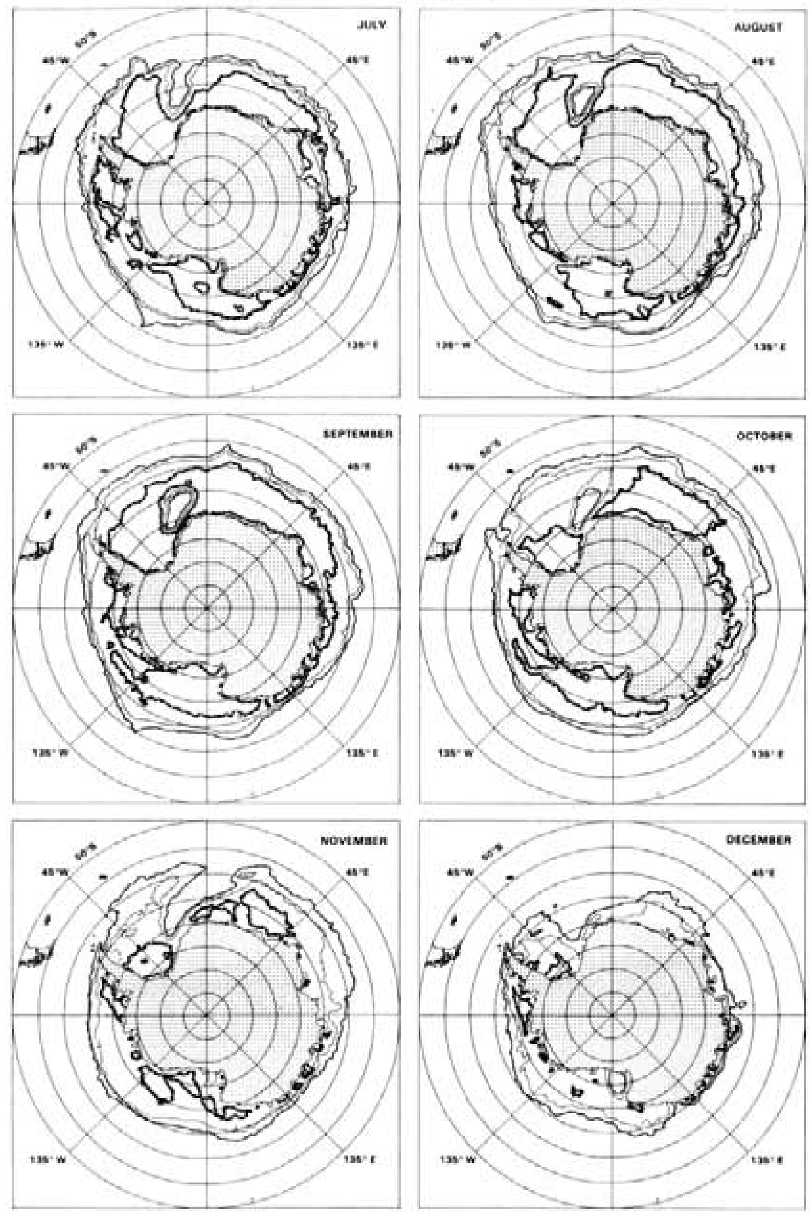
ICE CONCENTRATION BOUNDARIES FOR 1976

15.0% BOUNDARY — 50.0% BOUNDARY — 85.0% BOUNDARY



ICE CONCENTRATION BOUNDARIES FOR 1976

15.0% BOUNDARY — 50.0% BOUNDARY — 85.0% BOUNDARY



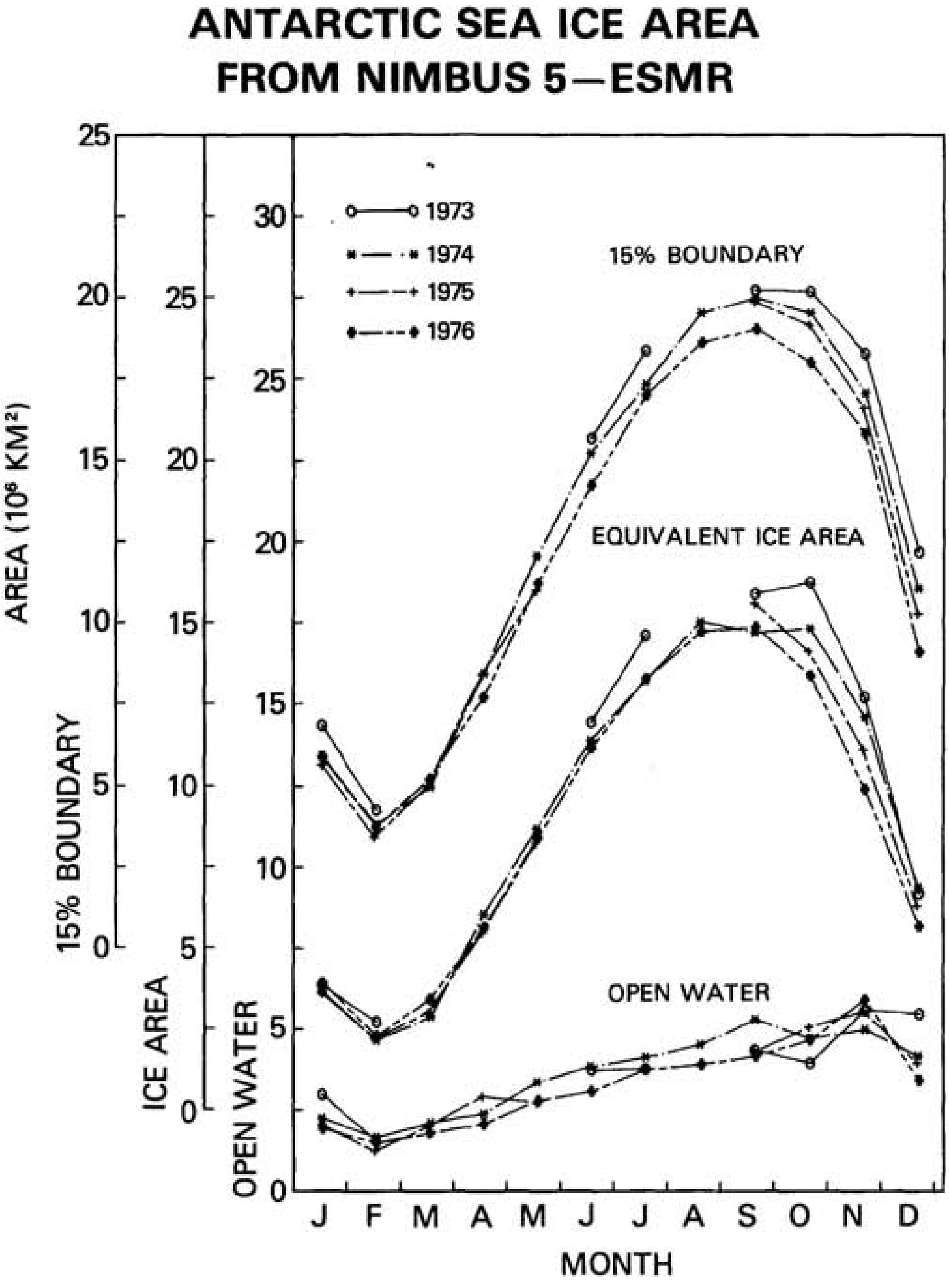


Figure 9. Extent of ice in different concentrations during 1973-1976 as a function of season.

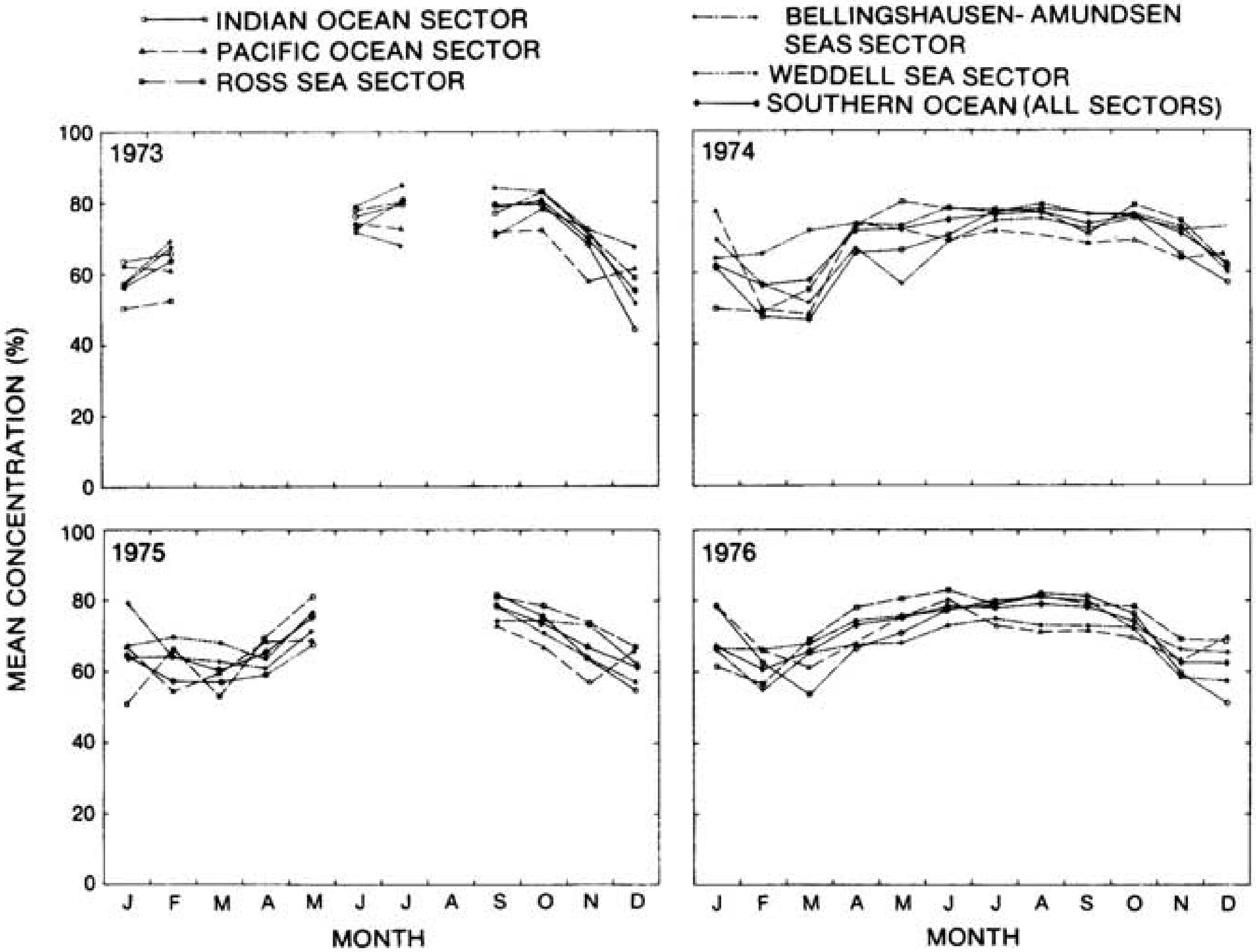


Figure 10. Mean ice concentration as a function of season for individual sectors during 1973-1976.

Kukla, G; Hecht, A.; Wiesnet, D. eds. (1981) SNOW WATCH 1980. Proceedings of the Workshop held 1-2 October 1980 in Washington, D.C. Boulder, Colorado, World Data Center A for Glaciology (Snow and Ice), Glaciological Data, Report GD-11, p. 87 - 91.

Lamont Climatic Snow Cover Charts

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A climatic series of snow cover charts is produced at the Lamont-Doherty Geological Observatory of Columbia University. The objective of the work is to increase the accuracy and homogeneity of the NOAA snow cover series from 1966 through 1973. For that interval, the NOAA weekly charts are considerably less accurate and less detailed than the more recent products (Kukla and Robinson, 1979; Kukla and Robinson, p.103 this volume). Most seriously affected is the information on the relative reflectivity and the position of snow cover in the zone of poor illumination in autumn. The early inaccuracy is due to the inferior quality of early satellite imagery and the relative inexperience of the NOAA interpreters at that time.

Lamont charts (see figure 1) are designed to:

1. present the information in a manner compatible with the current NOAA series (Smigielski, p.59 this volume; Matson and Wiesnet, 1981). To that end, they indicate separately all snow cover visible on clear days;
2. be compatible with the recent U.S. Air Force charts (Woronicz, p.63 this volume). Therefore they indicate separately the snow cover under persistent clouds;
3. identify the charted information with a time resolution of two days or less. A numerical code is used which includes symbols specifying the date of the observation;
4. improve the information on the relative snow cover reflectivity.

Table 1 specifies the different features distinguished in the Lamont charts.

Snow Area Density (SAD) Index

The three grades of relative snow reflectivity in the NOAA charts are replaced by the six classes of the SAD index in the Lamont set. SAD approximates the areal proportion of snow covered ground visible from the nadir view in satellite imagery. The remainder is either a vegetation canopy or snow-free ground. SAD is expressed in percent. It should be nearly independent of the solar angle and the state of the atmosphere, therefore almost independent of the time of the satellite overpass. The proportion of the snow covered area in the analyzed scene explains most of the local variance of the winter surface albedo.

There are a few disadvantages to the SAD. The index depends on the spatial resolution of the satellite sensor because the SAD is based on the assumption of a bimodal distribution of fields fully covered by snow and those snow free. The size of the fields is expected to conform with the grid resolution of the analyzed satellite imagery. The subgrid features, which in reality break the continuity of any land-based snow cover, can't be distinguished. For instance, snow covered farmland with abundant small forest patches or remainders of standing crops will have apparent high brightnesses similar to homogeneous snow cover on top of lake ice. However, the albedo of the farmland will be lower than that of the frozen snow-covered lake. The reverse holds true for the subgrid snow patches located in predominantly snow-free fields.

In addition, SAD does not differentiate between fresh and aging snow surfaces. Albedo of the latter may be considerably lower due to changes in grain size, reduced thickness of the cover, surface dirt contamination, increased proportion of protruding dark objects, etc.

Empirical adjustments were made for the impact of differenct underlying surface types on the surface albedo of snow fields. The highest SAD class, 6, is assigned only to the areas where snow is deposited on top of glaciers, sea ice, lake ice, or arctic tundra.

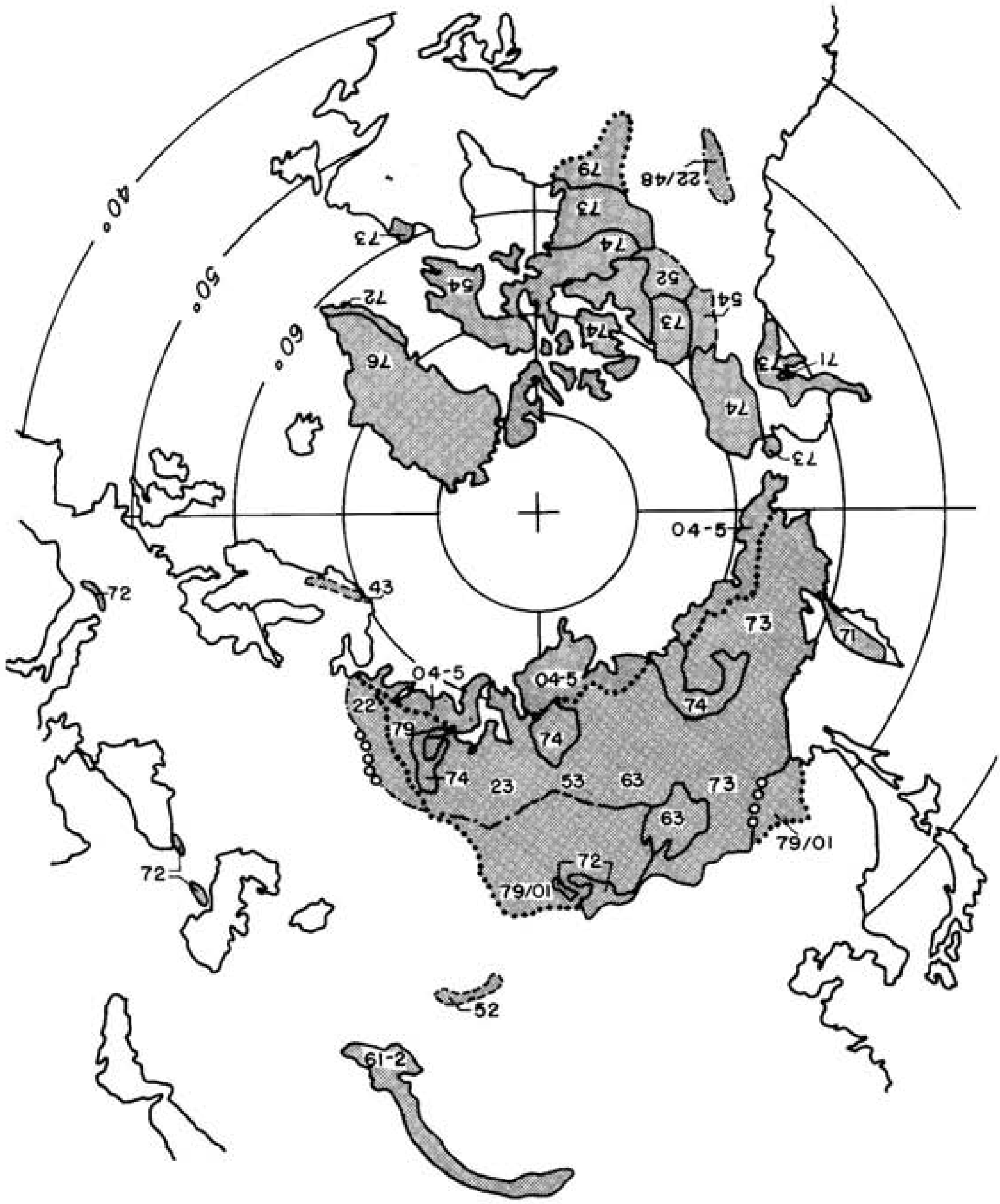

Figure 1. A sample of a Lamont climatic snow cover chart for the second week of October 1972. The symbols are explained in table 1.

A typical example of the large scale brightness differences between fully snow covered surfaces in winter is shown in Kukla p. 135 this volume. Correlation of the NOAA relative brightness classes with the SAD system is in table 2, with corresponding approximate mean values of surface albedo. Note that the average albedo of a stabilized compact snow cover on land is considered to be 70 percent; on sea ice 80 percent.

Table 1. Lamont Snow Charting Code

Satellite Observation										Climatology
Day of Observation			1	2	3	4	5	6	7	No Observation
Boundaries			Dash-Dot			Dashed		Full		Dotted
SAD (Snow area density) Class	Snow Limit %	Snow Mean %	Charted Symbol							Charted Symbol
0	0	0	10	20	30	40	50	60	70	00
1	$\leq$ 20	10	11	21	31	41	51	61	71	01
2	$\leq$ 40	30	12	22	32	42	52	62	72	02
3	$\leq$ 60	50	13	23	33	43	53	63	73	03
4	$\leq$ 80	70	14	24	34	44	54	64	74	04
5	$\leq$ 100	90	15	25	35	45	55	65	75	05
6	100	100	16	26	36	46	56	66	76	06

Ground Meteorology: Persistent Cloud or Poor Visibility (Dotted Boundary)

7	Meteorological conditions favor snowfall	17	27	37	47	57	67	77
8	Reported snowfall	18	28	38	48	58	68	78
9	Reported snow on ground	19	29	39	49	59	69	79

ooo Area where satellite observation of snowfield is obscured by clouds.

Table 2. Comparison of the NOAA relative brightness classes with the snow area density (SAD) and the approximate clear skies mean surface albedos.

NOAA Class	Approximate Mean Surface Albedo %		Lamont SAD Class	Approximate % of Snow Cover
Scattered Mountain Snow		15	0	No Snow
1	30	21	1	10
		32	2	30
2	45	43	3	50
3	60	54	4	70
		65	5	90
		80*	6	100

*75 percent over arctic tundra with a high proportion of water bodies.

Note: The approximate albedo of NOAA classes after Batten (1977). Albedo of Lamont SAD classes computed by assuming the average albedo of 100-percent snow-covered land to be 70 percent, of snow-covered ice 80 percent.

The Time Scale

The weekly chart is meant to show, when possible, the snow extent and the snow area density (SAD) on the last day of the seven-day-long interval, but this is not always possible because of the presence of clouds. For that reason the days are numbered 1 through 7, with 7 corresponding to the last day of the week (table 1). For instance, a charted set, starting with the 14th of February and ending with the 20th of February will recognize February 14th as day 1, and February 20th as day 7. The information obtained on days 6 and 7 is of the highest value.

Sources

The following sources are used in the Lamont recharting of the 1966-1972 set:

1. visual imagery of Tiros N and NOAA polar orbiting satellites (on loan from Sea Ice Consultants);

2. United Kingdom Meteorological Office snow cover data published semi-monthly from 1966-70 and every 5 days in 1971-72;

3. WMO daily synoptic weather charts of the middle and high latitudes of the Northern Hemisphere;

4. Weather and Crop Bulletin snow charts of the United States published weekly from December 1 through March;

5. reports of snow on the ground in Climatological Data, monthly NOAA publications of climate data from individual states or regions of the U.S.

Additional satellite information, such as visible and infrared NOAA-VHRR and AVHRR images and geostationary satellite imagery, is available for the analysis of post-1972 data.

Charting Procedure

The compilation of the charts proceeds in several steps.

Step 1. Satellite imagery of day 7 is examined and the obvious clouds are delimited.

Step 2. The snow on ground is charted where confidently recognized by its surface signature (see Barnes and Bowley, 1974; Barnes et al., 1974). This includes:

a. snow/water interfaces along the coastline, lake banks, and rivers,

b. treelines in the mountains, characteristic outlines, and brightness patterns of forested areas,

c. swampy river beds (snow free and dark against lighter background in autumn, reverse in spring),

d. characteristic relief texture in mountains and hills.

The SAD of the charted snowfields is estimated by visual or machine-assisted (image processor) comparisons with standard grey scales (table 1, SAD classes 0-6).

Step 3. Bright areas without characteristic local textures of land surface or clouds are compared with the maximum SAD chart (Kukla and Robinson, p. 135 this volume). If high maximum SAD is indicated, the image is compared with satellite imagery of earlier days. Repetitive boundaries are interpreted as boundaries of a snow field.

