REPORT GD-6

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GLACIOLOGICAL DATA

SNOW COVER

World Data Center A
for
Glaciology
Snow and Ice

August 1979

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National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C., U.S.A., 20418

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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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WORLD DATA CENTER A FOR GLACIOLOGY
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Operated for:
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National Oceanic and Atmospheric Administration
Environmental Data and Information Service
Boulder, Colorado 80303 U.S.A.

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
INSTAAR
University of Colorado
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.

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[1] International Council of Scientific Unions. Panal 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.

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*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 returns to the pattern of a selected bibliography and supporting data-related articles established in our first and second numbers. The contributions included here provide perspectives on the importance of snow and the organization of snow research in Norway and the United States, as well as accounts of global and regional data sets. The material thereby complements the workshop reports on snow cover data published in Glaciological Data Report GD-5. The last twelve months have seen the implementation of our computerized bibliographic data file described in GD-3, and a steady growth in the WDC's accessions of bibliographic and other data. We plan to describe specific data holdings in future issues. Specific information on existing snow cover (and sea ice) data sets, based on our current inventory assessment, will be contained in the next issue which we hope to send to press by October. We welcome information on other projects and data sources that we may have overlooked.

R. G. Barry
Director

PREFACE

Almost all of the articles in this issue were invited contributions. The article "Focus on U.S. Snow Research" is derived from a working paper of the ad-hoc study group on snow research and control of the Polar Research Board.

We acknowledge with thanks the contributions received from the various authors for this issue. We would also like to thank Greg Scharfen for compiling the bibliography, Gloria Manzanares and Carol Weathers for data entry of the text, and Annie Gensert and Margaret Strauch for figure typing.

Contributions to the Data Center from those who have donated data, both published and unpublished, are gratefully acknowledged.

Marilyn J. Shartran
Managing Editor

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Contributions

GUIDE TO INTERNATIONAL DATA EXCHANGE

The Fourth Consolidated Guide to International Data Exchange through the World Data Centres, issued by the Secretariat of the International Council of Scientific Unions Panel on World Data Centres (Geophysical and Solar), Washington, June 1979, is now available to interested scientists and institutions. The Guide reaffirms the principle that the World Data Centres exist for the benefit of the worldwide community of scientists. Research scientists are invited to make use not only of the vast store of data in the WDCs but also to avail themselves of the various services which some of the Centres are able to provide. All that is requested of those who use World Data Centres is that whenever appropriate a suitable acknowledgement be included in their scientific publications.

Because the various sections of the Guide are subject to frequent review and revision, the ICSU Panel on World Data Centres plans to issue periodic reports indicating the status of various sections, that is, whether any sections of the Guide have been revised, and where such revisions have been published. The Guide and status reports will be available from:

Secretary
ICSU Panel on World Data Centres
c/o National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418 U.S.A.

NOAA Satellite-Derived Continental Snow Cover Data Base

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Michael Matson
National Oceanographic and Atmospheric Administration
National Environmental Satellite Service
Washington, D.C., U.S.A.

Introduction

The severe North American winters of 1977 and 1978 stimulated renewed interest in continental winter weather. Snow cover is an important indicator of the severity of winter weather. The capability to monitor this parameter on a continental basis using the National Oceanic and Atmospheric Administration (NOAA) satellite data has existed since autumn 1966. The NOAA satellite data base is in the form of weekly snow and ice cover charts that have been issued for every week from November 1966 to the present. Kukla and Kukla (1974), Wiesnet and Matson (1976), Kukla, et al (1977), and Matson (1978) have examined this data base and derived a provisional satellite "climatology" of monthly, seasonal, and annual Northern Hemisphere snow cover, i.e., the areal extent and location of continental snow cover for North America and Eurasia. The NOAA satellite snow cover record of the past 12 years is the most complete record of the hemispheric snow cover known to exist. NOAA, NASA, and Defense Department satellites provide a reliable and rapid method of monitoring worldwide snow cover, which has important effects on global temperature and albedo, with attendant impact on hydrology, energy use, agriculture, and weather forecasting.

The NOAA Weekly Snow and Ice Cover Chart

The NOAA weekly snow and ice cover chart (figure 1) is prepared from satellite imagery for the current week and represents all snow and ice that is visible throughout this period. Areas of previous snow and ice cover that are cloud-covered during the week are included, unless subsequent cloud-free imagery shows that the extent of snow in these areas has changed. The weekly snow and ice boundaries are drawn on a 1:50,000,000 polar stereographic projection of the Northern Hemisphere. The snow-covered area is characterized by three types of reflectivity, of which class 1 is lowest (see figure 1). Areas of scattered mountain snow are so indicated but are considered to be of moderate (class 2) reflectivity. The quality of the weekly charts is affected by several factors:

1) The weekly snow maps are based on subjective interpretation by a number of observers.
2) The satellite images have come from a variety of satellites and sensors, all subject to instrumental variation, degradation, and drift.
3) The skill of the meteorologists who prepare the weekly maps has presumably increased with time so that today's charts are probably more detailed than those of the first few years. When considering the above factors, the error in positioning the snowline on the weekly charts is estimated to be 5 to 7 percent from 1966-70, 5 percent from 1970-73, and 3 percent from 1974 to the present.

Determination and Measurement of Monthly Mean Continental Snow Cover

Monthly mean snow cover charts (figure 2) are constructed from the weekly charts by the Environmental Sciences Group of NOAA's National Environmental Satellite Service (NESS). The mean monthly snow boundary is determined by subjective analog averaging of the weekly snowline boundaries. The area measured within this boundary included all three classes of reflectivity as well as scattered mountain snow, and the measured area is corrected to represent true surface area.

During the months of October, November, and the period of December through March, northern boundaries of 70° N, 60° N, and 52° N, respectively, are chosen for snow cover analysis. The lack of solar illumination for satellite visible imagery north of these latitudes during these months is the reason the boundaries were chosen. Fortunately, the area covered by snow north of these boundaries is nearly constant during the winter season when considered on a continental basis. All winter snow cover values given, however, are for each entire continent and not just the area south of these latitudes. Land area measurements north of the latitudinal boundaries are considered completely snow-covered, so their area is added as a constant to the snow cover areas south of the boundary.