Step 4. The procedure in steps 1, 2, and 3 is repeated for days 6. Only the areas covered by clouds or with unclear textures the previous day are analyzed.

Step 5. Imagery of day 5 is analyzed and comparisons made with earlier days. This is only done for areas with no useful data from previous analysis. The same is then repeated for days 4, 3, 2 and 1, if necessary. Boundaries are drawn in solid lines for day 7 and 6, dashed for days 5 and 4, and dash-dot for the remainder.

Step 6. Ground station reports of the WMO network for days 7 and 6 are incorporated in order to:

a. delimit the snow extent in the areas of persistent cloudiness; and

b. show the snow boundary on day 7 or 6 in the areas where the surface was only seen on the earlier days (table 1. SAD class 9).

Step 7. Where no information is obtained in the previous steps, the ground station reports on the occurrence of snowfall are used (table 1 SAD class 8).

Step 8. Where no reports on snowfall or on snow on the ground are available, stations reporting precipitation at subzero (Celsius) temperatures are shown and such are separately marked (table 1 SAD class 7).

Step 9. Where no data are obtained in steps 1-8, the average extent of snow for day 7 isplotted from climatology or the snow boundary is interpolated through the blank zone (table 1, Climatology).

Compatibility of the Lamont Charts with the NOAA and U.S. Air Force Charts

Area S_{NOAA} compatible with the methodology of the NOAA snow charts is defined as:

$$S_{NOAA} = [(11,12...16) + (21,22...26) + (31,32...36) + (41,42...46) + (51,52...56) + (61,62...66) + (71,72...76)]$$

Reflectivity grade 1 of the NOAA chart corresponds approximately to SAD classes 1 and 2, grade 2 to SAD class 3, grade 3 to SAD classes 4, 5, and 6 (See table 1). Scattered mountain snow corresponds either to SAD 0 or rarely, to SAD 1.

The area S_{AF} compatible with the methodology of the U.S. Air Force snow charts for day 7 is definded as:

$$S_{AF} = [(71,72...76) + 79 + (01,02...06)]$$

Final Remarks

Work on the climatic snow cover charts is still in progress. Though time consuming, this work is thought worth the effort since the resulting product is the most complete weekly compilation of snow cover data and it could serve as a reliable base for climate modeling.

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Smigielski, F. (p. 59 this volume)

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Snow and Ice Mapping in Canada

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Introduction

Archiving and mapping of Canadian snow cover and sea ice data were reviewed at the Workshop on Snow Cover and Sea Ice Data (Findlay and Goodison, 1978) at Boulder in 1978. An update of those activities and comments and questions relating to the topics at hand are included below.

Overall activity in the Atmospheric Environment Service (AES) snow research and applications is centered within the Canadian Climate Centre. This excludes, however, those aspects of snow chemistry being studied in relation to the long range transport of air pollutants. Sea ice activities are carried out in the Ice Branch and at Ice Central in Ottawa.

Snow investigations in the past have generally been in response to the needs of hydrologists and climatologists with emphasis on the meso or regional rather than continental scale. Although snow and ice are recognized as important factors in climate modelling, resources have not permitted expansion of research activity into this field. It is important to realize, however, that the AES does not produce national satellite snow cover maps. Regional mapping on an operational basis is done by the Hydrometeorology Division to meet selected user's special needs. Present resources do not permit large scale expansion of this service. Thus, the availability of satellite snow cover analysis is very different from that in the United States.

NOAA Snow Charts - Discussions

The Monitoring and Prediction Division of the Canadian Climate Centre receives the snow and ice boundary maps prepared by the Synoptic Analysis Section of NESS. However, since they are received by mail, they are often two weeks old when received and are not really used effectively. If they were received in near real-time, the information might be included in the weekly Climatic Perspectives for distribution to more Canadian users.

For climate modelling purposes, the satellite-derived snow cover information is potentially more valuable than ground-based data currently available on a near real-time basis. A 5° latitude - longitude grid is a reasonable scale and format in which to have the information if the observations are representative. A smaller grid size is desirable for many process oriented studies.

Questions:

1. Can the information be obtained in near real-time, for example, over NWS/AES circuits?
2. Is there historical digital data available for use by climate modellers?
3. Is there an archive of gridded snow cover data or just primary observations?

NOAA/NAVY Ice Charts

Again the problem is their receipt by mail. Because of this delay, they have not been used in monitoring applications.

Question:

1. Can this information be digitized and put on the NWS circuit or obtained from a facsimile circuit?
2. Are there any digitized historical data sets which could be used for statistical studies?

Snow Cover - AES Products

The archiving and mapping system for snow course data outlined by Findlay at the 1978 Boulder Workshop has not yet been implemented by AES. It is hoped that is will be ready sometime in 1981 (Findlay and Goodison, 1978).

During the winter, maps of snow cover depth are included in the weekly Climatic Perspectives. The map is based on 1200 G.m.t. observations made at synoptic stations. The representativeness of these observations is certainly a problem in the analysis and their use in climate models.

The Hydrometeorology Division is currently processing near real-time water budgets for approximately 225 synoptic stations across Canada. This effort is part of the monitoring role of the Canadian Climate Centre to quickly assess variations of climatic parameters in time and space with respect to hydrological activities. The water budget technique is based on the Thornthwaite model using daily temperature and precipitation observations as input. Derived components from the model include estimates of evaporation, soil moisture, snow pack water equivalent, and snowmelt. These water budget components are accumulated and averaged over seven-day periods and, using an objective analysis scheme, may be made available in map form for all of Canada about two days after the end of each period. Also available are the normal water budget components generated from the long-term temperature and precipitation normals for the corresponding seven-day periods and the deviation from normal values.

The Hydrometeorology Division also processess in near real-time a snow cover map for the Saint John Basin and its sub-basins. Digital Tiros IR, near IR, and visible data are used to construct the map which is sent by facsimile to the Frederiction Flood Forecasting Centre. A recent paper by Waterman et al (1980) dicusses the procedure.

AES Ice Program - Future Plans

1. Ice data acquisition

   a. continued airborne reconnaissance in support of marine activities in ice-covered waters (currently 2400 hours of reconnaissance per year);
   b. increased airborne reconnaissance of winter ice conditions in Arctic waters;
   c. use of special sensors including Side Looking Airborne Radar and laser surface profilometers;
   d. direct data transmission via radio facsimile from aircraft to Ice Forecasting Central;
   e. continued use of near real-time NOAA, TIROS, and LANDSAT imagery in operational forecast program;
   f. implementation of iceberg survey program on Davis Strait and Labrador Sea.

2. Ice forecasting

   a. continued production of daily assimilated ice condition charts, three-day and monthly forecasts, and seasonal outlooks;
   b. increased automation in forecast production through digital processing of data;
   c. implementation of ice motion models;
   d. development of automatic satellite data enhancement and processing.

3. Ice Climatology

   a. archival of manuscript ice charts and original data;
   b. development of a readily accessible digital data bank;
   c. publication of annual Ice Summary and Analysis Reports;
   d. analysis of laser profilometer data for ice topography;
   e. publication of detailed ice atlases for: Arctic Waterways (Completion 1980), Gulf and Eastern Seaboard (completion 1980), Hudson Bay and Approaches.

4. Research and development

   a. extensive involvement in development of long-range radar satellite programs;

   b. improved application studies of airborne radar data, particularly under summer melt conditions;

   c. development of real-time air-ship photo-facsimile data links;

   d. completed design of new laser profilometer system.

Precipitation Modification

Snowpack augmentation is now being seriously considered for areas of the Rocky Mountains in Alberta. The ultimate proof that precipitation modification has taken place would be a demonstration that precipitation measured at the ground was actually increased (decreased) under some type of controlled experimental treatment of cloud systems. This is not an easy task. Hypothesizing 15-25 percent changes in snowpack, how might one attempt to measure changes in snowpack induced by cloud seeding operations? Do we have remote sensing capabilities to help in such a problem?

Climate Modelling Needs

Climate modelling and diagnostics have been tied largely to the NWP operational analysis grid for obvious reasons. This is likely to continue and thus what is needed is to have synoptic observations of ice and snow at least on this scale and possibly on smaller scales for process study/parameterization purposes. The variables needed are not just snow or no-snow, but those physical variables which are required to calculate budgets for the grid square. Information on snow depth and water equivalent is ultimately required. A climatology of snow and ice can be compared with GCM budgets. Models can give some idea of the sensitivity of the system to snow and ice, but only if included in a reasonable way in the model. A particular problem in which AES modellers have an interest is the interactive ice model. GCMs do not usually include interactive ice models and there is interest in beginning a project to include this in their model. Have any others begun such a project?

A practical question has been raised by our network standards division. Particularly, what accuracy levels of snow measurement would be considered satisfactory to validate the output of a model or to test a climatic change hypothesis? Would the existing accuracy of snow measurement set by WMO be considered satisfactory?

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Study of the Sea Ice Distribution in the North Polar Regions

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Abstract

With regard to the important role of the polar regions in the general atmospheric circulation and to the interaction between atmosphere and surface, a systematic study was made to investigate the behaviour of sea ice in the north polar regions in relation to the monthly pressure and temperature distribution for the period 1966 - 1979. For this study the polar regions were partitioned into seven areas which are shown in figure 1.

Main Data Sources

On the basis of the data and the analyses available for this investigation (table 1), it was difficult to get a uniform set for an estimation and a comparison of the ice extent in the different areas of the north polar regions. However, this is the presupposition for a detailed study in relation to the atmospheric circulation.

The factors responsible for the differences in the data and analyses are:

1. spatial factor
2. spectral factor
3. time factor
4. interpretation factor

Using APT-pictures, SR-, VHRR- and AVHRR-data, ice parameters, measurable and identifiable vary and the degree of accuracy in the evaluation is different; the determination of an ice cover more or less than four tenths (4/10) is often difficult.

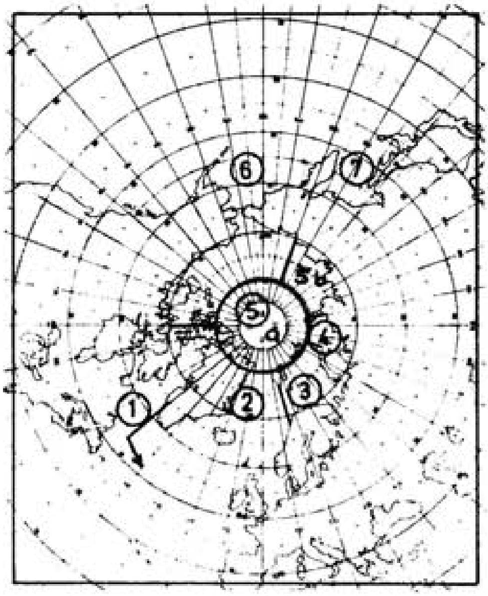
There are problems in distinguishing among sea ice, clouds, and snow. In the Visible images, the gray tones of sea ice (albedo) are dependent on the time of the year, position of the sun, cloud cover, snow cover and depth, ice concentration and thickness, melting water, etc. The interpretation of IR-images for ice reconnaissance is more suitable in the winter season.

Atmospheric conditions such as clouds influence the frequency of satellite observations and measurements. In view of the high percentage of cloud cover, especially ion summer, satellite data are not available each day. Consequently the basic data sets for weekly or monthly analyses are of varying quality.

There exist various weekly ice charts, charts of the ice extent at the end of each month, and also mean monthly ice data. They are all produced by different techniques. More details about these are given in other papers of this workshop (Smigielski, p. 59 and Kukla and Robinson, p. 103 this volume).

The British Monthly Ice Charts are produced for most of the Northern Hemisphere including the polar areas 1 through 5 a, b (see figure 1). Charted features are classes of ice concentration, classes of age and types of ice, and also classes of ice thickness. Additional information such as sea isotherms, degree days, monthly speed of U.S. and USSR ice islands, etc., are also included in these maps.

The weekly NOAA/Navy Eastern and Western Arctic sea ice analyses are manually produced as a synthesis of ice data and satellite information of varying resolution and utility (see Godin p. 71 this volume). The ice cover is mapped in relative detail. The ice concentration is reported in octas or in tenths. Visible, infrared, and microwave imagery are used to construct the charts. These data are supplemented by ship and coastal station reports.



Area 1	Baffin Bay, Davis Strait, Labrador Sea
Area 2	Greenland Sea, Denmark Strait, Irminger Sea
Area 3	Barents Sea
Area 4	Kara Sea
Area 5	North Polar Basin with its adjacent seas: East Siberian Sea, Chukchi Sea, Beaufort Sea, Canadian Archipelago, Laptev Sea
Area 6	Bering Sea
Area 7	Okhotsk Sea

Figure 1. North polar regions areal subdivisions.

Table 1. Main data sources.

1.	Meteorologische Satellitenforschung (MSF), Berlin	Satellite pictures ESSA 2,4,6,8 NOAA 2 - 5 TIROS N, NOAA 6	Area 1 - 4	1966-present
	NOAA-NESS	ESSA NOAA 2 - 5(VHRR) TIROS N, NOAA 6 (AVHRR)	Area 1,5,6,7	1972-present
	WDC-A Boulder, Colorado, USA	NOAA 2 - 6 (VHRR, AVHRR)	Area 1,5,6,7	1972-present
2.	British Met. Office, Bracknell, U.K.	Monthly Ice Charts	Northern Hemisphere	1965-present (monthly)
3.	U.S. Fleet Weather Facility	Eastern Arctic Sea Ice Analyses	Eastern Arctic	1972-1980 (weekly)
	U.S. Fleet Weather Facility	Western Arctic Sea Ice Analyses	Western Arctic	1972-1980 (weekly)
4.	Lindsay, D.G. Energy, Mines an Resources-Canada	Sea Ice Atlas of Arctic Canada, 1961-1964, 1965-1974	Arctic Canada	1961-1974
5.	Kukla, G.J. et al. Lamont-Doherty Geological Observatory Palisades, N.J.	Weekly and Monthly Ice Extent	Northern Hemmisphere	1972-present
6.	Inst. fur Meteorologie Freie Universitat, Berlin	Berliner Wetterkarte	Atlantic, Eurasia	1965-present (daily)
7.	Inst. fur Meteorologie Freie Universitat, Berlin	Weltwetterlage	Northern Hemisphere	1966-present (monthly, seasonal)
8.	US Weather Bureau-ESSA National Weather Service NOAA	Circulation and Weather	Northern Hemisphere	1966-present (annual)
9.	Deutscher Wetterdienst (DWD)	Grosswetterlagen Europas	Europe, Northern Hemisphere	1966-present

The evaluation of the weekly and monthly ice extent by Kukla and others at Lamont is mainly done on the basis of the NOAA/Navy operational charts of sea ice cover mentioned above. These charts were checked again using VHRR visible and infrared NOAA satellite imagery and DMSP (Defense Meteorological Satellite Program) transparencies. In general, the quality of these maps was found to be sufficiently high for use in climate-related studies.

Sources 6 to 9 in table 1 are studied in relation to the general circulation.

Methodology

On the basis of the ice analyses listed in table 1, but giving special consideration to the British ice charts, and on the basis of more than 400 satellite pictures supplied with geographical coordinates and evaluated for detection and mapping sea ice, a number of data sets has been prepared at MSF-Berlin. Table 2 gives a summary of the most important products. They are the result of critical scrutiny and crosschecking.

The schematic representation of the ice border at the end of each month (an example for March 1966-1973 is given in figure 2) is self-explanatory; the variations from one year to another are considerable.

Table 2. Data sets prepared at Meteorologische Satellitenforschung (MSF), Institut fur Meteorologie, Freie Universitat, Berlin.

Schematic representation of the ice border at the end of the month	January - December 1966 - 1980
Schematic representation of the monthly variations of the ice border	January - July July - January 1966 - present semi-annual
Maximum - minimum ice charts	1966 - 1979 monthly
Ice extent at the end of each month (in km^2)	1966 - 1980
Deviation of 1000/300 mb thickness from the 10-year mean 1951-1960	Seasonal: Autumn IX - XI Winter XII - I Spring III - V Summer VI - VI
Mean pressure distribution in mb averaged for the months August to April within the period 1966 - 1980	1966 - 1980
Departures of the pressure in mb from the normal 1931 - 1960 averaged for the months August to April 966 - 1980.	August - April 1966 - 1980

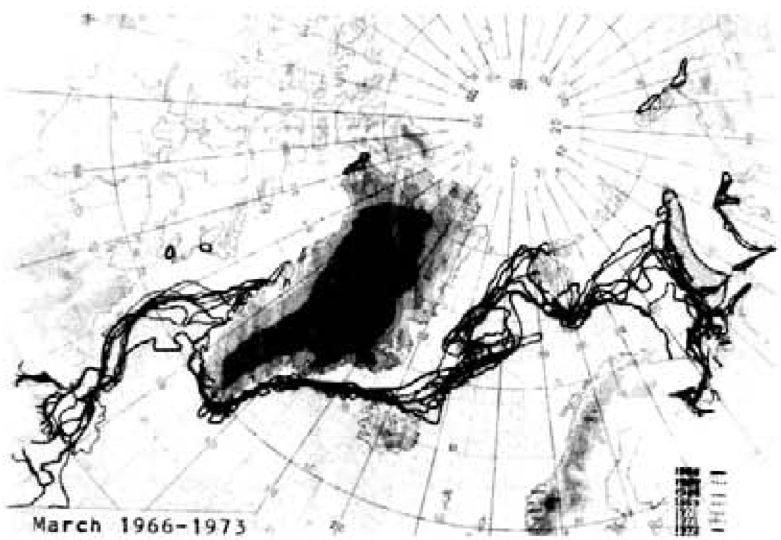


Figure 2. Schematic representation of the ice border at the end of March, 1966-1973.

The maximum-minimum ice charts reflect the mean 4/10 ice limits at the time of greatest and of least extent. The two examples for March and August (figure 3 a, b) clearly indicate the broad range in which the ice edges have varied within the period 1966 - 1979. The schematic representations of the monthly variations of the ice border in form of semiannual charts make it possible to study the monthly ice advance and retreat in detail and also to control these movements relative to the weather situation. No example is included here.

In figure 4, the total ice cover in km^2 is given for all seven areas. The data for area 1 to 4 are evaluated at MSF-Berlin, the data for area 5 a,b, 6, and 7 are estimated by Kukla/Lamont. Area 5a is only a part of the East Siberian Sea between 100° and 160° E.

A comparison was made between our data of area 1 with those of Kukla for area "LAB = Labrador", and between the data of area 2, 3 and 4 with those of area "NAT - North Atlantic". Normally the discrepancies are less than 10 percent. In fall and early witner, the Berlin data, as well as the British data, indicate a light overestimating, in winter and in spring generally there is an underestimating of the total ice extent compared with the Kukla data. There is probably a dependence of the proportion of young dark ice to open water which varies with the season. Some large discreplancies as in January/February 1972, March 1973, or in August 1979 are difficult to explain.

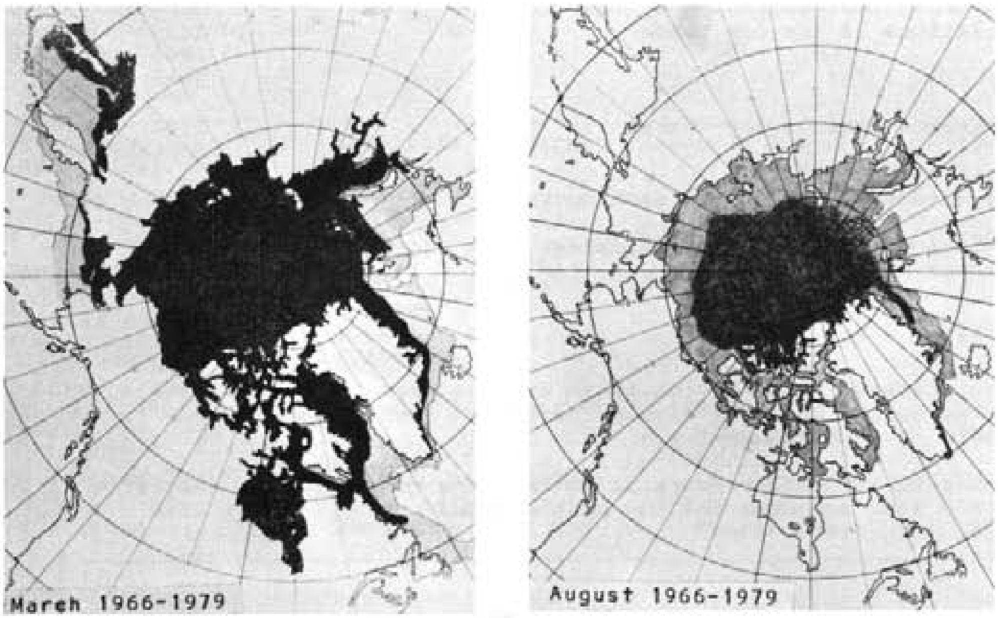


Figure 3 a, b. Maximum-minimum ice charts.

Acknowledgement

We wish to thank George Kukla and his group for the kind support in giving us weekly and monthly data of the ice extent. We are also grateful to the personnel of NOAA/NESS in Washington and of the World Data Center-A for Glaciology in Boulder for supplying us with satellite imagery.