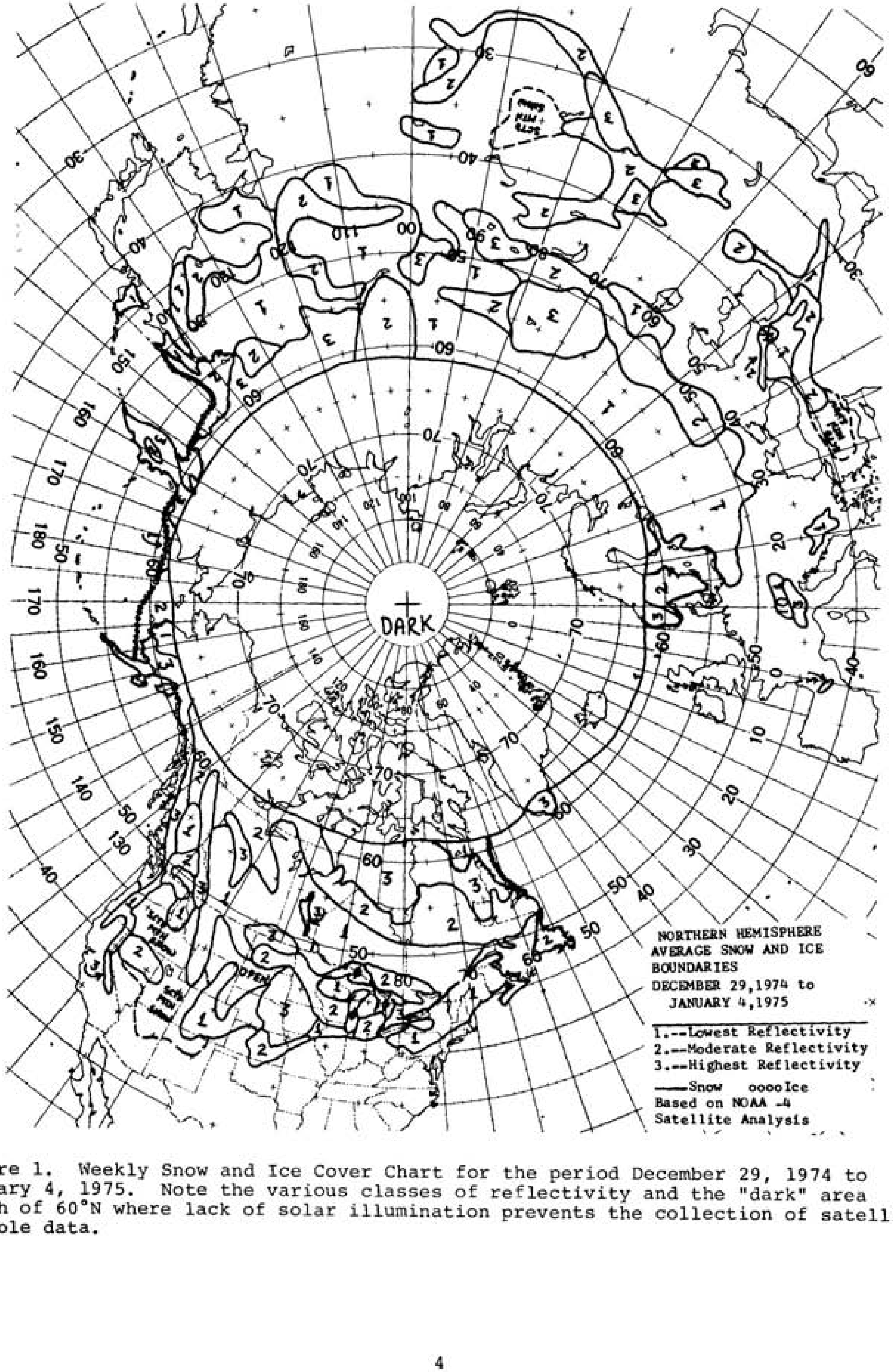

Figure 1. Weekly Snow and Ice Cover Chart for the period December 29, 1974 to January 4, 1975. Note the various classes of reflectivity and the "dark" area north of 60°N where lack of solar illumination prevents the collection of satellite visible data.

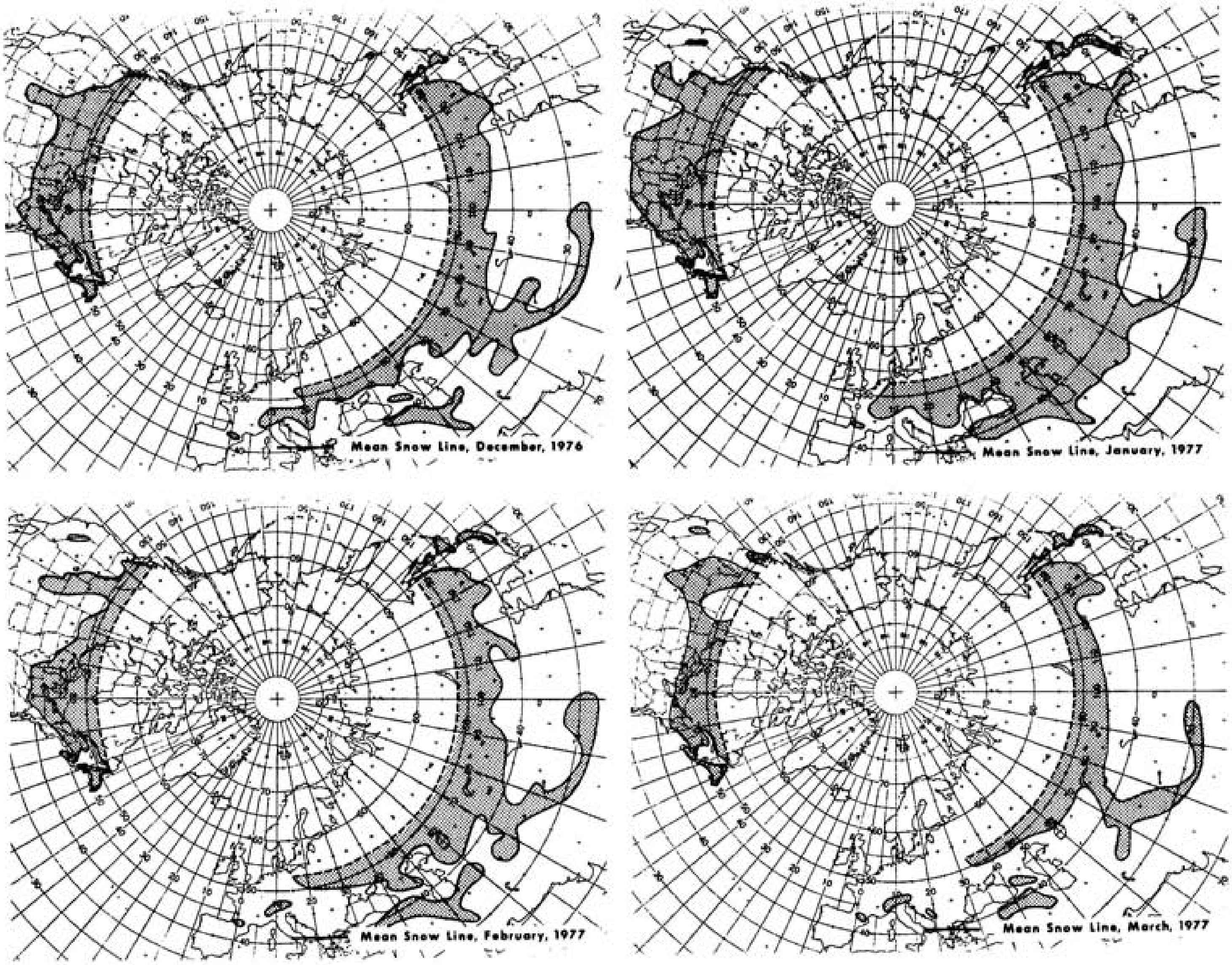

Figure 2. Monthly mean snow cover maps of the Northern Hemisphere for December 1976, January 1977, February 1977, and March 1977. Due to lack of sufficient solar illumination for satellite visible data, the snow line is terminated at 52°N.

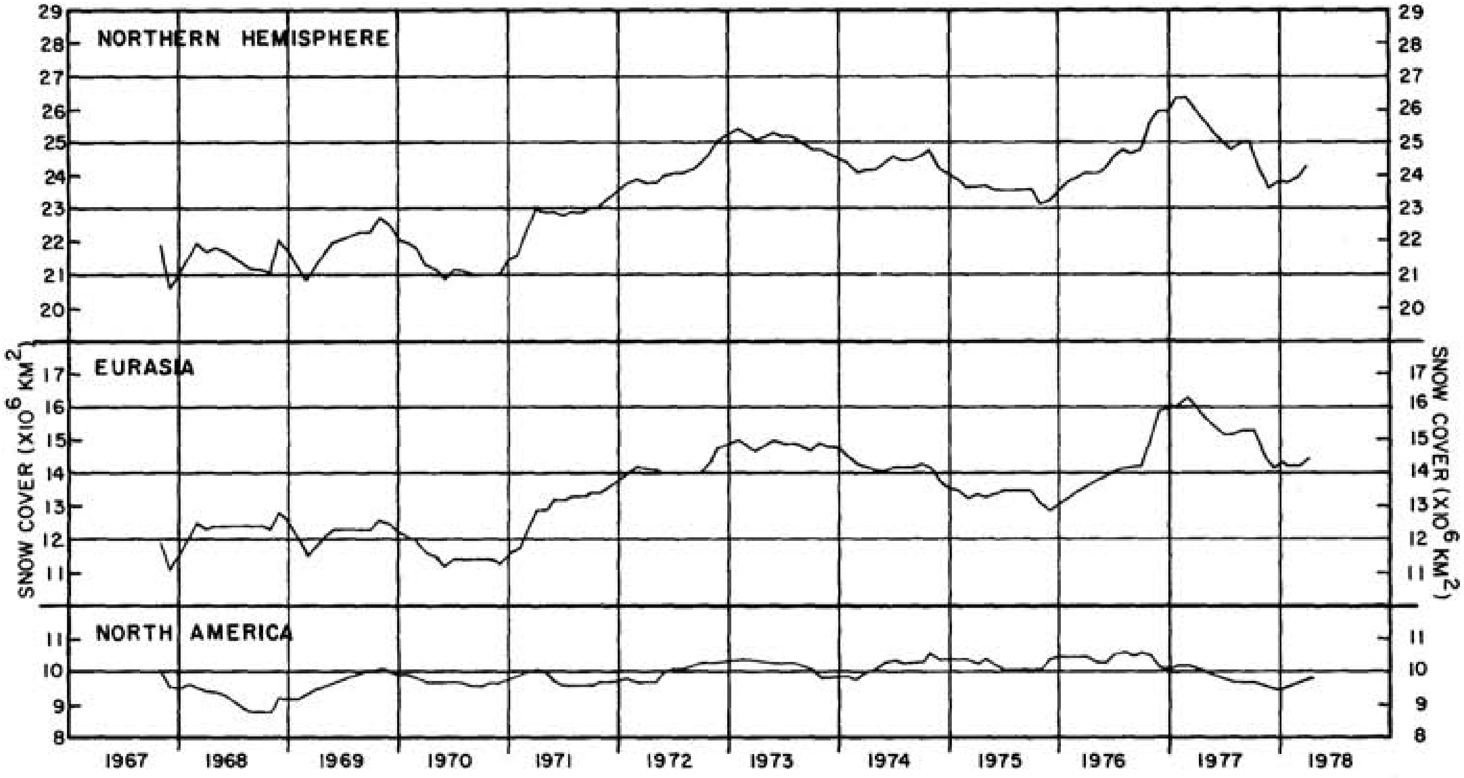

Figure 3. Graph of 12-month running mean of monthly mean snow cover for the Northern Hemisphere, Eurasia, and North America for the period 1967-78.