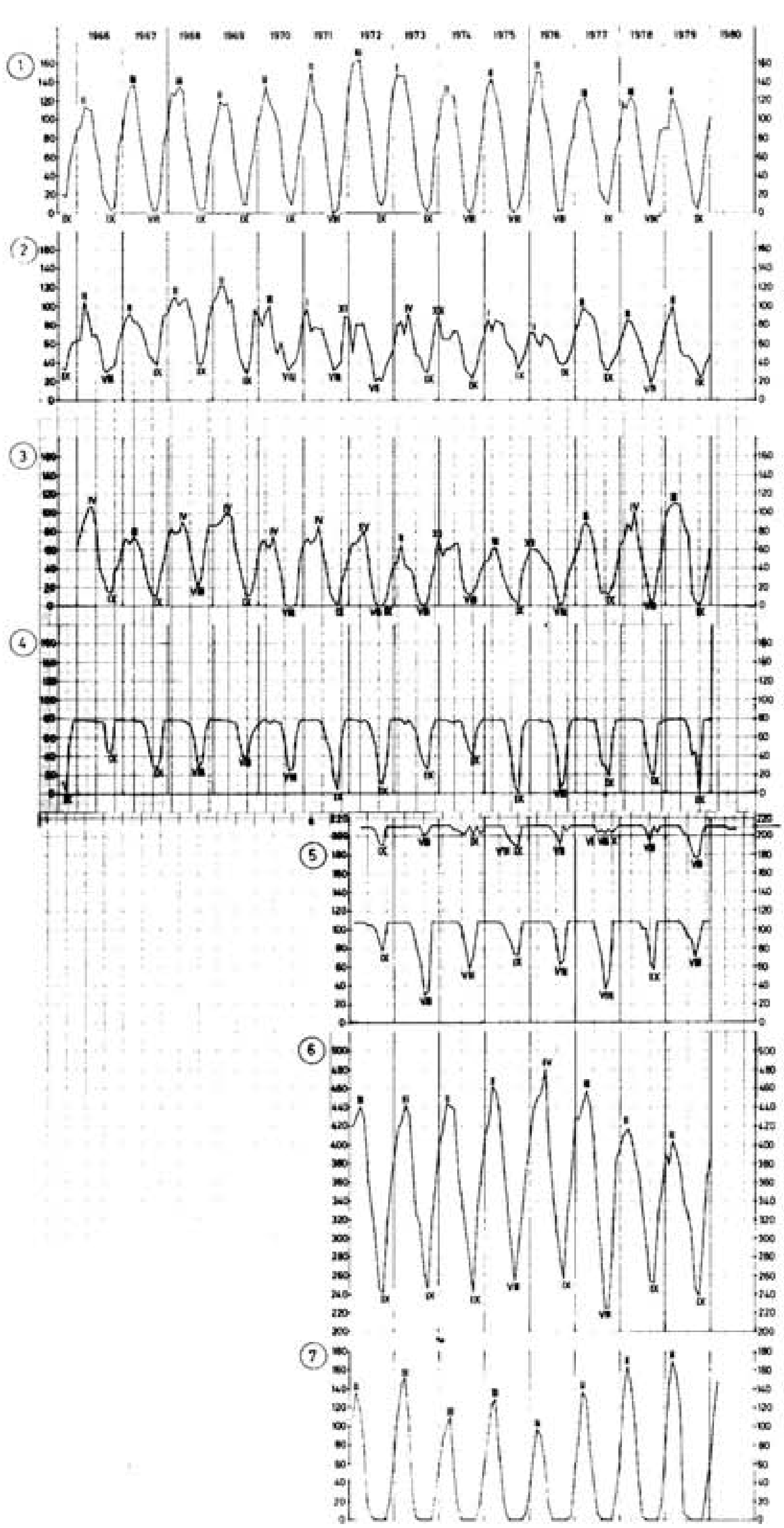


Figure 4. Monthly ice extent for area 1-7 in $x(10^5)km^2$(>4/10) from 1966 through 1979.

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Climatic Value of Operational Snow and Ice Charts

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ABSTRACT

Operational snow and ice cover charts produced by NOAA, the Navy and the U.S. Air Force Global Weather Central (AFGWC) were compared with ground station reports and original satellite imagery. Our objective was to find out how accurately snow presence and thickness, as well as the snow impact on surface albedo, are depicted in space and time.

We conclude that the information on snow line postion is sufficiently accurate for use in the current generation of global circulation models in all seasons except autumn.

However, the quality of the information on surface albedo, on the thickness of snow covers, and on the proportion of open water within the pack needs radical improvements.

Introduction

It is well know that snow and ice covers have a large influence on the global heat budget (Hummel and Reck, 1978; Fletcher, 1965; Untersteiner, 1961; King, et al., 1964; Radok, 1978). Knowledge of the variation of these covers in time and space is essential for understanding climate changes (Wiesnet and Matson, 1976; Kukla and Kukla, 1974; Kukla, 1981).

The climatic significance of seasonal snow and ice fields is a result of their:

1. maintenance of low surface temperature of 0°C, or lower,
2. high shortwave reflectivity,
3. very high longwave emmisivity,
4. latent heat consumption in melting,
5. maintenance of a low evaporation rate, and
6. generation of cold, dry high pressure atmospheric masses, resulting from 1-5.

Since our team analyzes NOAA, Navy, and Air Force snow and ice charts in order to generate a series of climate related cryospheric indices (see Kukla and Gavin, 1979; Kukla and Gavin, p.145 this volume), we decided to test the accuracy of the operational charts as sources of information on the:

1. position of the snow and ice boundaries,
2. surface albedo,
3. depth of snow on ground, and
4. time accuracy of the plotted information.

We emphasized periods when maximum regional changes occur in the observed variables. Charts were constructed and compared with operational products. Additional information unavailable at the time of operational chart construction was often used. Both NOAA/NESS, Navy-FLEWEAFAC, and NOAA /Navy interpreters cooperated in the work and frequently provided the original satellite imagery used in generating the charts. The main focus was directed at this stage to the quality of snow charts. This is because the regional changes in the extent and character of snow covers occurring during a single day are much larger than those of sea ice.

Each group producing snow and ice charts uses different techniques. These are described in more detail in other papers presented at this workshop (see Smigielski, p.59 this volume; Godin, p.71 this volume; Woronicz, p. 63 this volume) and reviewed in table 1 of this paper. NESS uses satellite images and relies on skilled interpreters recognizing characteristic textured surface features of the snow-covered land. Images for each day of the particular week are used. The snow areas are placed in one of three relative reflectivity classes depending on the visible surface brightness (See Wiesnet and Matson, 1979; Matson and Wiesnet, 1981; Smigielski, p.59 this volume).

Table 1. Current series of snow and ice charts used in the study.

Symbol	Chart Name	Produced By	Area	Projection and Approx. Scale	Interval	Content
NOAA NESS	Northern Hemisphere Average Snow and Ice Boundaries	Synoptic Analysis Branch of the National Earth Satellite Service, NOAA	Continents of the Northern Hemisphere north of 25°-30°N. latitude	Polar stereographic 1:50,000,000	Weekly: 1967-present	Boundaries of Snow and ice-covered areas in 4 classes: 1. Least reflective 2. Moderately reflective 3. Highly reflective 4. Scattered mountain snow
Air Force	Current Snow and Ice Depth	USAF, Global Weather Central	Both hemispheres 0-90°N	Polar stereographic 1:30,000,000	Weekly: 1967-present	Depth of snow and ice for 6 categories: 1) <2"; 2) >2"; 3) >4"; 4) >6"; 5) >8"; 6) >10"
Weekly Weather and Crop Bulletin	Weekly Weather and Crop Bulletin Snow Chart	NOAA and U.S. Dept. of Agriculture	Continental U.S.	Albers Equal Area 1:30,000,000	Weekly: 1934-present	Depth of snow on ground at 7 a.m. e.s.t. for Monday, December-March only
Navy	Southern Ice Limit	U.S. Navy Fleet Weather Bulletin	2 sections north of 40°N: ~120W-90E ~90E-120W	Polar stereographic ~1:15,000,000	Weekly: 1972-present	Sea ice concentration in oktas (from 1980 in tenths), ice age isoline of +2°C sea surface temperature, and 0°C air temperature
Navy	Northern Ice	U.S. Navy Fleet Weather Facility	Antarctic south of 50°	Polar stereographic ~1:18,000.000 1973-74: 1:35,000,000	Weekly: 1973-present	Same as above

The Air Force charts show the extent and depth of snow on the ground, the data being generated by a sophisticated computer program. The depth of snow is determined by combining and comparing ground reports, precipitation and temperature data, etc. with satellite brightness fields. Blank spots are reconstructed from climatology (See Woronicz, p.63 this volume). The Weekly Weather and Crop Bulletin reports snow cover extent and depth once a week from December through March in the continental United States at 7 a.m. e.s.t. on the chart date. The map is produced from telegraphic reports of selected stations across the country.

Additional operational charts are produced by various agencies from outside the U.S. We used them in tests for comparisons. They all show the depth of snow in winter in selected regions.

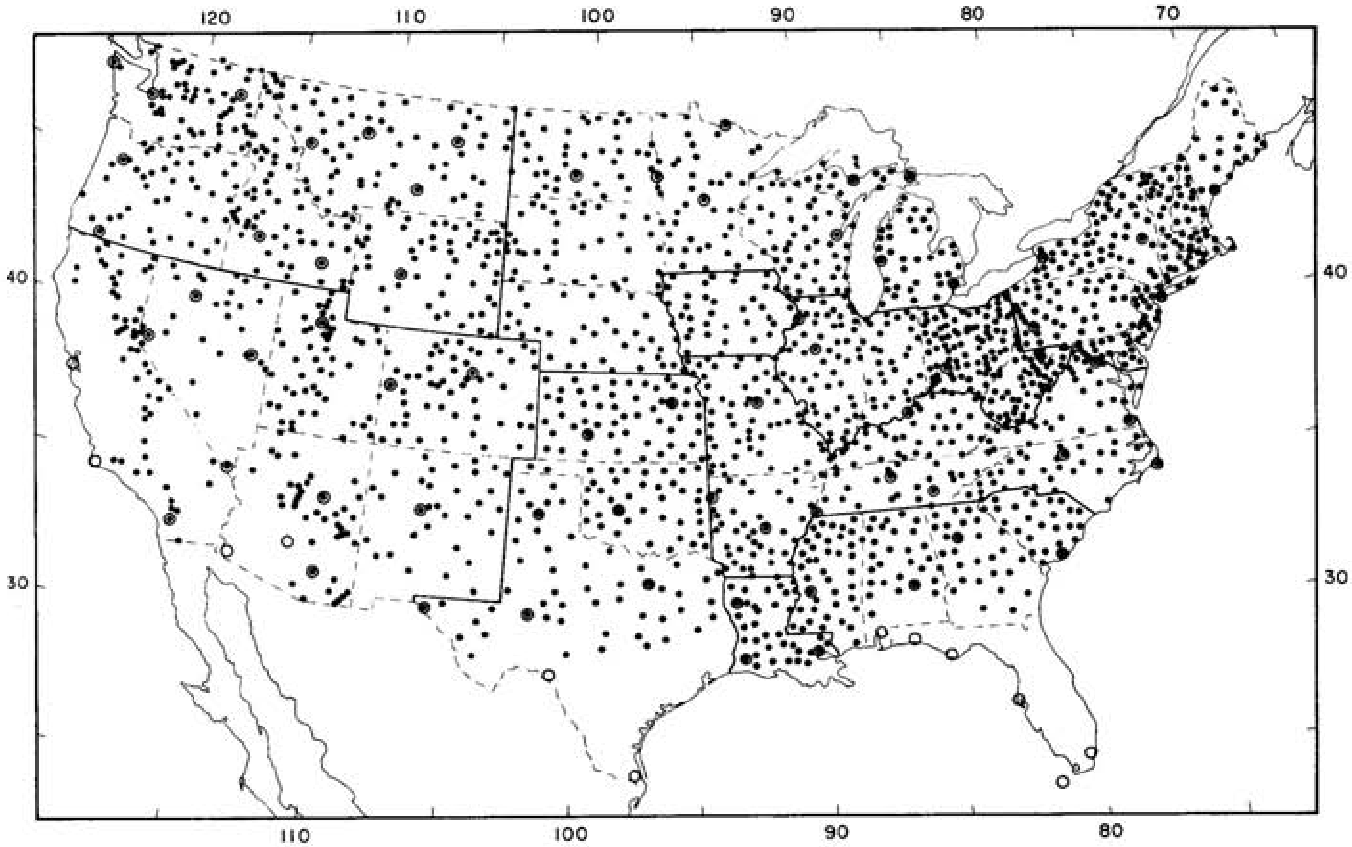

Figure 1. Location of the ground stations reporting snow used in the Lamont study shown in dots. Stations of the WMO network included in the snow depth charts of the British Meteorological Office are marked in circles.

Table 2. Difference in percent of ground snow covered within selected U.S. blocks (see also figure 3) as reported in operational charts (last one in period) and in Lamont daily snow charts. Numbers without the minus sign show operational result to be larger.

NESS	BLOCK	1	2	3	4	5	6	7
11/10-16/75	3	26.5	18.1	-14.6	-17.3	- 4.8	11.8	22.7
11/17-23/75	3	63.5	65.8	43.3	15.6	4.5	1.2	13.9
3/ 1- 7/76	3	34.6	23.8	19.2	.6	- 4.7	- 1.2	.6
3/ 8-14/76	3	-41.7	-28.5	-19.6	-14.0	-26.8	-12.8	- .3
3/15-21/76	3	-38.5	-35.4	-19.9	- 8.0	- 4.2	- 6.2	-10.2
1/31-2/6/77	5	-10.7	- 9.9	- 3.6	- 3.0	- 1.2	- 2.7	3.0
2/ 7-13/77	5	-45.1	-43.0	-38.5	-31.2	-20.6	-12.4	- 2.6
2/ 6-12/78	1	-26.7	26.0	21.1	22.8	16.5	- 9.3	5.5
2/12-18/79	4	- 9.4	- 8.6	1.5	5.8	10.7	- 7.6	-29.0
AIR FORCE		1	2	3	4	5	6	7
2/ 1- 7/77	5	1.3	7.6	8.2	10.0	8.5	14.0	11.5
2/ 8-14/77	5	-18.8	-14.3	- 7.0	3.6	11.8	21.6	14.0
2/ 7-13/78	1	23.4	18.5	20.2	13.9	6.7	2.9	2.9
2/13-19/79	4	28.9	36.0	43.3	48.2	29.9	8.5	22.9
WEATHER AND CROP BULLETIN		1	2	3	4	5	6	7
3/ 2- 8/76	3	- 3.6	- 1.0	-19.6	-24.9	-21.4	-19.6	-18.7
3/ 9-15/76	3	-18.7	- 9.8	- 4.2	-17.0	- 3.0	9.5	- 8.1
3/16-22/76	3	-34.8	-19.3	- 7.4	- 3.6	- 5.6	- 9.6	- 2.8
2/ 1- 7/77	5	-17.1	-10.8	-10.2	- 8.4	- 9.9	- 4.2	- 6.9
2/ 8-14/77	5	-40.0	-35.5	-28.2	-17.6	- 9.4	.4	- 7.2
2/14-20/79	4	- 1.2	6.1	-11.0	- 7.3	-28.7	-14.3	- 8.5

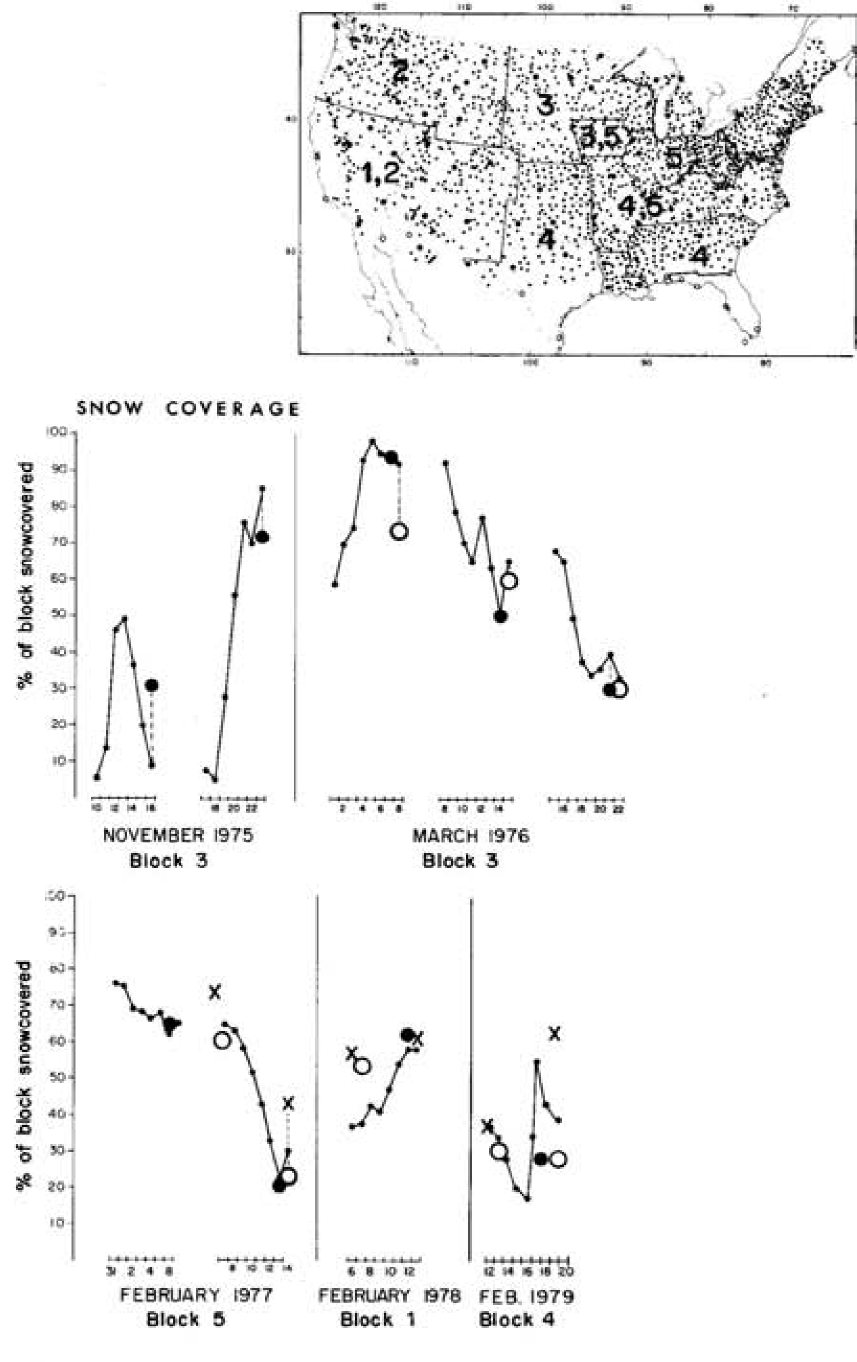

Figure 2. Snow coverage, in percent of total area, of selected U.S. geographic blocks. Blocks, some overlapping, are shown in the upper right. Daily data obtained from Lamont charts are shown by dots; area in the weekly NOAA/NESS snow chart is shown by a full circle plotted on the last day of the charted week; areas from the Weekly Weather and Crop Bulletin are shown by an open circle; and areas in the Air Force charts are shown by a cross.

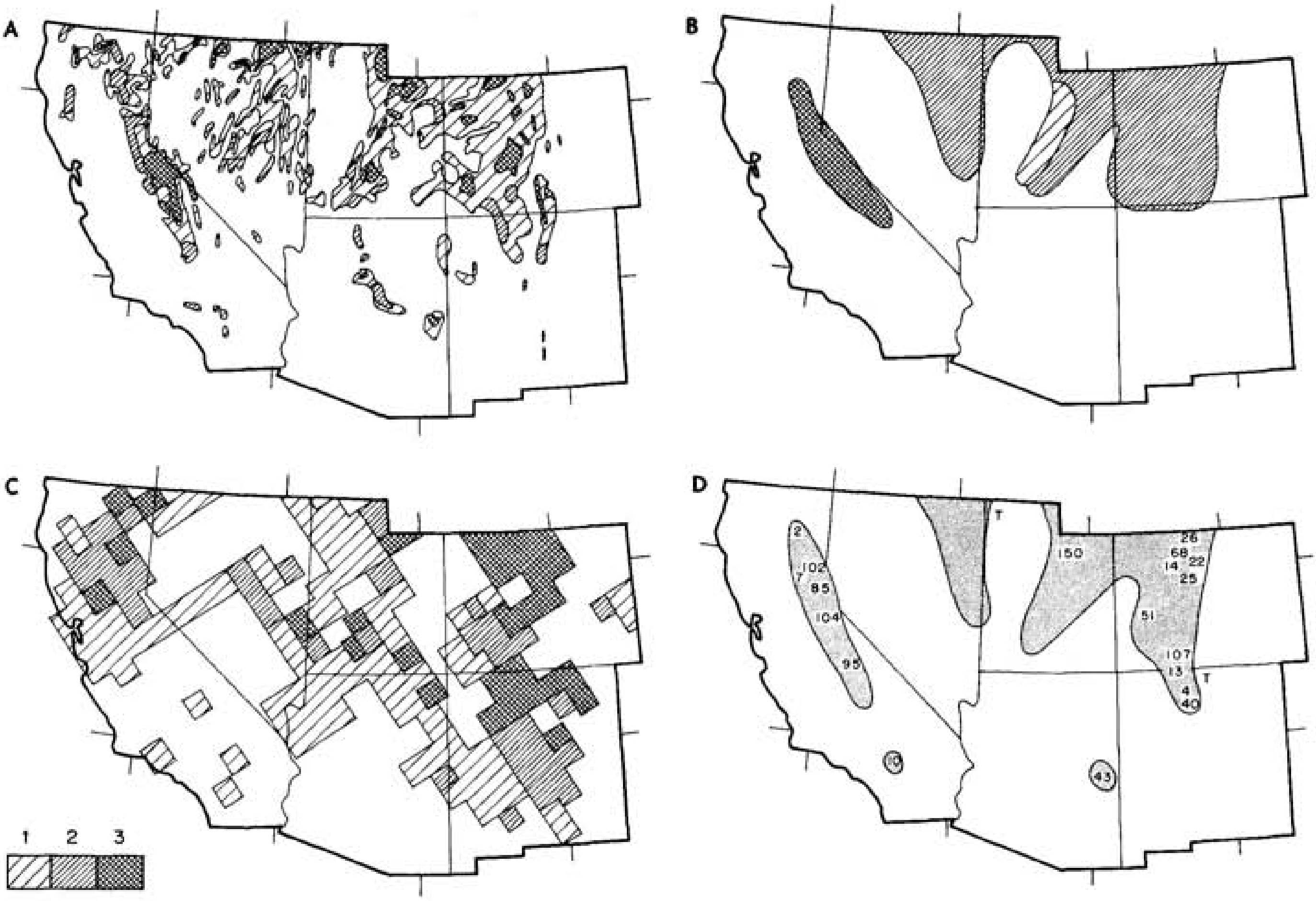

Figure 3. Snow cover in the southwest U.S. in mid-March 1978 as charted on the 16th by Lamont (A), for the week 13-19 by NESS (B), for the 20th by the Air Force (C), and the Weekly Weather and Crop Bulletin (D). Snow field reflectivities in A and B range from low (class 1) to high (class 3). Snow depths in C are <2in. for class 1, and <6in. for class 2, ≥6 in. for class 3. Depth in D is in inches.