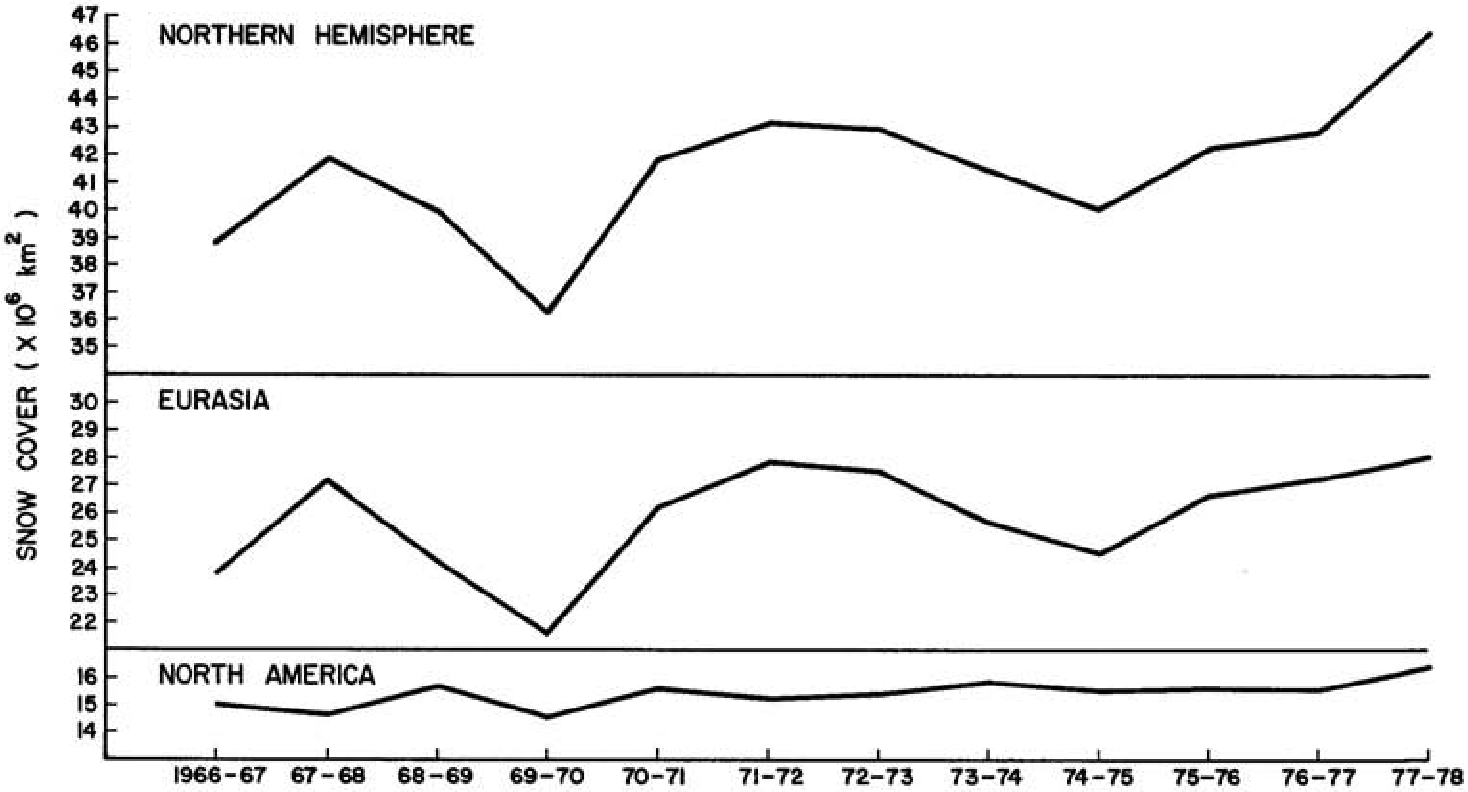

Figure 4. Graph of mean winter snow cover for the Northern Hemisphere, Eurasia, and North America for the period 1967-1968.

The NOAA Satellite-Derived Snow Cover Record

Figure 3 is a 12-month running mean of monthly mean snow cover from 1967-78 as determined for North America, Eurasia, and the Northern Hemisphere. The plot shows no systematic increase or decrease in North American snow cover extent. Thus, it appears that even if North American snow cover fluctuates widely on a regional scale (e.g., the winters of 1977 and 1978), the *continental* snow cover remains fairly constant. Two large increases in snow cover extent occurred in Eurasia and the Northern Hemisphere; one during 1971-72, and the second during 1976-77. An overall increasing trend in snow cover extent is also evident for both of these areas in the decade shown.

Mean winter snow cover (December-March) from 1967-78 is shown in figure 4. Once again North American snow cover extent is rather consistent at a point slightly greater than $15x10^6$ km^2. Eurasian winter snow cover is clearly much more variable, ranging from approximately $22x10^6$ km^2 to $28x10^6$ km^2 in area. This represents a 10 percent variability in Eurasian winter snow cover when compared with the entire continental area of Eurasia. Extensive Eurasian snow cover occurred in the winters of 1968, 1972, and 1978. A notable feature is the steady 3-year increase in Eurasian winter snow cover beginning in the winter of 1976.

The vast winter snow-covered areas of Eurasia statistically dominate the smaller areas of snow cover on the North American continent. The result is that the trends in the winter Northern Hemisphere and Eurasian data are similar. The 12-year record high North American winter snow cover of 1978, however, combined with the 12-year record high 1978 Eurasian winter snow cover to produce a 12-year record high Northern Hemisphere winter snow cover ($3.2x10^6$ km^2 or 7.4 percent greater than the 1972 peak).

Concluding Remarks

The use of satellite data for certain aspects of climate monitoring, especially in the polar regions, is not merely a potential application of a new technology; it is the application of an established observation system that has been operational for many years. As the satellite sensors improve and become more varied, workers in the field of climate monitoring and climate change will become increasingly dependent upon this reliable and relatively unbiased source of data. The satellite data provide a rapid means of synthesizing global snow cover information to assess current conditions. Although the satellite snow cover data comprise only 12 years of record, they establish a provisional climatological base for monitoring Northern Hemisphere snow cover variability. As the data base expands, it will undoubtedly be carefully considered and critically evaluated by those whose research deals with climate variability and its attendant impact on man and his environment.

References

Kukla, G.J.; Kukla, H.J. (1974) Increased surface albedo in the Northern Hemisphere. *Science*, v. 183, p. 709-714.

Kukla, G.J.; Angell, J.K.; Korshover, J. et al. (1977) New data on climate trends. *Nature*, v. 270, p. 573-580.

Matson, M. (1978) The satellite snow cover record: status, trends, and relationships. (In: *Annual NOAA Climate Diagnostics Workshop, 2nd, Proceedings*. LaJolla, California, p. 10-1 to 10-16.)

Wiesnet, D.R.; Matson, M. (1976) A possible forecasting technique for winter snow cover in the Northern Hemisphere and Eurasia. *Monthly Weather Review*, v. 104, p. 828-835.

Snow and Pack Ice Indices

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Lamont-Doherty Geological Observatory
Palisades, New York, U.S.A.

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
4) the energy absorbed by the surface under specified atmospheric conditions and solar angle - q

The data are obtained by analyzing charts produced primarily by the U.S. Navy and the National Oceanic and Atmospheric Administration (NOAA). Additional sources are used either to extend the information back in time or to make quality checks (see table 1). A total of 70 geographic segments in both hemispheres (figures 1 and 2)[†] are assessed. The meridional divisions of the segments were designed to approach boundaries of major climatic provinces.

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° by 2° between latitudes 20° and 60°, 2° of latitude per 4° of longitude between 60° and 80°, and 2° by 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 a set of digitized Arctic sea ice charts for the end of each month in the 1953-76 period which is generated by J. Walsh (1978)].

A separate set of snow and ice cover indices is obtained by planimetering NOAA charts, irrespective of reflectivity grade, in latitudinal bands separately for five meridional segments as shown in figure 3.[†] Data are produced in 2-week intervals, and the area is adjusted for distortions. Scattered mountain snow is taken as one-third of measured extent. The position of the pack ice edge is revised using U.S., British, and Canadian ice charts.

Indices Generated

The primary data set consists of the areas of snow and ice classes as measured in each chart. An open water index, based on the proportion of open water within the pack ice perimeter, is calculated in percent. 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)[*] will be produced in the second stage of the investigation. The former represents an estimate of surface reflectivity for clear Arctic air and a solar angle of 30° in a spectral range of $0.2\,\mu m$ to $4.0\,\mu m$. 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.