Table 3. Snow cover in percent of the six state total area as shown in figure 3. This includes California, Nevada, Utah, Colorado, Arizona, and New Mexico.

Date in March 1978	Source	Snow Depth	Percent Cover of the Six State Area
16	Lamont	-	14.7
Week of 13-19	NESS	-	15.1
20	Air Force	≥ Trace	44.0
20	Air Force	≥2"	18.5
20	Weather & Crop Bulletin	Scattered reports	18.7

For instance, the snow depth in centimeters over Canada is published once a week by the Canadian Climate Centre in Ontario (Climate Perspectives, 1972-). Depth of snow cover in the Northern Hemisphere as reported by the World Meteorological Organization network is charted every 5-10 days by the British Meteorological Office in Bracknell (see Crane, 1979).

Ice cover in both hemispheres is mapped weekly in relative detail by the Navy, recently joined with NOAA. The ice concentration is reported in octas (eighths) or, recently, in tenths (Godin, p.71 this volume). Visible, infrared, and microwave imagery, the majority of which is gathered during three consecutive days, is used to construct the charts. Data are supplemented by ship and coastal stations. On a less detailed scale, the extent of sea ice is also shown in the NOAA/NESS snow charts, the only source which shows the relative reflectivity of the combined snow and ice cover. The Air Force snow charts depict the outline of the sea ice covered by snow.

Several other agencies around the world produce regional ice cover charts (see Godin, p.71 this volume). These, without exception, classify the ice according to its concentration and/or age. An overview of the availabe data sets is in Crane (1979).

Snow Cover Outline and Areal Density

The snow cover on land is frequently discontinuous. For example, south facing slopes are commonly exposed more rapidly than horizontal surfaces or north facing slopes. Bare ground may be exposed by drifting. More importantly, the presence, type, height, and density of vegetation affect local and regional albedos, even with an otherwise thick snow cover on the ground. A dense coniferous forest with 30 cm of snow on the ground, but with a dark canopy, or steep rock cliffs may not look too different in winter than in summer. Conversely, grass-covered pasture land with even 5 cm of fresh snow may reach an extremely high brightness, comparable to that found over Antarctica and Greenland.

To examine the accuracy of the operational snow charts, we produced a new, independent, updated set of snow maps for selected blocks in the United States and Asia.

Satellite information was recharted and completed by incorporating reports from ground stations. The U.S. ground station network is shown in figure 1. The area covered by snow was measured and expressed as the percentage of the total area of the block. Results were then compared to the area of snow shown in the tested operational charts. Selected results are shown in table 2 and figure 2 . It is seen from the results that:

1. the best fit is reached on the last, or the penultimate day of the week;
2. the departures between the Lamont snow values and those shown in the operational charts tend to be smaller in the more recent years; and
3. the average differences were less than 10 percent of the area of the block.

It must be added that the location of the snowline within individual blocks was quite similar in all tested products, with the exception of the mountainous west. Figure 3 shows snow in six southwestern states (see figure 3, block 2) as charted by four independent groups. There was no significant snowfall during the four days for which the information was plotted. A gradual dissipation of the snowfields occurred in the period between March 13 and 20. While the area of snow cover as found in the Lamont, NOAA/NESS, and Weekly Weather and Crop Bulletin charts is similar (table 3), the geographic distribution of the snow fields differs. The Lamont outline, delimited from NOAA-VHRR imagery, shows a rather complicated patchy structure of snow fields whereas the other charts are highly generalized. The Air Force product also overestimated the cover and extended it into areas where we were unable to locate any snow on the ground either in satellite images or in ground station reports. Excluding the under-two-inch class, the Air Force areal coverage comes closer to the other groups, but the areal distribution fails to improve significantly.

The previously discussed tests in the United States include only one month in autumn. Additional autumn tests, particularly those done over Asia, show frequent large differences between the snowline plotted in the NOAA charts and that shown in the Air Force set. The Air Force charts correlate better with meteorological reports. This is because the middle and high latitudes are frequently covered by persistent clouds in autumn. NOAA interpreters show snow cover only if it is visible in cloud-free scenes. They do not plot snow reported by ground stations which are covered by clouds, and whose relative brightness therefore cannot be determined (Smigielski, p.59 this volume). The Air Force charts, on the other hand, are principally based on the ground station reports and snow is charted whether cloud covered or not (Woronicz, p.63 this volume).

Figure 4 shows the difference of snow coverage as plotted in Central Asia by NOAA/NESS and the Air Force. Figure 5 shows that large-scale snowfalls occurred within the area one day before and on the day of the NOAA chart as well as earlier in the week. Temperatures were below 0°C both days over the area in question so that the difference between the NOAA and Air Force charts cannot be explained by timing. Rather persistent clouds prevented the NOAA interpreters from determining the state of the ground from the satellite imagery.

Large discrepancies were also found in the early NOAA snow cover charts for autumn between 1967 and 1972. In this case, however, the relatively low quality of the earlier satellite imagery and the lack of sufficient experience with the recognition of snow in poorly illuminated scenes contributed to the omission of the snow fields over substantial portions of northern Asia and sometimes also North America. This finding has direct implications for the conclusions of Kukla and Kukla (1974) on the considerable increase of the average annual snow cover between 1970 and 1972. While the average in the Northern Hemisphere did indeed increase, the change was less extreme and more gradual than the NOAA snow charts indicate. This is, to a large degree, due to the underestimation of the autumn snow cover extent in the carts of the late 1960's.

Sea Ice Edge and Concentration

The Navy (now NOAA/Navy) operational charts of sea ice cover were checked in a manner similar to the snow charts. VHRR visible and infrared NOAA satellite imagery and DMSP (Defense Meteorological Satellite Program) transparencies were used in the checks. An example may be seen in figure 6, a and c. In general, the quality of Navy charts was found to be sufficiently high for use in climate-related studies. They relatively accurately indicate the median proportion of ice floes which are either snow covered or formed of white and light grey ice.

Open water or young dark ice surrounds such floes. In most situations the thin dark bare ice cannot be reliably distinguished from the open water. Thus, an ice field shown to have a 7/10 concentration represents an area with 70 percent of light grey or snow-covered ice floes, but additional fresh dark colored ice may be present in the area. The proportion of young dark ice to open water varies with the season. In late spring and summer open water dominates while in fall and in winter ice dominates.

In some recent publications it was argued that the proportion of open water in the winter pack ice around Antarctica is considerably higher than in the Arctic (Ackley and Keliher 1976; Zwally et al., 1976). This conclusion was based on the interpretation of microwave satellite imagery. Our comparison of the enhanced cloud free infrared scenes of the Weddell Sea and of the Ross Sea in August 1976 with the simultaneous Nimbus 5 microwave brightness fields indicated that the proportion of open water within the pack ice interior in winter is not noticeably different from the Arctic basin (Kukla and Dehn, 1981). There the range is <1-5 percent at most.

The Albedo of Snow Fields

Surface albedo is not yet charted on a real-time basis anywhere in the world. Kung et al. (1964) measured the surface albedo over a fixed flight path in Wisconsin in monthly intervals throughout a single year. This is the most detailed observance of time-related changes in surface albedo on a regional scale to date. Rashke and Preuss (1979) computed the surface albedo at four typical intervals of the year from Nimbus 3 satellite composite minimum brightness fields. However, arbitrary corrections which had to be made for atmospheric transmissivity decrease the accuracy of their results.

Because snow causes by far the largest variability of surface albedo on a seasonal basis, operational snow and ice charts can be used to aid in estimating approximate regional surface albedo values (Kukla and Robinson, 1980; Robock, 1980; Adem and Donn, 1981). So far, only the average monthly values for a year have been published.

Kukla and Gavin (1979 and p.145 this volume) generate, on a weekly basis, an index related to the short term variations of surface albedo. This is based on the NOAA weekly products which indicate the relative reflectivity of snow fields (Smigielski, p.59 this volume). The large scale brightness of the snow fields is visually classified in three grades, where 1 is the lowest, and 3 the highest. Batten et al. (1977) analysed VHRR images from Canada and the United States and determined the average albedo of class 1 as 30 percent, class 2 as 45 percent, and class 3 as 60 percent. The variability in each class may reach ± 20 percent.

Six grades of relative reflectivity are visually subdivided from satellite imagery in the Lamont climatic charts (Kukla et al., p.87 this volume). We have not yet had an opportunity to correlate these reflectivity grades with synchronously-measured albedo values.

Figure 7 shows a comparison of the three NOAA relative reflectivity classes of the Eurasian snowfields with the six reflectivity classes of the Lamont chart. The NOAA charts depict the snow outline quite well. However, the distribution of the relative brightness field is greatly generalized. Our sample represents the early gneration of the NOAA/NESS

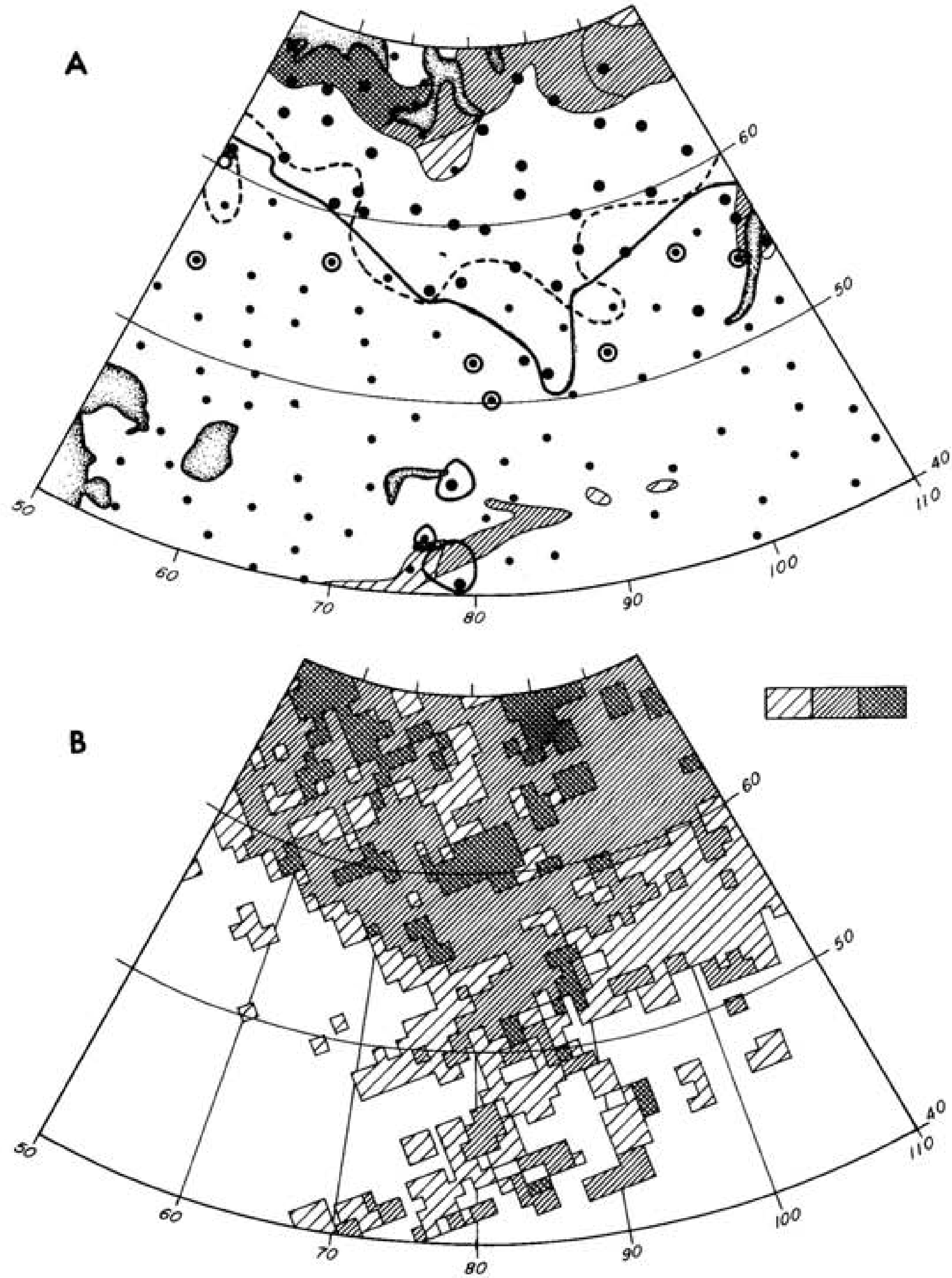

Figure 4. Snow cover plotted in Central Asia for mid-October, 1979. NOAA results for the week ending on the 14th are shown in (A) using the same reflectivity classes as in figure 3. Air Force, for the 15th, is shown in (B). Depth classes are the same as in figure 3. WMO stations reporting snow cover in British charts on the 17th are shown with large dots, those reporting no snow on the ground, with open circles. Snow cover >2cm on October 17 are enclosed within the solid line, on the 12th within the dashed. These and remaining WMO stations (small dots) are used in figure 5.

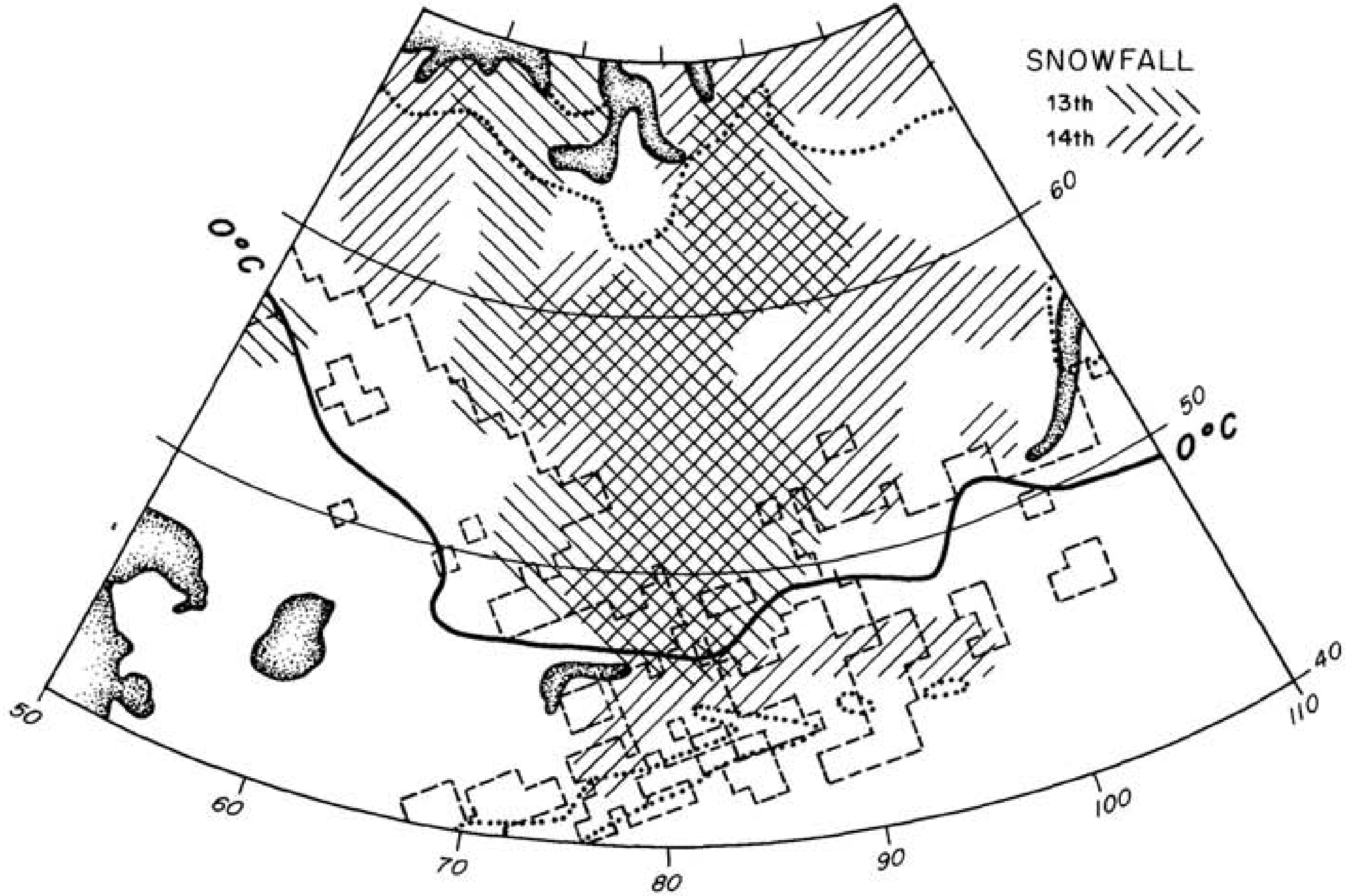

Figure 5. Areas of snowfall reported by WMO ground stations at 00 Gmt (see figure 4A for location) on October 13 and 14 (hatched). Stations north of the 0°C isoline had below freezing morning surface air temperatures on both days. The NOAA/NESS snow outline is dotted, the Air Force dashed. Lakes are stippled.

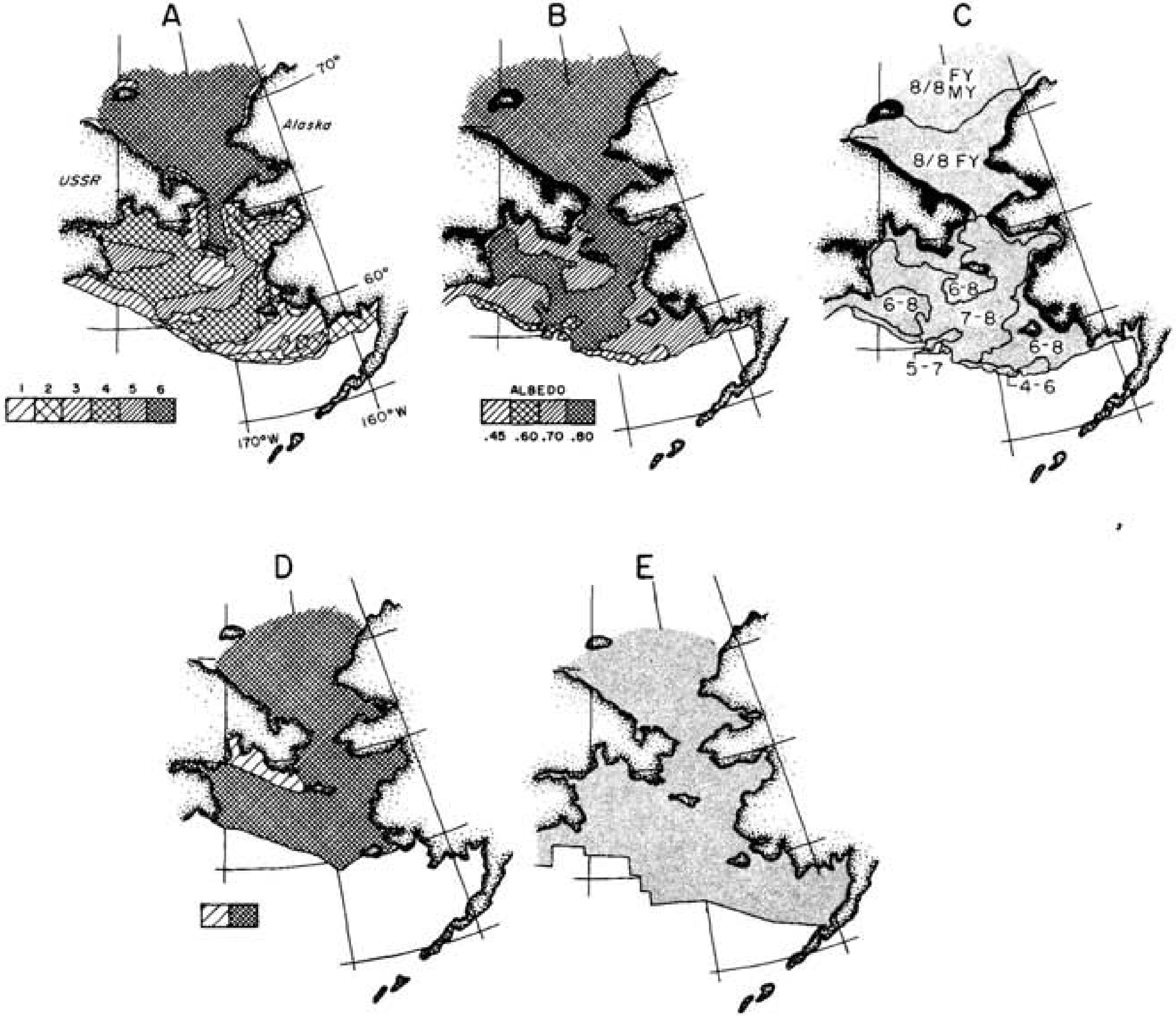

Figure 6. Sea ice extent, concentration, and surface reflectivity in the Bering Sea in March 1978. Lamont chart (A) is constructed from the NOAA/VHRR visible and infrared imagery taken on the 21st. It shows lowest (1) to the highest (6) relative reflectivity. The Navy chart (C) for the three days ending 21 March shows snow concentration in octas. FY is first-year ice. MY is multi-year ice. Albedo estimated from the Navy product by the method of Kukla and Robinson (1980) is shown in (B). The NOAA chart for the week ending 19 March (D) has reflectivity classes the same as in figure 3. Air Force chart for the week ending 20 March (E) shows stippled area with snow over 10 in. thick.

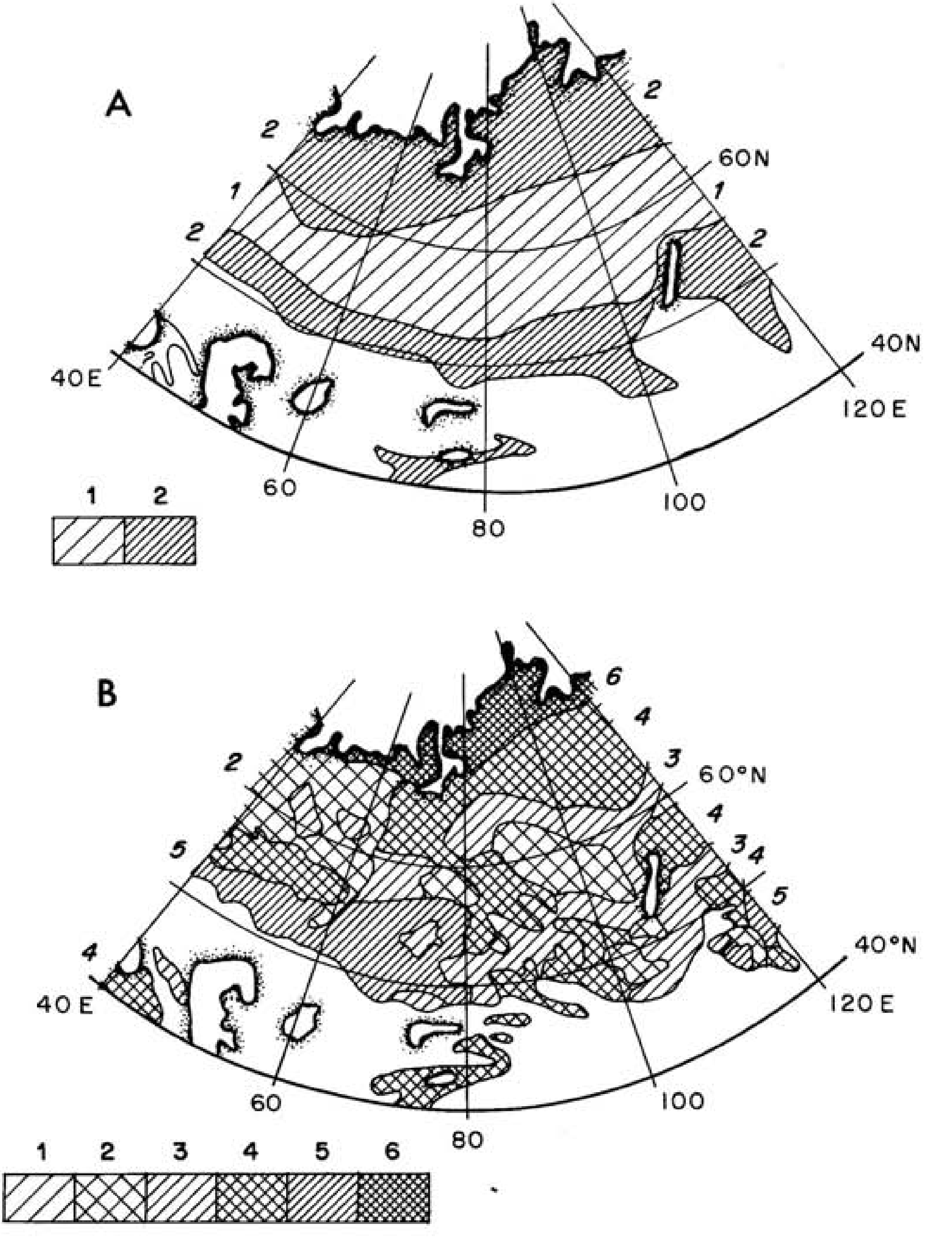

Figure 7. Relative reflectivity of snow cover as shown by Lamont (B) and NOAA (A) for the week ending 29 March 1970. NOAA reflectivities are the same as in figure 3. Lamont reflectivities form 1 (low) to c (high) are described in Kukla et al., p. 87 this volume. Corresponding albedo estimates are shown in table 4.

series. The charts produced after 1973 show the distribution of relative brightness fields in much greater detail. Using the approximate estimates of average surface albedo values corresponding to the NOAA and to the Lamont classes (table 4), the surface albedo of the studied segment is 39 percent from the NOAA and 50 percent from the Lamont product. This large discrepancy is caused by the highly generalized boundaries and high range of albedo values corresponding to reflectivity class 2 in the early NOAA products (pre-1973).

Mountainous zones present a quite complicated surface albedo distribution (figure 3). This is, firstly, because of the irregular and patchy form of the snowfields and, secondly, because of the intricate interfingering of dense forests, bare basins, rocky slopes, and alpine tundras. In the example shown, the snow outline is relatively accurately delimited in the Lamont chart for the 16th of March, but highly generalized in the NOAA/NESS and the Weekly Weather and Crop Bulletin products. The relative reflectivity of the snow fields in the NOAA/NESS chart is overestimated.

The Albedo of Ice Fields

The shortwave albedo of a bare ice surface ranges from about 8 to 60 percent. A fresh snow cover only a few millimeters thick is sufficient to raise the ice albedo to over 80 percent. The potential impact of this variability on climate is obvious. Unfortunately, except for NOAA snow and ice cover charts, no attempt has been made to chart the sea ice albedo changes on a regular basis.

An example of the relative reflectivity distribution of the sea ice cover in the Bering Sea is shown in figure 6. The relative brightness of the sea ice in 6 grades was charted at Lamont (A) from the NOAA-VHRR satellite images in the visible band. This product is compared with the NOAA/NESS representation of the same areas distinguishing two classes of relative reflectivity (D). It appears that NOAA class 1 correlates with the Lamont classes 3 and 4, whereas the darker ice is not shown at all in the NOAA product. The ice concentration classes shown in the weekly operational product of the Navy (C) are transformed into an albedo index (B) after a formula described in Kukla and Robinson (1980). The Air Force (E) reported more ice than was actually present and the ice is charted as if covered by snow at least 10 inches thick. Independent data on snow depth on top of the ice are not available, so the corresponding accuracy of the Air Force chart cannot be established.

The albedo index in version B is higher than the estimated reflectivity in the product A. A comparison of variants A and C shows that this is due to the fact that the ice concentration does not accurately correlate with the brightness distribution.

A considerable change of surface albedo of the Arctic ice occurs in summer. From the end of June through the second half of August, the snow on top of the ice melts and develops puddles of meltwater. The few published measurements taken at ice floe stations indicate that the regional albedo of such a surface drops from about 80-85 percent to 50-60 percent or less. No data yet exist on the areal extent and intensity of the summer melt on top of the Arctic ice and on its seasonal and year-to-year variability. Frequent clouds reduce the utility of satellite imagery in visible bands. There is a potential for microwave charting of the summer melt progression, but no demonstration was yet made of an operationally applicable method.

Table 4. Albedo of March 29, 1970 central Asia sector (figure 7) derived from NOAA and Lamont reflectivity classes.

Class	Percent of Snow Covered Area	Average Albedo: Percent	Albedo of Snowcovered Region: Percent
LAMONT			
2	30.6	32	
3	23.6	43	
4	35.3	54	
5	13.2	65	
6	7.4	75	50
NOAA			
1	43.0	30	
2	57.0	45	39

Snow Thickness

Several national agencies produce daily, weekly, and monthly snow depth charts for different parts of the Northern Hemisphere. The British Meteorological Office in Bracknell produces comprehensive snow depth charts of the whole Northern Hemisphere. However, the spatial variability of snow depth is so large that a reliable regional parametrization based on ground station data is next to impossible.

Figure 8 shows the mid-month depth in February 1977 in Ohio. The thickness measured at ground stations is shown for February 14 (C). This is also the date of the Weekly Weather and Crop Bulletin chart (D), and the Air Force snow depth chart (E).

Determination of the snow thickness from the relative reflectivity of a snow field was attempted by McGinnis et al. (1975) who found increasing regional brightness with increasing depth of fresh snow. A thickness greater than about 25 cm resulted in little further increases of albedo. In our example from Ohio, the forested area (B) in the eastern and southeastern portion of the state displays a low brightness, even though the snow is relatively thick, while farmland with only 3-5 cm of snow displays a high surface albedo. If the parametrization of the real snow depth in a flat or moderately hilly region, such as Ohio, causes serious problems, then in the mountainous regions the task is next to impossible.

Figure 3 illustrates how inadequate the data spacing is reported by the Weekly Weather and Crop Bulletin and by the Air Force in the western United States given the high regional variability of the snow depth. In selected mountain ranges, state hydrologic services collect and evaluate data on the snow thickness and water equivalent. However, even if the existing network were used, it is not dense enough to substantially upgrade the continental or hemispheric snow depth charts.

Snow Cover Changes in Time

The snow-and ice-covered area in the Northern Hemisphere changes from about 10 million km^2 in summer to about 60 million km^2 in winter (Kukla and Kukla, 1974; Kotliakov and Krenke, 1981). Between September and December, it increases by about 40 million km^2 in less than 90 days. Thus, a single day represents almost 1 percent of the total seasonal change from a summer to a full winter condition.

Obviously, any meaningful monitoring of snow cover variability for climate related studies must be accurately dated. Figure 9 depicts a huge change of the snow extent in Nebraska, Iowa, Kansas, and Missouri in a single day in March. Figure 2 shows similar large variations in regional snow cover within a single week in autumn and in winter. The day-to-day variability of snow cover in the middle latitudes may be large in all seasons. This fact may significantly influence the precision of the weekly and monthly snow cover charts.

We have tried to determine on which day of the week the charted information comes closest to the real situation. As stated earlier, we have independently charted, from satellite and ground station data, and measured the snow cover area in various parts of the United States. We did it for every day of the week and then compared our results with the area shown in the operational weekly maps (figure 2 and table 2). We found that the operational charts most accurately depict the snow extent on the last two days of a charted week. Our comparisons were done in relatively small blocks and compensations are likely on a hemispheric scale. Thus, the time accuracy of the operational charts is judged sufficient for use in global general circulation models. However, for regional studies considerable improvements are needed.

Results

The tests reported here and in Kukla and Robinson (1979) lead us to the following conclusions:

1. The NOAA snow charts for the 1966 to 1973 interval show snow boundaries with acceptable accuracy for large scale climate studies in winter, spring, and summer, but not in the fall. The information on the relative reflectivity of snow fields is inadequate throughout the year.

2. The NOAA charts from 1974 through 1980 show snow boundaries with acceptable accuracy for large-scale climate studies. However, users must keep in mind that snow fields under persistent clouds are systematically not shown, which leads to the under-representation of snow extent, particularly noticeable in autumn. The relative reflectivity of snow fields is depicted with acceptable accuracy for gross climate system studies on a hemispheric scale, but not on regional scales.

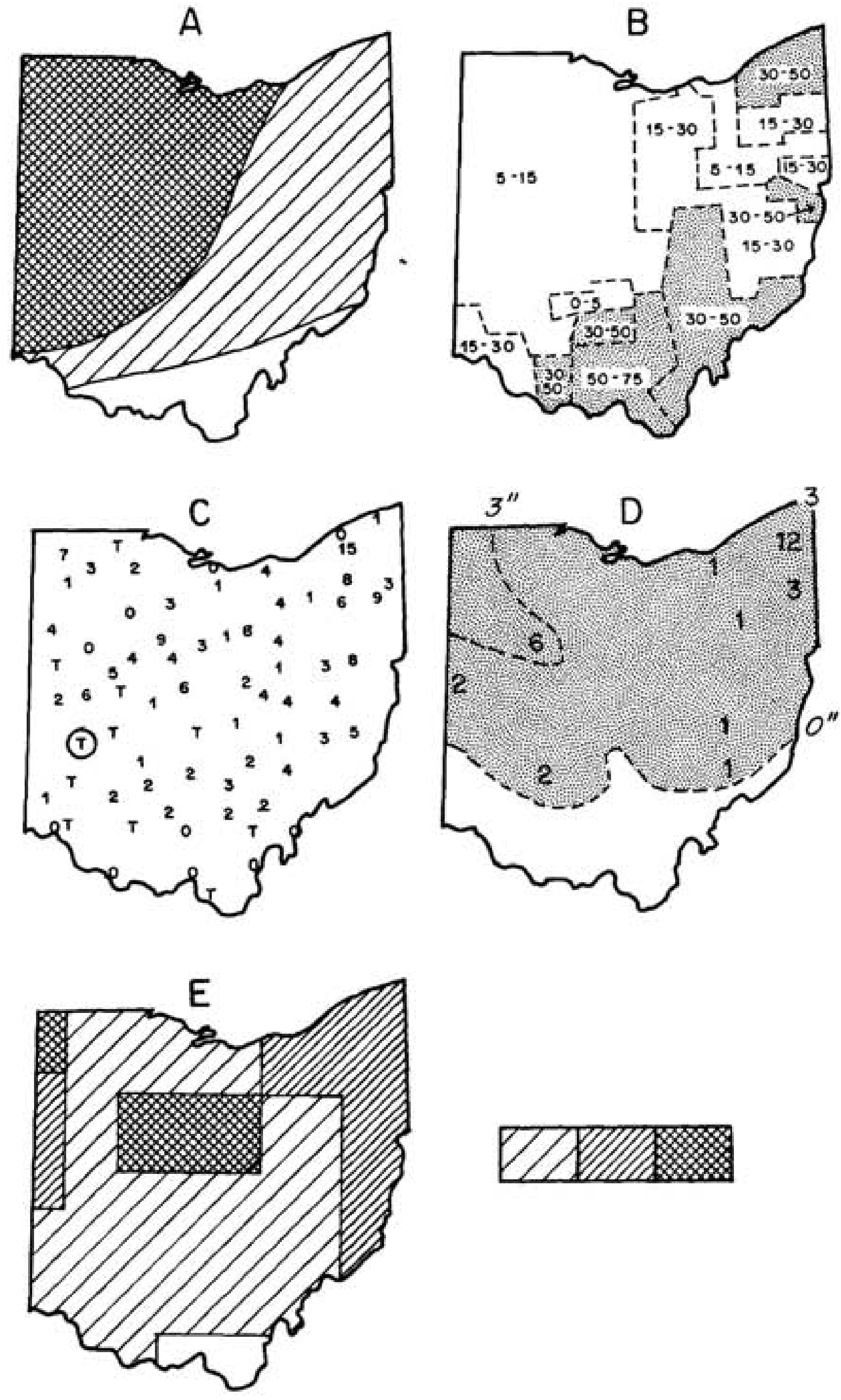

Figure 8. Snow cover in Ohio in mid-February 1977. The NOAA chart (A) for the week ending the 13th shows relative reflectivity the same as in figure 3. Reported snow depth in inches (C) from NOAA climatological data and from the Weekly Weather and Crop Bulletin (D) are shown for the 14. Air Force snow depth is the same as shown in figure 3 for the week ending 14 February. Percent of forest cover (B) is from the World Forestry Atlas (Wiebecke, 1971). WMO stations reporting snow depth are circled in (C).

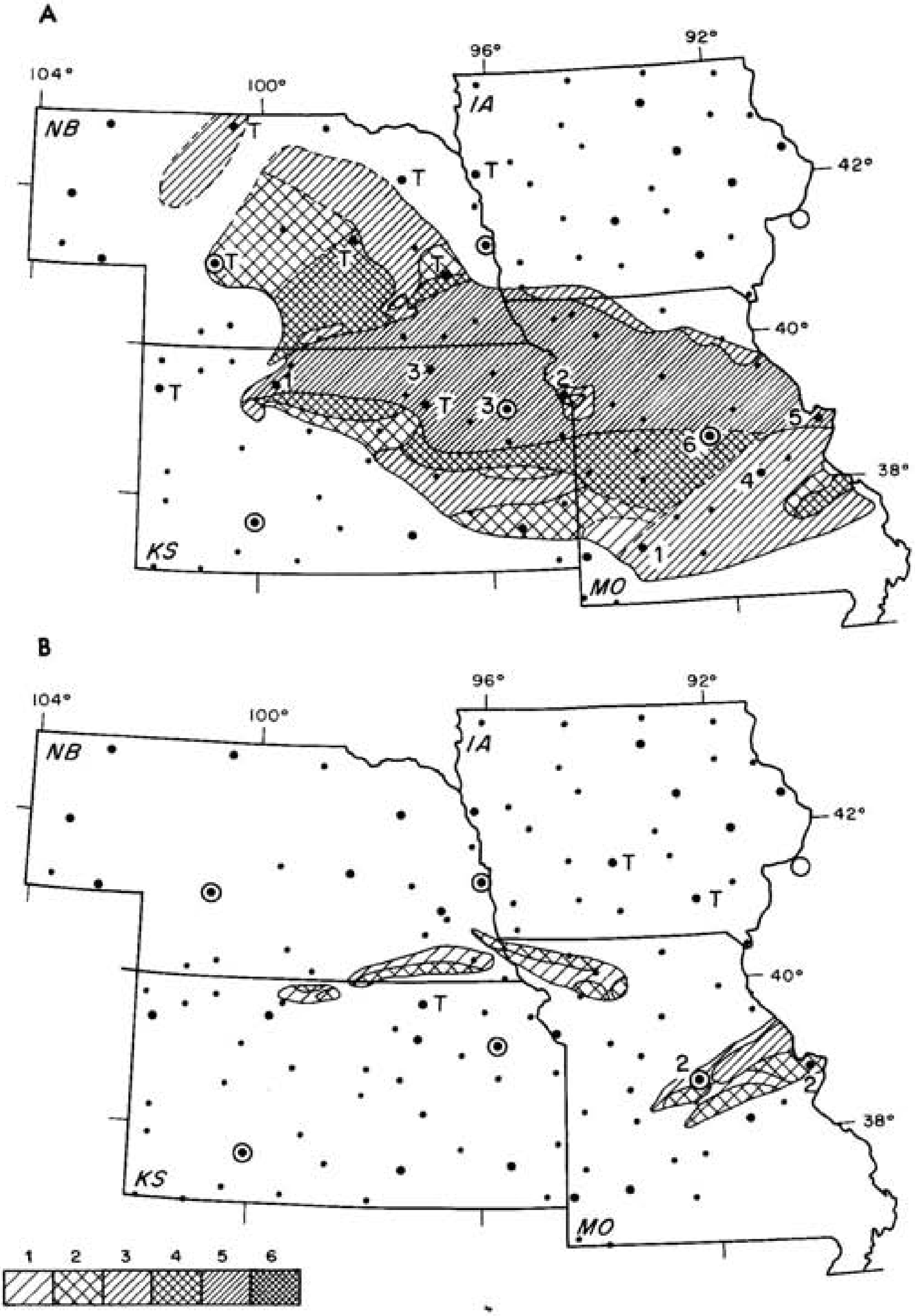

Figure 9. Snow cover in the central U.S. on 16 March (A) and 17 March (B), 1976, constructed from NOAA, GOES, and VHRR imagery. National WSO stations are marked with large dots, WMO stations with circles. Those reporting snow on the ground give depth in inches.

3. The Navy and NOAA/Navy operational sea ice charts present, with sufficient accuracy for climate studies, the ice boundaries and the proportion of white or grey ice to dark ice and open water. Thin dark ice is frequently not distinguished from open water. Reflectivity is not reported, nor is any information given on the thickness and state of the snow on the ice.

4. The Air Force weekly snow depth charts in most cases overrepresent the snow cover extent, especially in the thickness class below two inches. They do not seem to reliably parametrize the real snow depth on a regional scale. They are less suited for climate-related studies involving albedo than the NOAA and Navy charts in winter, spring, and summer, but are the best existing operational source on snow edge position in autumn. We noted that the quality of the recent charts is considerably higher than those produced a few years ago.

Acknowledgements

We are grateful to the personnel of NOAA/NESS, the Navy, and Air Force, as well as to the DMSP Library in Madison, Wisconsin, for supplying us with needed charts and satellite imagery, and for many helpful comments and advice. We especially thank F. Smigielski, M. Matson, D. Wiesnet, E.P. McClain, R. Godin, and R. Woronicz. We are indebted to B. Dehn and N. Untersteiner for help and advice on sea ice charts, and to J. Gavin, R. Lotti, J. Brown, A. Gordon, and K. Hunkins for reading the manuscript. The research was supported by National Science Foundation grants ATM77-28522 and ATM80-01470. It is a Lamont-Doherty Geological Observatory of Columbia University Contribution.

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Digital Products and Snow Cover Indices
Introduction

In order to incorporate the snow cover data in numerical climate models, the NOAA charts are digitized as reported by Matson and Varnadore (p.123 this volume) and Dewey (p. 129 this volume). The digital products described in the aforementioned two contributions only recognize the snow-covered and snow-free modes. To transform such information into estimates of approximate surface albedo, the values derived from the maximum SAD index can be used as given in the contribution of Kukla and Robinson (p.135 this volume). They are compatible with the grid used by Matson, Varnadore, and Dewey and can be also obtained from the Lamont group on cards or on tape.

The Air Force snow depth charts are already produced in digital format as are the snow age charts. Information on the availability of this data is in the contribution by Woronicz, p.63 this volume.

Any eventual user of the digitized products should be aware of the limitations of the original input charts. The article by Kukla and Robinson (p.103 this volume) should be consulted in this respect.

John Walsh (p.139 this volume) discusses the data sets and the derived digital products describing the variability of sea ice. Different indices referring to the extent, albedo and the surface heat absorption in the snow and ice covered area are described by Kukla and Gavin (p.145 this volume). These are based on the NOAA and Navy charts, only a few of which were verified by the ground truth data. These indices collected along the 2° latitude bands were designed for studies of seasonal interaction between the snow and ice fields and incoming radiation.

The Editors

Kukla, G; Hecht, A.; Wiesnet, D. eds. (1981) SNOW WATCH 1980. Proceedings of the Workshop held 1-2 October 1980 in Washington, D.C. Boulder, Colorado, World Data Center A for Glaciology (Snow and Ice), Glaciological Data, Report GD-11, p.123-127.