[†] The designations assigned to the segments in the figures are used internally by Lamont.

[*] Ly/day = cal/cm^2/day.

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

Chart Name	Produced By	Area	Projection and Approx. Scale	Interval	Content	
Northern Hemisphere Average Snow and Ice Boundaries	Analysis and Evaluation Branch of the National Environmental Satellite Service, NOAA	Continents of 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	
Current Snow and Ice Depth	U.S. Air Force, Global Weather Central	Northern Hemisphere 0°-90°N	Polar Stereographic 1:30,000,000	Weekly: 1976-present	Depth of snow and ice for 6 categories 1) ≤2"; 2) ≥2"; 3) ≥4" 4) ≥6"; 5) ≥8"; 6) ≥10"	
Age of Surface Snow/Ice	U.S. Air Force, Global Weather Central	Northern Hemisphere 0°-90°N	Polar Stereographic 1:30,000,000	Weekly: 1976-present	Age of snow and ice in 7 categories: 1) No snow 2) Fresh ≤24 hrs. 3) New ≤48 hrs. 4) Aging at least 3 days old 5) Old at least 3 weeks 6) Very old at least 2 months 7) Permanent at least 6 months	SNOW
Weekly Weather and Crop Bulletin Snow Chart	U.S. Dept. of Commerce, National Weather Service, NOAA, U.S. Dept. of Agriculture and Statistical Reporting Service	Continental U.S.	Albers Equal Area 1:30,000,000	Weekly: 1976-present	Depth of snow on ground at 7 a.m. e.s.t. for Monday, December - March only	
Southern Ice Limit	U.S. Naval Oceanographic Office, Fleet Weather Facility	Two sections, Eastern and Western, north of 40°N ~120°W-90°E ~ 90°E-120°W	Polar Stereographic ~1:15,000,000	Weekly: 1972-present 1971: incomplete information on charts	Sea ice concentration in oktas open water polynyas. Also shown: isoline of +2°C sea surface temperature, 0°C average air temperature	ARCTIC ICE
Ice at the End of the Month	Climatological Services, Meteorological Office, Bracknell, United Kingdom	Northern Hemisphere north of 40° in the North Atlantic, and north of 45°-60° in the North Pacific	Polar Stereographic ~1:22,000,000	End of month: 1960-present 1906-61 (North Altantic only)	Sea ice concentration in tenths, open water polynyas. Also shown: isopleths of degree days, sea surface isotherms, 0°C air isotherm	
Ice Summary and Analysis 1) Canadian Arctic 2) Hudson Bay and approaches 3) Eastern Canadian Seaboard	Ice Forecasting Central, Environment Canada	Eastern Canadian Arctic, including Foxe Basin, Western Arctic including North Coast of Alaska, and Western Queen Elizabeth Islands	Polar Stereographic	Weekly: May-October 1964-73	Sea ice concentration in tenths and by age including open water polynyas. Also included: mean temperature and wind flow chart + 1200 G.m.t. and central sea level pressure of migratory lows	
Northern Ice Limit	U.S. Naval Oceanographic Office, Fleet Weather Facility	Antarctic south of 50°	Polar Sterographic ~1:18,000,000 (1973-74 1:35,000,000)	Weekly: 1973-present	Sea ice concentration in oktas including open water polynyas. Also shown: isopleths of degree days, sea surface isotherms, 0°C surface air isotherm	ANTARCTIC ICE

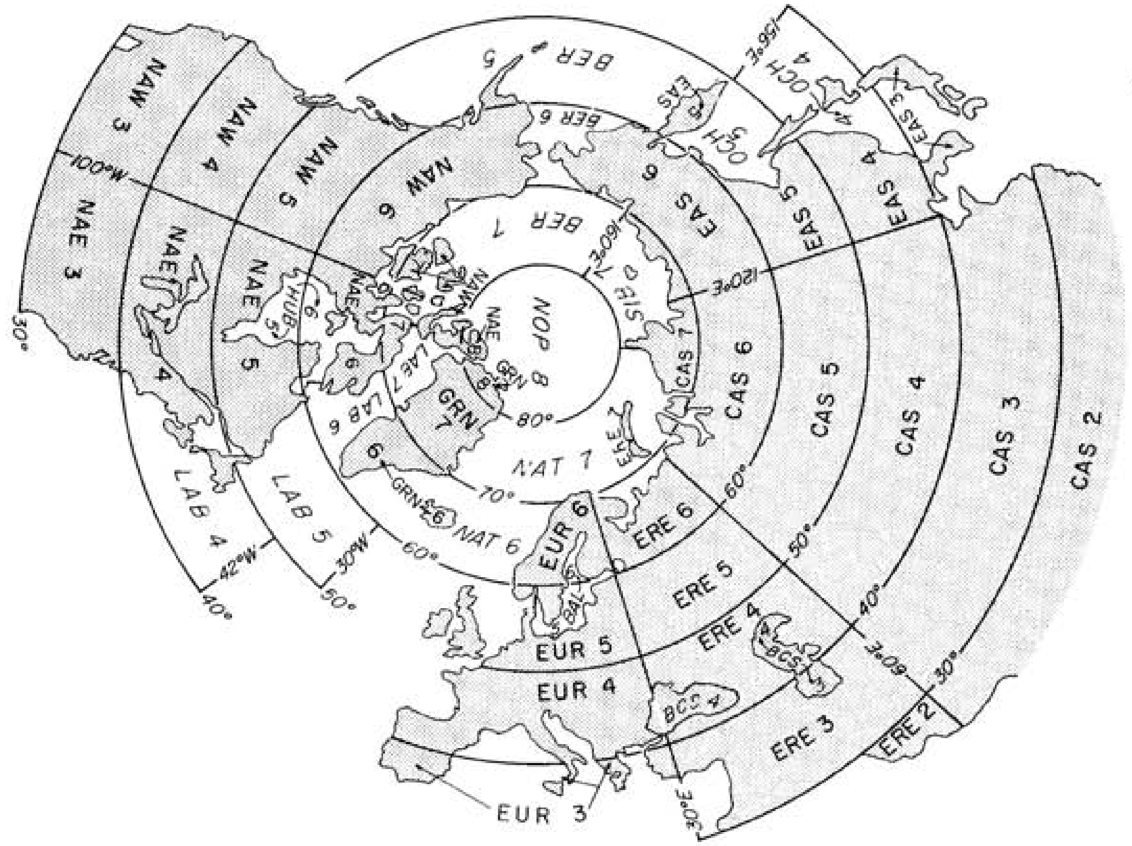

Figure 1. Geographic segments for the Northern Hemisphere.

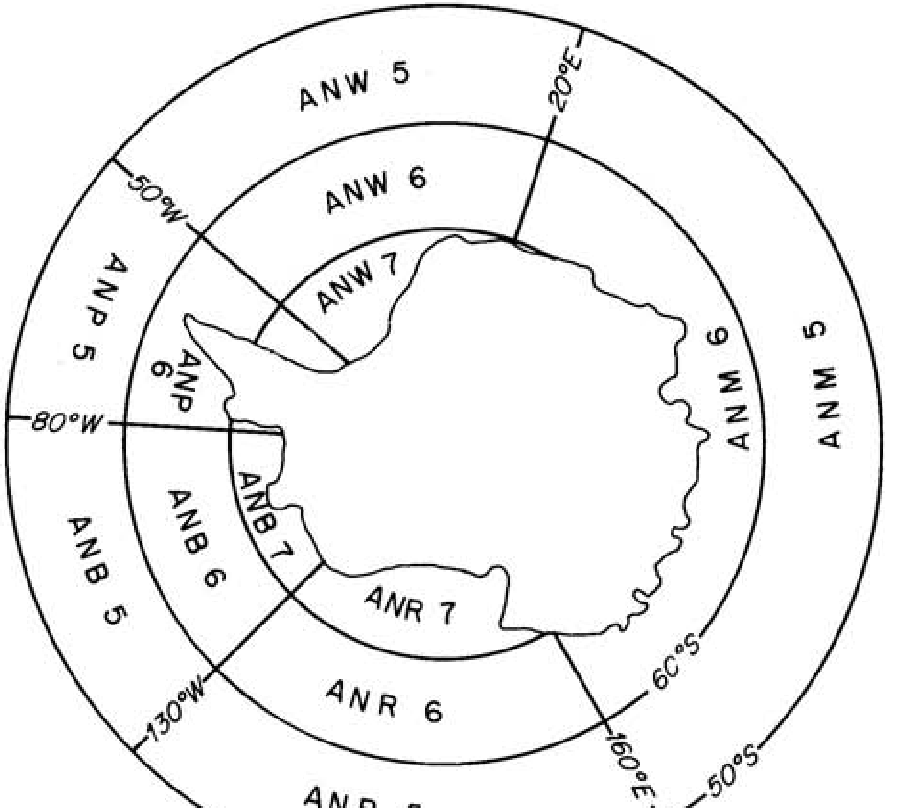

Figure 2. Geographic segments for the Southern Hemisphere.

Table 2. Ice concentration and snow reflectivity classes.

Recognized Ice Classes	Corresponding U.S. Navy Chart Classes	Corresponding British and Canadian Chart Classes
00	Open water outside pack ice boundary	Open water outside pack ice boundary, new, rotten or brash ice
0	Open water within pack ice boundary	Open water within pack ice boundary, new, rotten or brash ice
1	0-2, 1-2, 1-3, 2-4 oktas	1-3 tenths
2	3-4, 3-5, 4-5, 4-6 oktas	4-6 tenths
3	5-6, 5-7, 6-7 oktas	4-6 tenths
4	6-8 oktas	7-9+ tenths (Canadian) 7-10 tenths (British)
5	7-8, 8-8 oktas, fast ice	7-10 tenths, fast ice

Recognized Snow Classes	NOAA Chart Classes
0	(Snow-free)
1	1 : Least reflective
2	2 : Moderate reflectivity
3	3 : Highest reflectivity
4	Scattered mountain snow
5	Snow in areas of poor illumination, indistinguished reflectivity as reconstructed

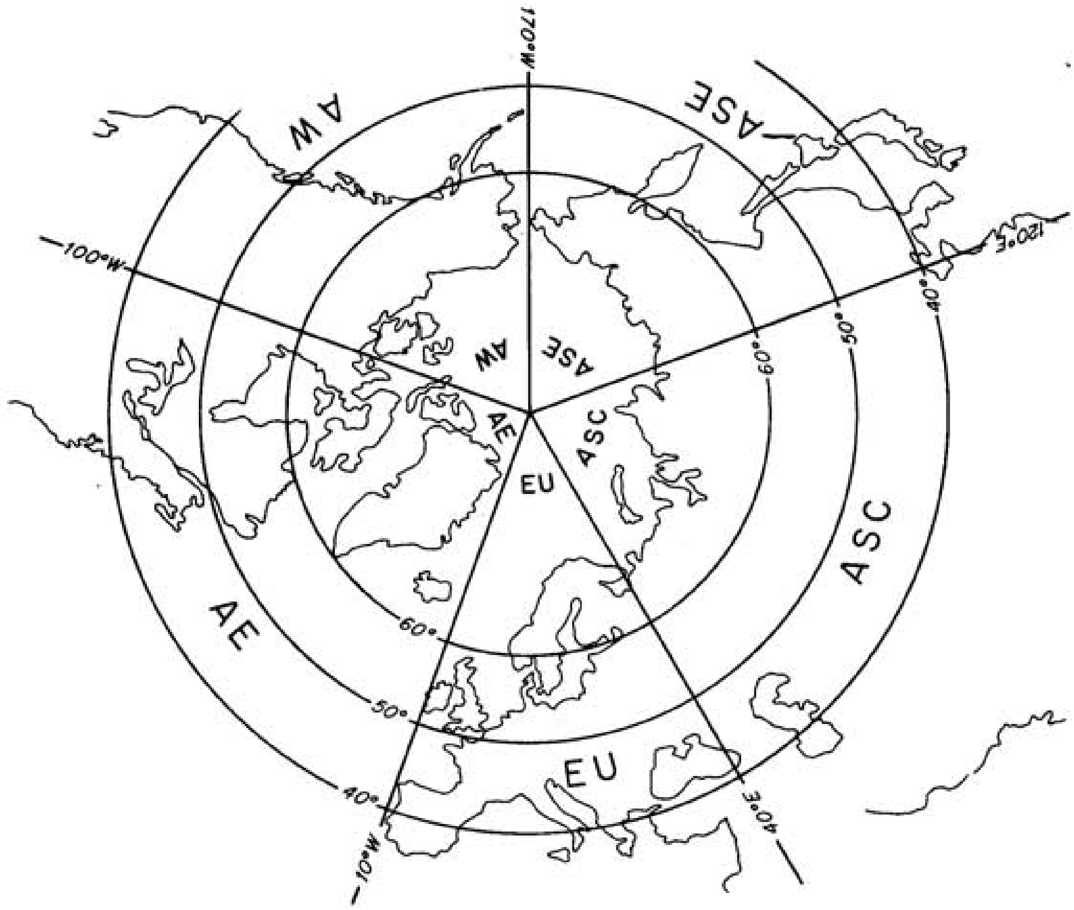

Figure 3. Planimetered segments of the Northern Hemisphere. Measurements are separately done for 60°-90°, 50°-60°, 40°-50° and south of 40°N latitudes.