Digitization of the NOAA/NESS Continental Snow Cover Data Base

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The NOAA/NESS Northern Hemisphere continental snow cover data base is approaching its fifteenth data year and, although not a climatology by strict definition, is being incorporated more frequently into climte modeling and diagnostic studies. In an effort to facilitate this integration, NESS, in conjunction with the University of Nebraska-Lincoln, has undertaken the digitization of the continental snow cover data base from 1966-1980. The Northern Hemisphere Weekly Snow and Ice Cover Chart (figure 1) is being digitized using a NMC I, J box grid overlayed on a polar-stereographic map. The grid selected is the same as that used for the satellite-based earth radiation budget atlas of Winston et al. (1979). After establishing the appropriate geography into the data base (figure 2) each grid box is designated snow-covered if the grid box has 50 percent or more snow cover; non-snow covered if there is 50 percent or less snow cover. The reflectivity classes are not digitized. An example of the computer printout display of a Northern Hemisphere snow cover map is shown in figure 3. Since latitude-longitude information is also provided for each grid box, it is possible to determine the true earth surface area of each box and in turn the snow-covered area of each continent (table 1) or a region of the continent. To enhance the display of snow cover on the computer printout, a microfilm product has been developed which allows the snow-covered areas to be displayed on an appropriate background geography (see figure 4). Although not shown here, a color microfilm map has also been developed with water as blue, land as green, and snow as gold. Archival of the digitized continental snow cover data will not only be on microfilm, but also on punch cards and computer-compatible tape. Complete documentation will be provided for all archived products and repositories of the archives will be the Environmental Data and Information Service (EDIS) of NOAA and World Data Center A for Glaciology (Snow and Ice). Archival should be completed late in 1981.

Operational digitization of the Northern Hemisphere Weekly Snow and Ice Cover Chart is now being performed by the Synoptic Analysis Branch of NESS using the same grid and procedure as that used for the historical data. Therefore the archival of digital continental snow cover will continue in the future, providing climate researchers with a format for analyzing snow cover compatible with other climate data bases.

Table 1. North America snow cover area

Year	Week	Area (x 10^7 km^2)	Percent of continent covered
1967	1	1.677	79.2
1967	14	1.338	63.2
1967	36	0.347	16.4
1971	10	1.635	77.2

Reference

Winston, J.S.; Gruber, A.; Gray, T.I.; Varnadore, M.S.; Earnest, C.L.; Mannello, L.P. (1979) Earth-Atmosphere Radiation Budget Analyses Derived from NOAA Satellite Data June 1974-February 1978. U.S. National Oceanic and Atmospheric Administration, 2v.

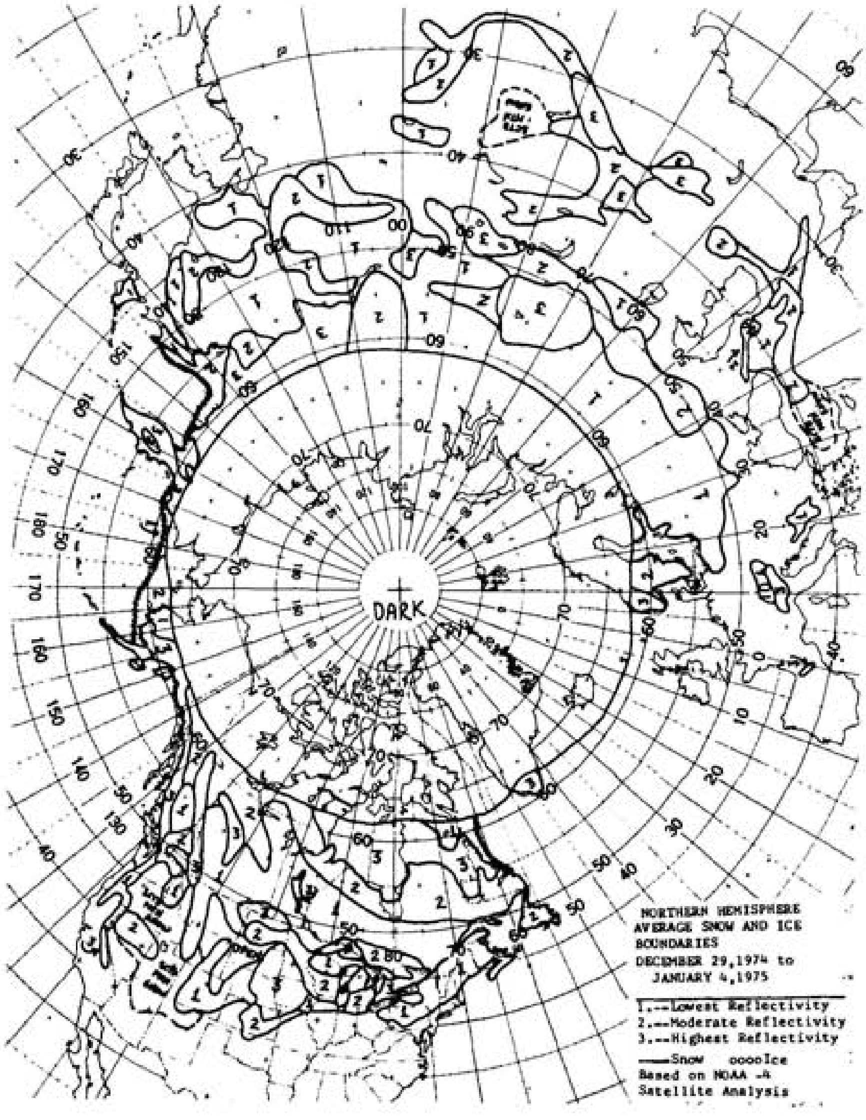


Figure 1. Snow and ice chart of the Northern Hemisphere for the 7-day period 29 December 1974 through 4 January 1975 prepared by NOAA/NESS. Note the several classes of reflectivity and the areas of scattered mountain snow. Also note the "dark" area where visible data cannot be collected during the polar night.

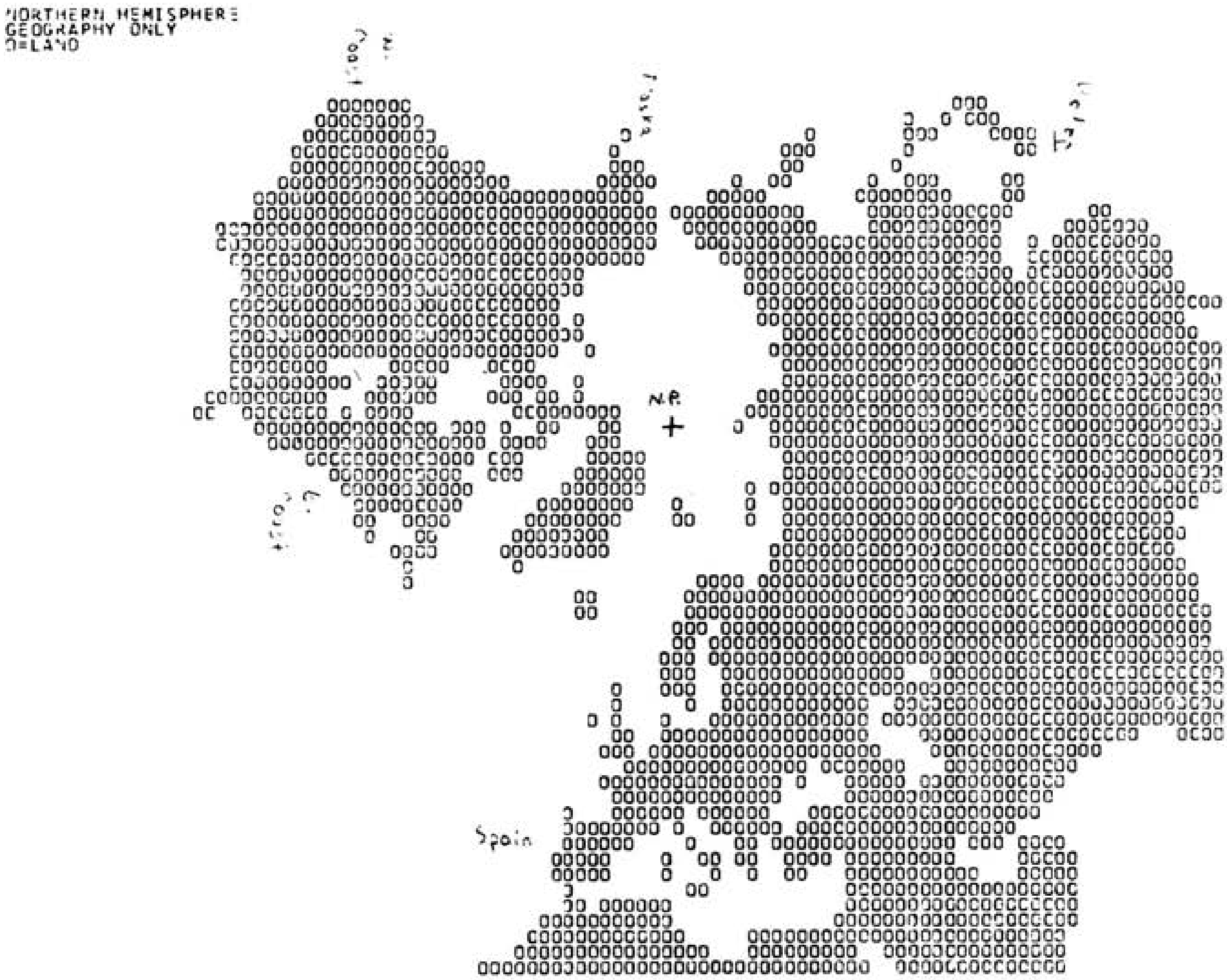


Figure 2. The digitized Northern Hemisphere geography. North America is to the reader's left, Eurasia is to the right. N.P. is the North Pole.

NORTHERN HEMISPHERE
SNOWCOVER
O=BARE GROUND, X=SNOW

YEAR = 1967 WEEK NO. = 1: JAN. 2-8

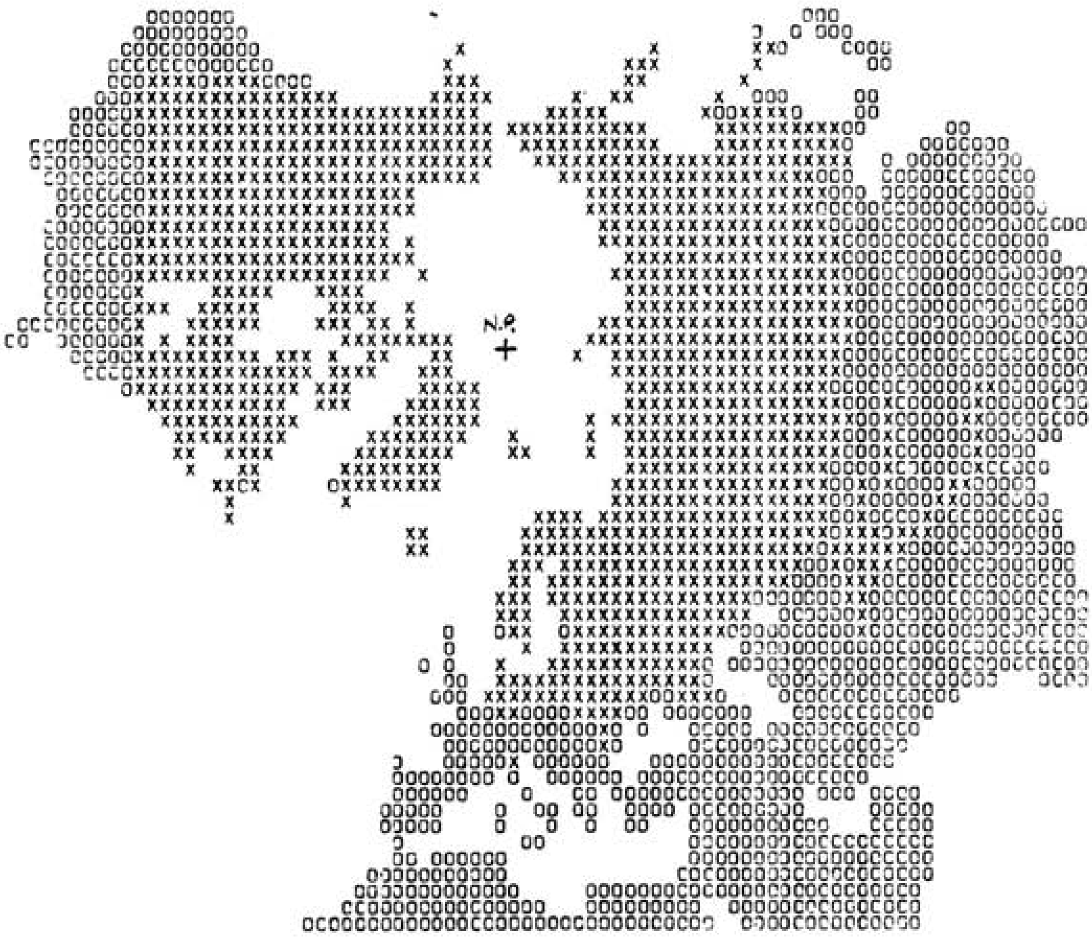
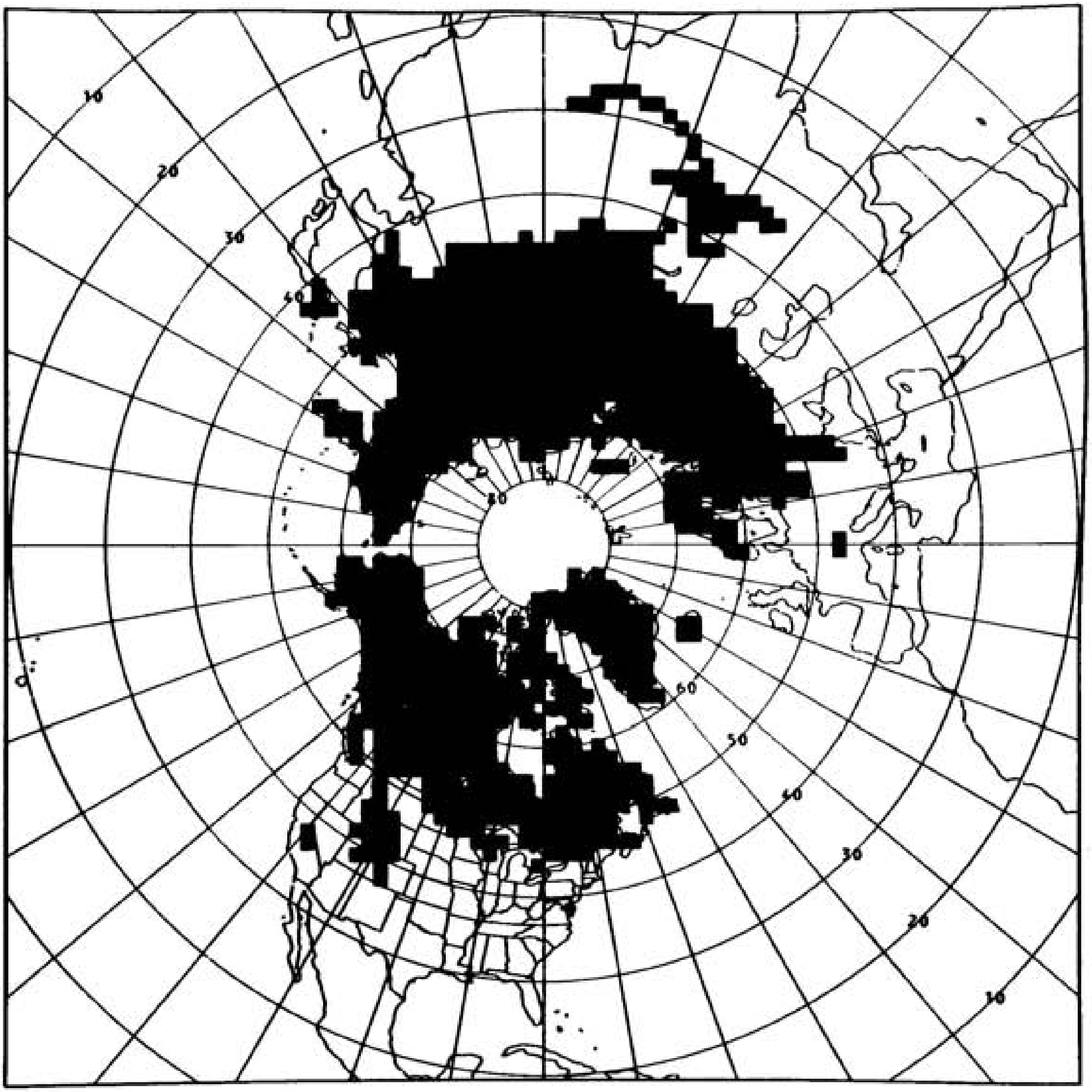


Figure 3. A digitized Northern Hemisphere snow cover chart for the period 2-8 January 1967. North America is to the reader's left, Eurasia is to the reader's right.



NOAA/NESS DECEMBER 1979 MONTHLY MEAN SNOW COVER

Figure 4. A microfilm product displaying Northern Hemisphere snow cover for December 1979. The snow cover shading can also be displayed as various gray tones rather than black.

Kukla, G; Hecht, A.; Wiesnet, D. eds. (1981) SNOW WATCH 1980. Proceedings of the Workshop held 1-2 October 1980 in Washington, D.C. Boulder, Colorado, World Data Center A for Glaciology (Snow and Ice), Glaciological Data, Report GD-11, p.129-133.

Snow Cover Digital Products

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Numerous researchers have argued that there is a significant interaction between the extent of snow cover and synoptic-scale atmospheric conditions. One of the limiting factors in a study of this interaction has been the lack of digitized snow cover data. The Climatology program at the University of Nebraska-Lincoln received a research grant from the National Earth Satellite Service which has resulted in the digitization of all Weekly Snow and Ice Charts back to 1966. Figure 1 is an earlier chart produced in 1967. See Smigielski (p. 59 this volume) for a recent chart. A comparison of these two charts reveals that an increased amount of detail is now appearing on these products. Accepting the fact that detail is now appearing on these products. Accepting the fact that detail and accuracy have probably improved through time, we also recognize that this is the only complete record of Northern Hemisphere snow cover dating back to the 1960's. Therefore, a decision was made to retain all charts and to digitize the complete set.

An I, J matrix overlay (based upon the NMC grid) was provided by NESS and utilized in the digitization of each of the snow and ice charts. Figure 2 illustrates this grid centered over North America. Any individual grid box was indicated to be snow or ice covered if, through visual interpretation, at least 50 percent of the box was marked in the chart as covered by snow or ice. The format that the data are stored in is presented in table 1. The left-hand portion of this figure presents a sample of the data in raw form and the right hand portion includes a summary of this data. The sixth entry, for example, reads 1967013004164548526060636 6 which can be read to mean 1967, first week, row 30, 4 snow patches along the row at J 16-45, 48-52, 60-60, and 63-66. The display of the digitized product is illustrated in figure 3 for the entire Northern Hemisphere. The data are stored by continent so it is possible to have, for example, just a display of Eurasia or North America.

Table 1. Format of the snow cover digitized data.

	Year	Week No.	Row No. (I)	No. of Patches	J Range of Each Snow Patch
196701260341415656646 5	1967	1	26	3	41-41,56-56,64-65,
19670127034040545664 64	1967	1	27	3	40-40,54-56,64-64,
1967012805172022254042545562 63	1967	1	28	5	17-20,22-25,40-42,54-55,62-63,
1967012905163139435050535561 61	1967	1	29	5	16-31,39-43,50-50,53-55,61-61,
19670130041645485260606366	1967	1	30	4	16-45,48-52,60-60,63-66,
196701310217556170	1967	1	31	2	17-55,61-70,
196701320217566170	1967	1	32	2	17-56,61-70,
19670133011771	1967	1	33	1	17-71,
19670134011768	1967	1	34	1	17-68,
19670135011769	1967	1	35	1	17-69,
19670136011768	1967	1	36	1	17-68,
19670137011769	1967	1	37	1	17-69,
19670138011670	1967	1	38	1	16-70,
19670139011670	1967	1	39	1	16-70,
19670140011670	1967	1	40	1	16-70,
196701410216162271	1967	1	41	2	16-16,22-71,
196701420216182171	1967	1	42	2	16-18,21-71,
196701430216172071	1967	1	43	2	16-17,20-71,
1967014403161618182071	1967	1	44	3	16-16,18-18,20-71,

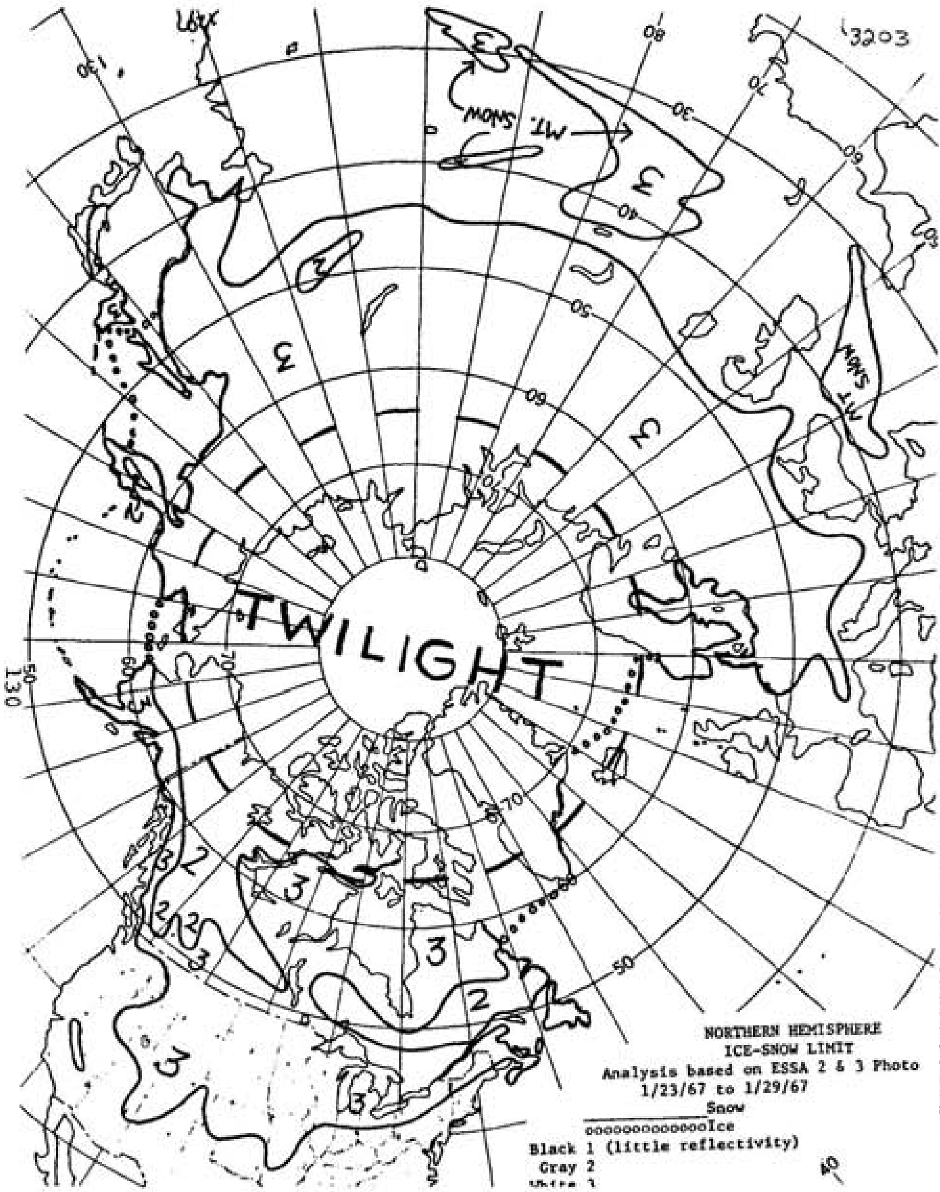

Figure 1. Weekly snow and ice chart, 23-29 January 1967.

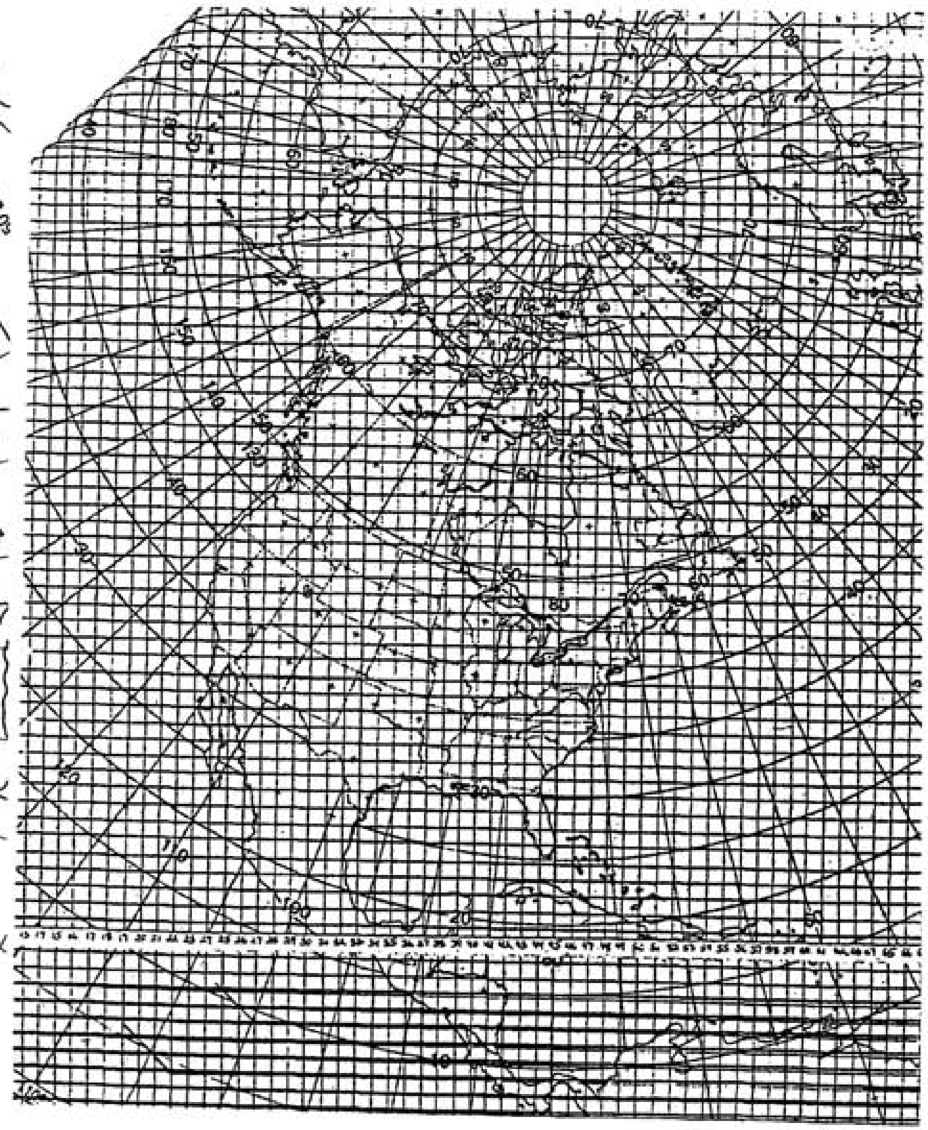

Figure 2. A portion of the grid overlay utilized in the digitization process. The grid is centered over North America.

Table 2. Variation in grid box area (J-1 in the sub-tropics and J-44 near the pole).

I	J	AREA (SQ. KM.)	I	J	AREA (SQ. KM.)
43	81	0.230483E 05	44	21	0.310920E 05
43	82	0.225669E 05	44	22	0.319808E 05
43	83	0.216040E 05	44	23	0.328696E 05
43	84	0.211226E 05	44	24	0.333140E 05
43	85	0.206638E 05	44	25	0.342028E 05
43	86	0.197463E 05	44	26	0.348208E 05
43	87	0.192876E 05	44	27	0.351298E 05
43	88	0.188288E 05	44	28	0.357479E 05
43	89	0.183701E 05	44	29	0.363659E 05
44	1	0.188288E 05	44	30	0.366750E 05
44	2	0.192876E 05	44	31	0.372930E 05
44	3	0.197463E 05	44	32	0.378685E 05
44	4	0.206638E 05	44	33	0.384439E 05
44	5	0.211226E 05	44	34	0.387316E 05
44	6	0.216040E 05	44	35	0.393071E 05
44	7	0.225669E 05	44	36	0.398826E 05
44	8	0.230483E 05	44	37	0.403324E 05
44	9	0.235297E 05	44	38	0.406568E 05
44	10	0.244926E 05	44	39	0.408189E 05
44	11	0.249740E 05	44	40	0.411432E 05
44	12	0.259369E 05	44	41	0.414676E 05
44	13	0.263191E 05	44	42	0.417919E 05
44	14	0.270835E 05	44	43	0.421162E 05
44	15	0.274657E 05	44	44	0.422784E 05
44	16	0.282300E 05	44	45	0.422784E 05
44	17	0.286122E 05	44	46	0.421162E 05
44	18	0.293766E 05	44	47	0.417919E 05
44	19	0.297588E 05	44	48	0.414676E 05
44	20	0.306476E 05	44	49	0.411432E 05

NORTHERN HEMISPHERE SNOW AND
ICE COVER
C=GROUND, X=SNOW, I=ICE

YEAR = 1967 WEEK NO. = 1: JAN. 2-8

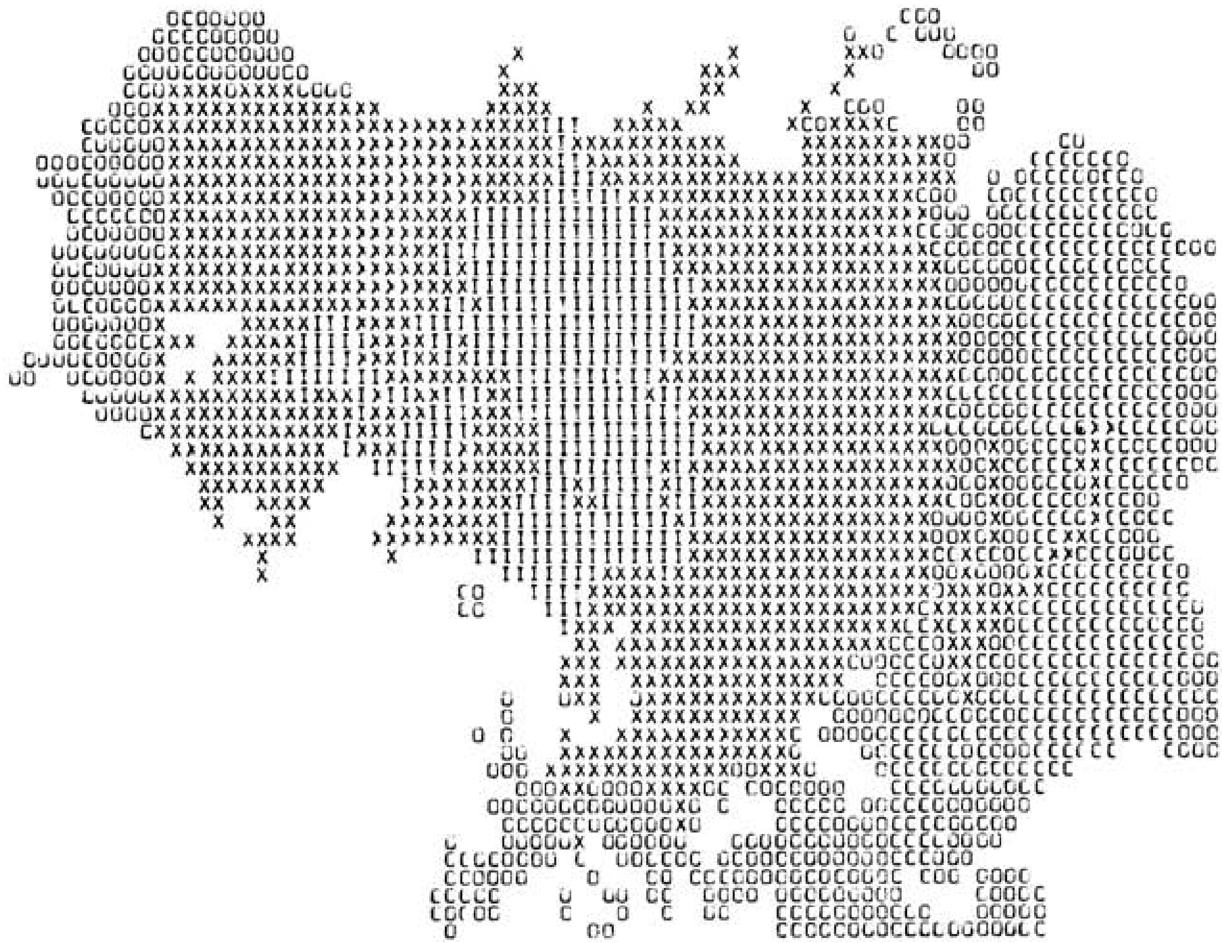

Figure 3. Digitized map for 2-8 January 1967 illustrating snow and ice cover for the Northern Hemisphere.

NORTH AMERICA
SNOWCOVER
O=BARE GROUND, X=SNOW

YEAR = 1967   WEEK NO. = 1: JAN. 2-8

Figure 4. Digitized snow cover map of North America for the first week in January (total areal coverage= 0.1677×10^8 km^2).

The weekly snow and ice charts are prepared in a polar projection, therefore the true geographic areal coverage of each grid box varies with latitude. Table 2 illustrates this variation along row (I) 44 from the sub-tropics (J-1) to the pole (J-44). The J values greather than 44 are the continuation of the row beyond the pole and equatorward. The variation in geographical area of each grid box varies along this row from a minimum of 0.188×10^5 km^2 to a maximum of 0.423×10^5 km^2. Utilizing this factor, the areal coverage of snow was determined for each chart. Figure 4 is the digitized map for North America for the first week of 1967. From this chart, and including the variation in geographical area enclosed in each grid box, it was determined that the North American snow cover was 0.1677×10^8 km^2.

The digitized data will be available through EDIS and the World Data Center-A for Glaciology (Snow and Ice). The format of these data will be data tape, hard copy, and punch cards.

Reference

Smigielski, F. (p.59 this volume).

Kukla, G; Hecht, A.; Wiesnet, D. eds. (1981) SNOW WATCH 1980. Proceedings of the Workshop held 1-2 October 1980 in Washington, D.C. Boulder, Colorado, World Data Center A for Glaciology (Snow and Ice), Glaciological Data, Report GD-11, p.135-138.

Maximum Snow Area Density Digital Product

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ABSTRACT

Maximum snow area density (SAD) of stable snow cover in six classes is shown for the Northern Hemisphere. Data are available in digitized form in the NMC grid.

The surface albedo (understood here as a reflective property) of land surfaces with stabilized winter snow cover differs according to: 1) the type, density, and distribution of the vegetational cover; 2) the relief roughness and attitude; and 3) the proportion of water bodies.

It has been shown that the surface brightness of a region covered by about 10 in (25 cm) of snow changes relatively little by additional snow deposition (McGinnis et al., 1975; Petzold, 1977). Time dependent variations in the surface albedo of such a snowfield are largely due to the changing directional and spectral distribution of the incoming radiation (Kukla, 1981), and to the occasional deposition of wet snow or icings in the shrubs and tree canopies. Except for forests in high latitudes or altitudes, such deposits are not frequent. In practice, any given area with a sufficiently deep snow cover will attain, in winter and spring, a characteristic surface albedo which will vary relatively little with time and with meteorologic conditions, as long as the surface air temperatures remain low. We refer to such an albedo as the maximum stabilized snow cover albedo (MASCAL).

Closely related to the maximum albedo is the maximum snow area density (MASAD), measured as the percentage of visible snow within the total analyzed area observed from nadir (see Kukla et al., p. 87 this volume).

The regional MASAD in autumn differs significantly from that in the spring. This is because water bodies freeze over late in the season and are mostly ice free and dark in autumn. On the contrary, they would stay ice and snow covered late in spring even when the snow on surrounding land has dissipated.

Our MASAD reconstruction refers to late winter conditions with all the water bodies frozen and covered by snow. Snow depth is considered to be 10 in (25 cm) or more and the scene is observed about two days after the last snowfall. Snow on ground is partially obscured by vegetation or occasionally absent on steep sloping rock surfaces.

NOAA-VHRR, AVHRR, NOAA-GOES, and DMSP imagery were used in the analysis. An example of a DMSP satellite scene with full winter snow cover is in figure 1. In the few regions where snow depth specifications were not met, we reconstructed the maximum SAD by examining satellite imagery with a thin or missing snow cover, and vegetation atlases. Figure 2 shows the MASAD in the Northern Hemisphere in six classes.

Table 1 gives the median SAD and the estimated mean surface albedo for each charted class. We made a first order estimate of the mean surface reflectivity for each of the six SAD classes by assuming the average reflectivity of snow-free areas as 15 percent and fully snow-covered areas on land as 70 percent. The only exception is class 6 where a reflectivity of 80 percent is assumed over all snow-covered ice surfaces and 75 percent over arctic tundra. The 70 percent value for classes 1-5 takes into account the fact that areas appearing to be 100 percent snow covered actually contain subpixel-size dark objects, such as patches of tall vegetation or protruding rock and soil surfaces.

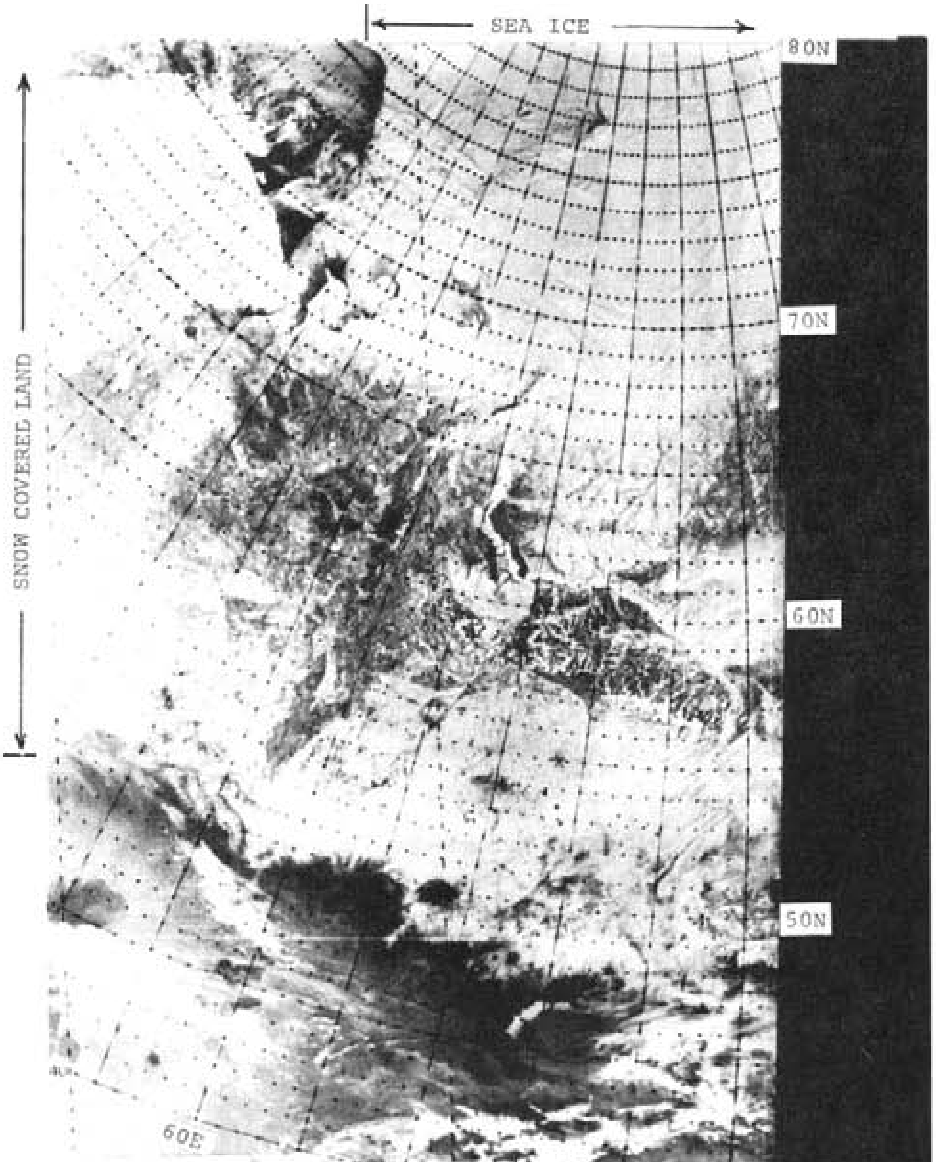

Figure 1. Snow covered section of Eurasia on 9 April 1979 as viewed by the DMSP (Defense Meteorological Satellite Program) satellite. Observe the low albedo of forested zones in the center of the picture.

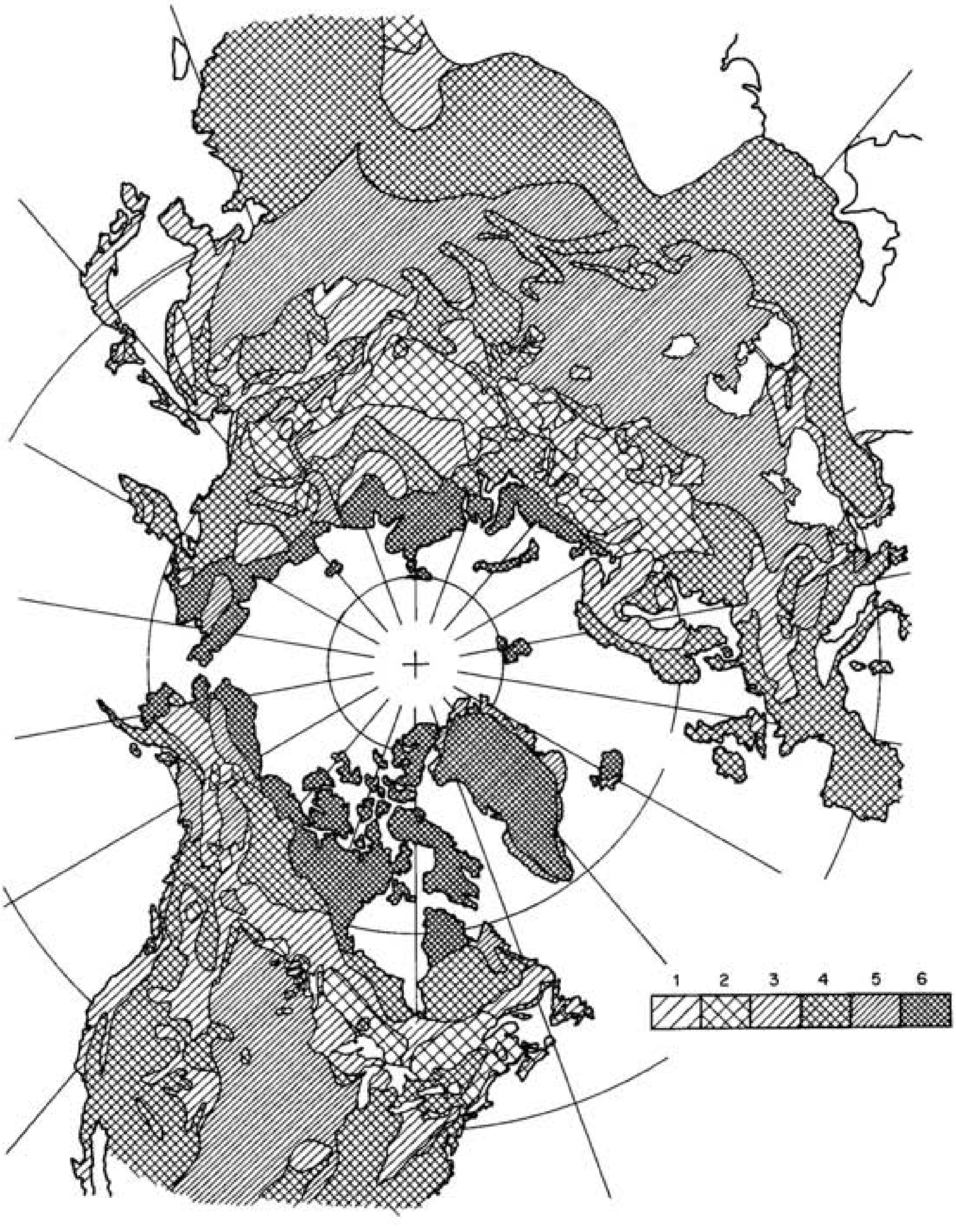

Figure 2. Maximum SAD (Snow Area Density) for portions of the Northern Hemisphere where snow cover can form. Classes are explained in table 1.

The SAD is a relatively objective and reproducible measure. With our newly acquired image processor, we plan to improve the estimates and provide a more accurate correlation with actual surface albedo values.

The digital tables, available at Lamont, present SAD class values for each grid box of a WMO 1/2 mesh grid, the same as used by Matson and Varnadore (p.123 this volume) and Dewey (p.129 this volume). The value for each grid box was determined from figure 2 by visually choosing the dominant class. This was done twice independently, and conflicting results were checked a third time.

At present our chart and tables represent the most complete and realistic assignment of maximum winter surface reflectivity of a mature snow cover on a hemispheric scale. Digitized data can be obtained from the author and can be used in combination with the digital product of Matson and Varnadore (see p.123, this volume) and of Dewey (see p.129, this volume), to assess the impact of the week-to-week variation of the snow cover extent on surface albedo. They also show which parts of the land exhibit the largest albedo change under the snow cover and have therefore, the highest sensitivity to the snow modulation.

Table 1. Maximum snow cover properties.

Class	Snow Area Density (SAD) (Percent)	Estimated Average Reflectivity (Percent)
1	10	21
2	30	32
3	50	43
4	70	54
5	90	65
6	100	80*

*75 over Arctic tundra in high latitudes.

References

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Kukla, G.; Robinson, D.A.; Brown, J.H. (p. 87 , this volume).

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McGinnis, D.F., Jr.; Pritchard, J.A.; Wiesnet, D.R. (1975) Snow depth and snow extent using VHRR data from the NOAA-2 satellite. U.S. National Oceanic and Atmospheric Administration. Technical Memorandum. NESS 53, p.1-10.

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Snow and Ice Data Sets

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The following is a summary of data sets describing the variability of sea ice. Since snow cover is the primary focus of this workshop, sea ice data sets are pertinent to the extent that sea ice serves as a platform for snow cover over the oceans. Aside from its association with snow cover, sea ice is a potentially important climatic variable in its own right.

The information summarized in the following tables has been obtained primarily from Glaciological Data, Report GD-5 and GD-7, which is published by the World Data Center A for Glaciology.

Three types of data sets will be distinguished: 1. regional data sets and indices describing ice variability over the synoptic scale; 2. hemispheric or global data sets in which there is some information pertinent to sea ice, but in which ice variability is not the major concern; and 3. hemispheric/global ice data sets directed specifically at sea ice variability. The last two categories should generally be most appropriate for large-scale climatic studies. The following summary does not include a number of "raw" data sets or operational charts which may serve as a basis for various "derived" data sets included in the tables.

1. Regional Data Sets

The regional data sets include a variety of ice indices and various sets of ice charts. Since ice indices often represent syntheses of ice information into one number per year for a particular region, they may be loosely regarded as digital ice products. As shown in table 1, these indices depict ice conditions in a variety of areas from the late 1800's to the 1970's. Although the reliability or representativeness is likely to be highly variable from one index to another, a host of indices are evidently available for studies of ice variability on the decadal time scale.

The various historical series of regional ice charts are summarized in table 2. With the exception of part of the Canadian set, these sets of charts are generally available only in map form. Regional data sets have, however, formed the basis for several of the digitized data sets summarized in Section 3.

2. Hemispheric/Global Data Sets in Which Variability is a Secondary Concern

The data sets summarized in table 3 have been compiled primarily for use in studies of snow cover. However, sea ice extent is depicted on each set of charts by either a plotted "boundary" (AFGWC) or by brightness levels over the high-latitude oceans. The second listed data set (NOAA/NESS brightness charts) will soon be available in digital form (See p.129, this volume). The primary advantage of these sets of products is their hemispheric coverage, although darkness often limits the informational content in polar latitudes during winter.

3. Hemispheric/Global Digital Ice Products

Table 4 contains the sea ice data sets that are most suited to climate-ralated analyses. While the advantageous features vary from one data set to another, there is a general trade-off between the record length and resolution/reliability.

Several pairs of complementary data sets can be distinguished in table 4. The East Anglia and Illinois data sets have been compiled on identical (1° latitude) grids and together cover the entire twentieth century (overlap years are 1953-1956). However, the reliability and inhomogeneity of the data present substantial problems through all but the most recent years.

The Arctic grids of the Max Planck data set are digitizations of the monthly charts compiled by the British Meteorological Office. Similarly, the Antarctic grids of the Max Planck set were digitized directly from the NAVY/NOAA Antarctic ice charts.

Table 1. Sea ice data for the Northern Hemisphere (from Kelly, 1979, p.104).

LOCATION	PARAMETER	PERIOD	SEASON	SOURCE
Arctic Ocean (eastern)	Weighted total of ice in Greenland, Barents and Kara Seas.	1895-1924	April-August	Brooks and Quennel (1928)
Arctic Ocean (eastern)	Index of ice severity in Greenland and Barents Sea and around Spitsbergen.	1897-1938	January-December	Walker (1947)
Kara Sea (a)	Area	1895-1915	April-August	State of the Ice in Arctic Seas: Supplement (1917)
(b)	Severity index	1868-1946		Nazarov (1947)
Barents Sea (a)	Area	1895-1915	April-August	State of the Ice in Arctic Seas (1917)
(b)	Area	1900-1960	April-August	Maksimov, Smirnov and Vorob'ev (1964)
Greenland Sea (a)	Area	1877-1915	April-August	State of the Ice in Arctic Seas: Supplement (1917)
(b)	Area	1924-1968	April-August	Kirillov and Khromtsova (1972)
Iceland	Weeks per year with drift ice on coast	1600-1975	October-September	Lamb (1977), Kock (1945), Thorarinsson (1956)
Baltic (a)	Date of final opening of Port Riga	1530-1958		Lamb (1977)
(b)	Maximum area	1720-1957		Betin and Preobazensky (1959),
(c)	Number of days with ice	1763-1926		Speerschneider (1915, 1927)
West Greenland	Northward extent of "Storis"	1821-1939		Koch (1945), Lamb (1977)
Newfoundland	Index based on maximum eastward and southward extent of ice	1920-1973	April	Miles (1974)
Western Atlantic: icebergs (a)	Severity index	1886-1939	March-July	Walker (1947)
(b)	Number of icebergs south of 48°N.	1900-1976	September-August	U.S. Coast Guard
Baffin Bay	Date of clearing	1952-1974		Keen(1977), Dunbar (1972)
North Slope, Alaska	Severity index	1953-1976	Summer	Barnett (1978)
Okhotsk Sea	Anomaly of drift ice period (days) at (a) Abashiri (b) Shana	1892-1945		Sawada (1957)

Table 2 Regional ice data sets (maps, charts).

SOURCE	PARAMETER(S)	REGION	LENGTH OF RECORD	SPATIAL RESOLUTION	TEMPORAL RESOLUTION	COMMENTS
U.S., NOAA	Ice concentration (tenths) Ice type, age (4 classes)	Great Lakes	1960 - present	5 km	Weekly	Currently being digitized by lake
U.S., NOAA/ NESS	Ice concentration Ice type, age (classes)	Alaskan waters (55°-80°N, 130°-180°W)	1973 - present	1-10 km	Weekly	Maps only; transmitted via facsimile
CANADA, ATMOSPHERIC ENVIRONMENT SERVICE	Ice concentration (tenths) Categories (3) of ice age, type, ridging-irregular	Canadian Waters I) Eastern Seaboard II) Hudson Bay & approches III) Eastern Canadian Arctic IV) Western Canadian Arctic	1960 - present		Weekly during period of ice variability	Map format and yearbooks; some digitized
DENMARK, DANSKE METEOROLOGISKE INSTITUT	Ice concentration (4 classes)	I) Northern Hemisphere	1900 - 1956		Monthly (April-August)	Maps only; "Yearbooks" include descriptive text
		II) Greenland waters (0°-60°W)	1957 - 1964		Weekly (not regular)	Maps only; most data from U.S. NAVOCEANO
NORWAY NORSKE METEOROLOGISKE INSTITUT	Ice concentration (octas); fast ice; sea surface temperature	North Atlantic (30°W-60°E)	1970 - present		3-4 days	Maps only
USSR ARCTIC AND ANTARCTIC RESEARCH INST.	Ice concentration	Soviet Arctic	1937 - present		5-10 days	Maps only; availability problematic

Table 3. Hemispheric/global data sets - ice variability not primary focus.

SOURCE	PARAMETER(S)	REGION	LENGTH OF RECORD	SPATIAL RESOLUTION	TEMPORAL RESOLUTION	COMMENTS
U.S. AFGWC	Snow depth (inches)	Northern Hemisphere Southern Hemisphere	1975 - present	46km x 46km	Daily	Digitized
U.S., NOAA/ NESS	Brightness levels (3)	Northern Hemisphere	1967 - present	Charts and digital grids (2-4 X $10^4 km^2$)	Weekly	Charts; digitized set available 1981
U.S., NOAA/ NESS	Composite minimum rightness (CMB)	Northern Hemisphere Southern Hemisphere	1968 - present		5-Day ('68-'72) 10-Day ('74-present)	Charts only

Table 4 Hemispheric/global digital ice products.

SOURCE	PARAMETER(S)	REGION	LENGTH OF RECORD	SPATIAL RESOLUTION	TEMPORAL RESOLUTION	COMMENTS
U.S., NASA	ESMR brightness temperatures (2-3° categories)	Northern Hemisphere Southern Hemisphere 50°-Pole	1972 - present	50 km (293 x 293 grid)	3 Days	Charts and digital tapes; Atlas of Antarctic charts in press (Zwally et al., In Press)
U.S., LAMONT-DOHERTY	Area of snow/ ice percent open water w/i pack Derived indices (e.g., albedo)	Northern Hemisphere 30°-Pole / Southern Hemisphere 50°-Pole	1967 - present (snow) / 1972 present (ice)	Geographical regions-- 10°, 2° latitude	Weekly	Areal parameters and derived indices available digitally
U.K., EAST ANGLIA	Ice concentration (tenths)	Northern Hemisphere	1901-1956	60 n mi	Monthly	Gaps in space & time; variable data quality Unreliable data "tagged
U.S., U. OF ILLINOIS	Ice concentration (tenths)	Northern Hemisphere	1953-1977	60 n mi	Monthly	Variable data quality, esp. in 1950's and early 1960's Unreliable data "tagged"
U.S., NAVY/NOAA	Ice concentration	Northern Hemisphere	1972 - present	Charts	Weekly	Weekly charts; digitization in progress

Table 4. Hemispheric/global digital ice products (cont.).

SOURCE	PARAMETER(S)	REGION	LENGTH OF RECORD	SPATIAL RESOLUTION	TEMPORAL RESOLUTION	COMMENTS
U.K., BRITISH MET OFFICE	Ice concentration (4 categories)	Arctic, N. Atlantic	1960 - present		Monthly	Charts only (see Max Planck set) Large areas of "unreliable data" in early years Normals digitized
FEDERAL REPUBLIC OF GERMANY, MAX-PLANCK INSTITUT	Ice-covered area, 70 percent, in 10° longitudinal sectors	Arctic	1966 - 1976	10° longitude	Monthly	Digitized set of U.K. (B.M.O.) monthly charts, Northern Hemisphere
		Antarctic	1972 - 1976			Digitized set of U.S. Navy charts, Southern Hemisphere

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Snow and Ice Indices

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Indices

To investigate the impact of recent seasonal and interannual variation of snow and ice covers on the earth's heat budget, several indices are currently being generated on a weekly basis. These represent: 1) the area covered by snow or ice - S; 2) the percent of open water within the pack-ice - W; 3) surface albedo estimates for varying conditions of snow and ice cover - A_s; and 4) the energy absorbed by the surface under specified atmospheric conditions and solar angle - q (see table 1).

The primary data set consists of the areas of snow and ice classes as measured in each chart. An open water index, in percent, is calculated based on the proportion of open water within the pack-ice perimeter. The ice edge is delimited as having an average concentration of at least 1 okta.

A time series of reflectivity indices A_s (in percent) and of absorption index q (in Ly/day) are also produced. The former represents an estimate of total SW reflectivity in clear dry air and under a solar angle of 30°. Reflectivity is here understood as a property of the surface to reflect a specific portion of incoming radiation over the full short-wave range. In the computation of the A_s index, all snow-free land north of 30N is considered to have a reflectivity of 17 percent. The absorption index is an estimate of the amount of short-wave radiation absorbed by the ground or ocean based on indices S and A_s, with the ground level downward daily radiance total assumed to be equal to 0.4 of the insolation on the top of the atmosphere.

A total of 70 geographic segments in both hemispheres (figures 1 and 2) are assessed. The meridional divisions of the segments were designed so as to approach boundaries of major climatic provinces.

Table 1. Currently generated series of indices.

Length of Record	Indices	Interval	Method	Number of Recognized Classes	Principal Chart Source	Area
1967-Present	S	2 weeks	Planimeter	2	NOAA	Northern Hemisphere Snow & Pack-Ice*
1974-Present	S, A_s, q	Weekly	Grid-Count	6	NOAA	Snow**
1972-Present	S, W	Weekly	Grid-Count	7	U.S. Navy	Arctic Ice
1960-Present	S, W	Monthly	Grid-Count	5	British	Arctic Ice
1973-Present	S, W	Weekly	Grid Count	7	U.S. Navy	Antarctic Ice
1967-1972	S	Monthly	Grid Count	2	NOAA Satellite Images	Antarctic Ice***

Note: S = Area of snow or ice in km^2
W = Percent of open water within the pack-ice boundary

* Reflectivity classes unreliable. 1967-73 to be updated with the Lamont recharted climatic series.
** Reflectivity classes of poor quality.
*** Summer only

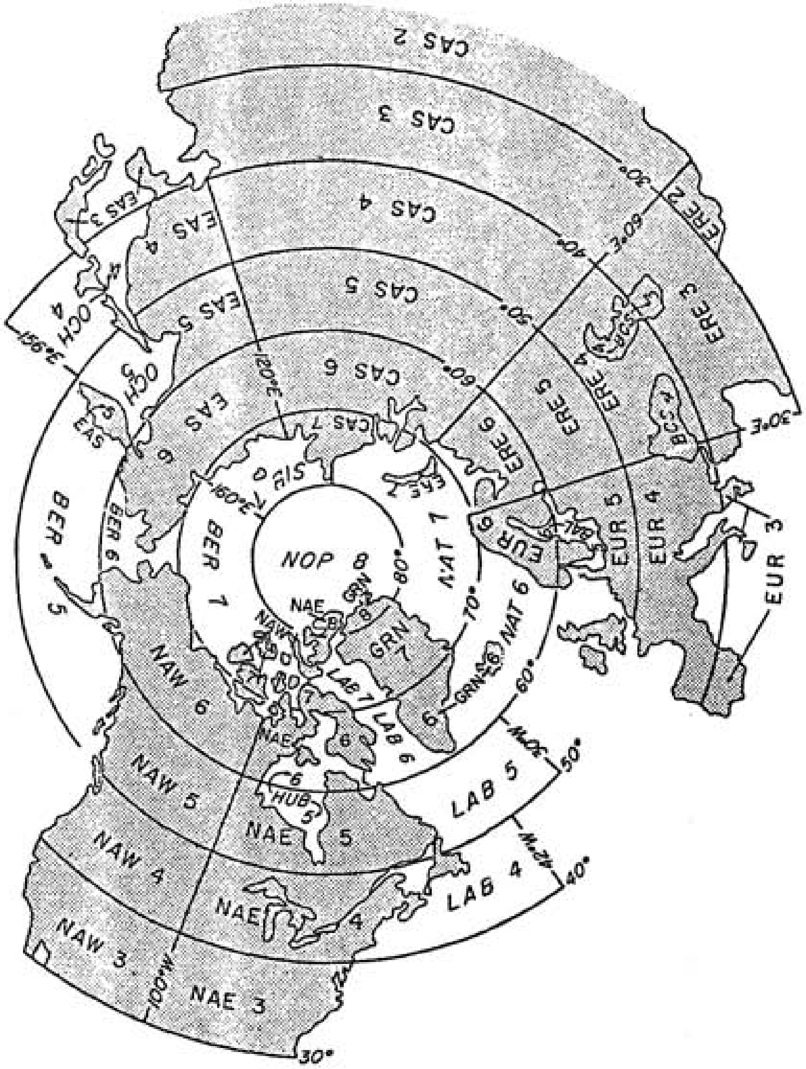

Figure 1. Geographic segments of the Northern Hemisphere.

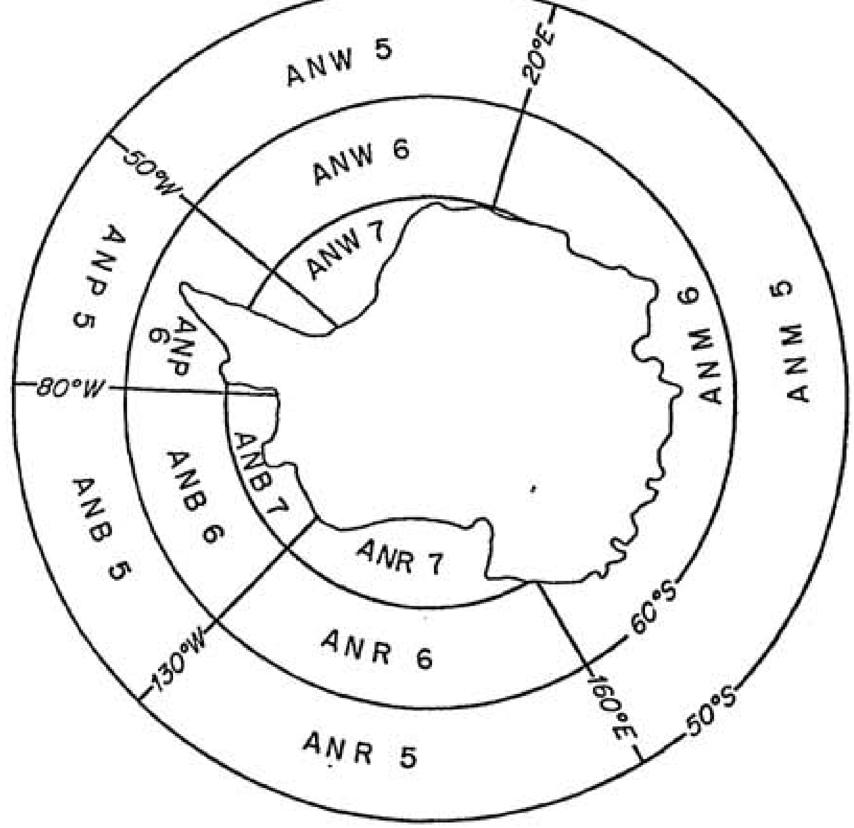

Figure 2. Geographic segments of the Southern Hemisphere.

Procedure

The data are obtained by analyzing charts produced primarily by the U.S. Navy and NOAA. Additional sources are used to either extend the information back in time or to make quality checks.

Measurement of the area is accomplished by counting grid points along latitudinal lines with the use of transparent overlays. The grid density for the Southern Hemisphere is 2° of longitude per 2° of latitude equatorwards of latitude 70° and 4° of longitude per 2° of latitude polewards of latitude 70°. For the Northern Hemisphere, it is 2° x 2° between latitudes 20-60, 2° of latitude per 4° of longitude between 60-80 and 2° x 8° north of latitude 80. Two counts are done independently for each chart. Areas covered in each 2° latitudinal belt within each meridional segment by recognized classes of ice concentration or snow reflectivity are separately recorded (see table 2). Longitudinal placement of individual classes of snow and ice concentration within meridional segments is not retained, as the principal use of the data set is to relate the changes of snow and ice to the seasonal shifts of insolation. In this context, we would like to call attention to the set of digitized Arctic sea ice charts for the end of each month in the 1953-1976 period of J. Walsh (1978; p.139 this volume).

A separate set of snow and ice cover indices was obtained by planimetering NOAA charts, irrespective of reflectivity grade, in latitudinal bands separately for five meridional segments as shown in figure 2. Data were produced in two week intervals. Scattered mountain snow was taken as one third of measured extent. The position of the pack-ice edge was revised using U.S., British, and Canadian ice charts.

Internal Consistency of the Records

The length of available records varies. In each of the series, the changing quality of satellite imagery and the improving skill of the interpreters has resulted in a gradually improving record over time. Several steps in the quality of the charts have been discerned. They result partly from improvements of satellite hardware.

Scale changes within a series should also be noted. Because of this situation, limits are placed on individual time series to assure sufficient uniformity of differentiated features (Kukla and Gavin 1979, 1979a, 1980).

Table 1 shows the time series currently being produced based on the above considerations.

The $\underline{S}$ indices for the Arctic and Antarctic ice and Northern Hemisphere snow are available at the World Data Center A for Glaciology. Indices $\underline{A_s}$, $\underline{W}$ and $\underline{q}$ will be available at the Data Center at a later date.

Table 2. Ice concentration and snow reflectivity classes.

Recognized Ice Classes	Corresponding U.S. Navy Chart Classes (Octas)	Corresponding U.S. Navy Classes (Tenths)
00	Open Water Outside Pack-Ice Boundary	Open Water Outside Pack-Ice Boundary
0	Open Water Within Pack-Ice Boundary	Open Water Outside Pack-Ice Boundary
1	0-2, 1-2, 1-3, 2-4	1-3, 2-4
2	3-4, 3-5, 4-5, 4-6	3-5, 4-6, 4-7, 5-7, 4
3	5-6, 5-7, 6-7	6, 6-7, 5-8, 6-8, 7-9
4	6-8	8-9, 8-10, 9
5	7-8, 8-8, Fast Ice	9-10, 10
Recognized Snow Classes	**NOAA Chart Classes**	**Lamont Recharts Approximate Equivalents**
0	(Snow-Free)	
1	1 : Least Reflective	1
2	2 : Moderate Reflectivity	2, 3
3	3 : Highest Reflectivity	4, 5, 6
4	Scattered Mountain Snow	1
5	(Snow in Areas of Poor Illumination, Indistinguished Reflectivity) as reconstructed.	7

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GLACIOLOGICAL DATA SERIES

Glaciological Data, which supercedes Glaciological Notes, is published by the World Data Center-A for Glaciology (Snow and Ice) several times per year. It contains bibliographies, inventories, and survey reports relating to snow and ice data, specially prepared by the Center, as well as invited articles and brief, unsolicited statements on data sets, data collection and storage, methodology, and terminology in glaciology. Contributions are edited, but not refereed or copyrighted. WDC publications are distributed without charge to interested individuals and institutions.

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