Table 3. Currently generated series of indices.

Length of Record	Indices	Interval	Method	Number of Recognized Classes	Principal Chart Source	Area
1967-present	S	Biweekly	Planimeter	0	NOAA	Northern Hemisphere snow and pack ice
1967-1971	S	Weekly	Grid count	0*	NOAA	Snow and pack ice
1972-1973	S	Weekly	Grid count	6**	NOAA	Snow
1974-present	S	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	0	NOAA Satellite photos	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
** Reflectivity classes of poor quality
† Summer only

Internal Consistency of the Records

The length of available records for individual chart series varies. In each of the series, the changing technical and interpretive capabilities throughout the available period of observation have resulted in a gradually improved record over time. Several breaks in the quality of the charts have been discerned, which in part result 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.

Table 3 shows the time series currently being produced, based on the above considerations.

The generated sets will be available to all interested researchers, and will be deposited in the World Data Center A for Glaciology, Boulder, Colorado.

Reference

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Global Snow Depth Data: A Monthly Summary

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The Rand Corporation's global snow depth data are the results of an attempt to gather all available mean-monthly snow depth climatologies into one global format. A global grid of 4° of latitude and 5° of longitude was used for the presentations. Machine-analyzed maps and listings based on these grid data are currently available from the Rand Corporation. (See table 1 for example of listing.)

Most of the observations were made in the Northern Hemisphere. These data were extracted from monthly climatologies valid for the last day of each month and prepared by the U.S. Army Corps of Engineers. Snow depths for data-sparse areas such as China, Greenland, the Arctic, and Antarctic were developed from special Rand methodologies. These calculations included an empirical evaluation of total precipitation, weather source regions, latitude, temperature, terrain, and annual snow depth data. Monthly ice-pack limits from the U.S. Navy Oceanographic Office were used to extend the "zero" snow accumulation line over the oceans. Unfortunately, through Africa and South America where the only snow accumulation is on the highest mountains, Rand's 4° by 5° grid was too coarse to pick up these variations. However, not more than two grid points were involved.

As far as can be determined, this global summary of observed snow depths is not available elsewhere. These mean-monthly data can be used strictly as a climatological summary. They may also be used for a systematic comparison with simulations from any General Circulation Model (GCM) or for initiating GCM calculation.

Other global summaries available at Rand include 20 climatic variables averaged by season. These appear in the Global Climatic Data for Surface, 800 mb, 400 mb reports by Schutz and Gates (1971).

Any questions concerning these data should be addressed to:

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Table 1. Global snow depth (inches).

```
      180W175W170W165W160W155W150W145W140W135W130W125W120W115W110W105W100W 95W
 90N   6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2
 86N   7.4 7.0 7.0 7.0 7.0 7.0 7.0 7.0 7.0 6.8 6.8 6.2 6.2 6.2 6.2 6.2 6.2 6.2
 82N  10.910.1 9.4 9.0 8.6 8.6 7.8 7.8 7.8 7.7 7.7 6.6 6.2 6.2 5.5 5.5 5.5 5.5
 78N  11.711.210.910.510.1 9.8 9.3 9.0 8.6 8.6 8.0 7.8 7.0 6.2 6.2 6.2 6.2 7.8
 74N   8.6 9.4 8.6 9.0 9.0 9.0 8.7 8.6 8.2 8.0 7.8 6.210.0 5.5 6.2 7.814.011.7
 70N   3.9 3.1 3.1 5.514.015.014.014.0 3.9 3.910.0 2.3 2.310.010.0 9.010.013.0
 66N   9.010.018.023.025.026.026.026.026.027.025.023.020.018.016.015.011.010.0
 62N  999. 2.0 6.018.016.016.012.020.016.020.026.025.023.021.020.019.017.017.0
 58N  999.999.999.999.999. 1.0999.999.999. 4.017.518.522.020.015.021.022.023.0
 54N  999.999.999.999.999.999.999.999.999.999.19.0999.10.011.020.012.019.027.0
 50N  999.999.999.999.999.999.999.999.999.999.999.999. 8.5 6.0 2.0 5.010.018.0
 46N  999.999.999.999.999.999.999.999.999.999.999.999.999. 1.0 1.0 1.0 4.5 7.5
 42N  999.999.999.999.999.999.999.999.999.999.999.999.999. 1.5 3.0 1.0 1.0 2.0
 38N  999.999.999.999.999.999.999.999.999.999.999.999.999. 1.0 1.0 1.0 1.0 0.5
 34N  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 30N  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 26N  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 22N  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 18N  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 14N  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 10N  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
  6N  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
  2N  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
GLOBAL SNOW DEPTHS - FEBRUARY
      180W175W170W165W160W155W150W145W140W135W130W125W120W115W110W105W100W 95W
  2S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
  6S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 10S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 14S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 18S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 22S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 26S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 30S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 34S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 38S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 42S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 46S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 50S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 54S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 58S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 62S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 66S  999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.999.
 70S  999. 1.8 1.8 1.8999.999.999.999.999.999. 3.5 3.6 4.1 5.0 5.3 5.4 5.4 5.4
 74S   3.7 3.7 3.7 4.2 4.8 5.1 5.4 5.4 5.9 6.3 7.2 7.2 7.2 6.910.810.810.810.8
 78S   4.1 4.4 4.8 5.3 5.4 5.9 6.0 5.1 3.6 3.5 3.5 3.6 3.6 3.6 4.2 4.7 5.0 5.1
 82S   3.5 3.3 3.1 2.9 2.8 2.7 2.6 2.6 2.5 2.4 2.4 2.5 2.5 2.7 2.7 2.9 2.9 2.9
 86S   3.6 3.6 3.6 3.6 3.6 3.6 3.5 3.2 3.0 2.7 2.5 2.3 2.1 2.0 2.0 2.0 2.0 2.0
 90S   1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2 1.2
GLOBAL SNOW DEPTHS - FEBRUARY
       90W 85W 80W 75W 70W 65W 60W 55W 50W 45W 40W 35W 30W 25W 20W 15W 10W  5W
 90N   6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2 6.2
 86N   5.8 5.8 5.7 5.8 5.5 5.5 5.2 5.2 5.1 5.1 5.6 5.6 5.6 5.8 5.8 5.9 6.0 6.2
 82N   4.920.020.020.0 3.9 3.9 3.5 3.522.621.020.824.130.7 4.2 4.2 4.3 4.6 4.6
 78N   6.215.015.0 1.642.937.421.818.715.613.212.512.513.319.1 2.9 2.5 2.1 1.7
 74N  13.014.012.0 7.0 3.1 2.3 0.836.255.036.219.820.631.034.432.6 1.4 2.1999.
 70N  13.016.016.016.016.011.0 5.5 5.539.655.037.830.046.579.2 2.1999.999.999.
 66N  15.021.025.030.035.040.017.5999.37.238.090.0 1.7999.999.999.999.999.999.
 62N  20.022.024.020.011.025.0999.999.999.88.0999.999.999.999.999.999.999.999.
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Alaskan Snow Cover

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Snow Cover Types

Snow forms a thin veneer on the earth's surface over most of Alaska for one-half to three-quarters of the year. The physical properties of this snow layer and the physical processes which occur in, above, and below it are important and fascinating. The Alaskan snow differs from the hydrologically important mountainous snow of the Western United States in that its temperatures are lower, steeper temperature gradients occur in it, and there is less of it per unit area. However, it lasts longer and enters more directly into human activity as snow itself, rather than serving primarily as a cold storage water reservoir. This is, of course, especially true of snow which falls in glacier basins and enters into the complex glacier-hydrology system. Some of it may appear as runoff during the same year it was deposited, but much of it becomes locked in the glacier system for many years before it appears as runoff.

Although Alaska is famous for its glaciers and has a large amount of perennial snow cover, it is especially well suited for the study of seasonal snow cover. Indeed, Alaska is virtually a made-to-order snow laboratory because it contains maritime, extreme continental, and Arctic climatic zones in proximity. Striking differences exist in the snow cover from one climatic zone to the next. This fortuitous situation is the result of two sharply defined climatic boundaries which cross Alaska:

1. The Alaskan coastal ranges separate the North Pacific maritime climate from a severe continental climate.

2. The Brooks Range separates the interior continental climate from the Arctic polar basin climate.

The two boundaries give three major climatic zones, each of which contains its own characteristic snow cover. Pruitt (1970) distinguished two primary North American snow types, tundra snow and taiga snow, which are widespread in Canada and Alaska. To these, we will add maritime snow as a third type (Benson, 1967a, 1969), and define the climatic zones and their snow types as follows:

1. Arctic. The Arctic slope north of the Brooks Range has the climate of the Arctic polar basin. Its precipitation comes from cyclonic disturbances moving eastward from the Bering Sea or from along the Siberian Arctic coast. Its snow cover lasts for nine months and is wind-packed, dry, and sastrugi-sculptured. Following Pruitt (1970), we shall refer to this snow as tundra snow.

2. Interior. The interior, between the Brooks and Alaska Ranges, suffers an extreme continental climate. Most of its precipitation is from cyclonic disturbances which move eastward from the Bering Sea. The most notable feature of its snow cover is the low density, loosely consolidated depth hoar which makes up most of the snowpack in the lowland brush forest areas. Following Pruitt (1970), we shall refer to this snow as taiga snow.

3. Maritime. The coastal mountains and lowlands of southeastern and south-central Alaska receive heavy precipitation from Pacific cyclonic disturbances which move through the Gulf of Alaska. The maritime snowpack is thick, sometimes exceeding 5 m, and may be wet, especially at low altitudes. Snow temperatures are significantly higher than in tundra or taiga snow. This snow type is common along the Pacific rim northward from Japan and California. We shall refer to this snow as maritime snow.

4. Transitional. In addition to these three major climatic types, there is a fourth zone which lies south of the Alaska Range and is transitional between the interior and maritime zones. It is called the transitional zone. Climatic conditions alternate between continental and maritime. In the interior, this transitional zone also becomes apparent as one progresses westward toward the Bering Sea, especially west of Koyukuk (about long. 158°W.) on the Yukon-Kuskokwim delta. Here, the temperatures and winds are higher than farther east and the climate becomes more maritime. Many of the

snowstorms are mixed with rain, and the snow cover is characterized by significant amounts of icing with depth hoar at the bottom. The snow cover is transitional between the three named types, but no special name will be applied to it.

The tundra snow and taiga snow differ significantly from each other and involve physical processes which lead to two extreme types of snow strata. These are the hard, fine-grained, wind-packed snow and the soft, coarse aggregates of loosely bonded depth hoar crystals. The tundra snow frequently has both wind-packed snow layers and depth hoar, but taiga snow is mainly characterized by its extensive development of depth hoar. Tundra and taiga snow and the processes leading to the end-member snow types will be briefly described.

The Tundra Snow of the Arctic Slope

Aside from perennial snow in mountainous areas, the snow cover lasts longest on the north slope of the Brooks Range. For three-quarters of each year, the entire Arctic Slope, from the foothills across the tundra to the Arctic Ocean, is covered with dry, wind-packed snow. This tundra snow has several distinct features, and research on it emphasizes the common ground which exists between studies of seasonal and perennial snow cover. It forms a windswept sastrugi surface which strongly resembles the year-round surfaces of the Greenland and Antarctic ice sheets, or the winter snow surface of the adjacent Arctic Ocean.

The similarity between tundra snow and snow on the polar ice sheets does not stop at the surface. Indeed, the structure of the entire tundra snowpack, thin as it may be, resembles the top annual stratigraphic unit of the perennial dry snow facies of the Greenland or Antarctic ice sheets. It consists of a hard, high density, wind-packed layer, overlying a coarse, low density, depth hoar layer. Although there is considerable variability in the stratigraphy of this snow, one can generally describe it by referring to only four major varieties of snow. In approximate order from top to bottom in the snowpack, these are indicated in table 1.

Table 1. Stratigraphy of tundra snow.

Snow type	Range of Grain Size (mm)	Range of Density (kg m^{-3})
1. Fresh new snow, variable crystal forms	0.5 to 1.0 sometimes 0.5	150-200
2. Wind slab, hard, fine-grained	0.5 to 1.0	350 - 450
3. Medium grained snow	1 to 2	200 - 350
4. Depth hoar, coarse loosely-bonded crystals	5 to 10	150-300

*The density ranges are only approximate, however, they indicate the differences one may expect between the various layers.

The virtually unbroken tundra snow surface has an albedo (surface reflectivity) of about 80 percent. When the snow disappears, in late May or early June, it goes rapidly and the albedo drops to about 15 percent. This five-fold decrease in albedo occurs at the same time that the amount of incident radiation is rapidly increasing, and results in a dramatic increase in the amount of absorbed radiation at the surface (Weller, et al., 1972; Benson, et al., 1975). Similar observations have been made on the Canadian tundra (McFadden and Ragotzkie, 1967).

The Taiga Snow of Interior Alaska

The winter climate of the interior lowlands of Alaska is typified by cold air and calm winds. The snow-covered surface favors the development of strong surface inversions which restrict the calm, cold air to a surface layer 50 to 100 m thick. However, hills, such as those around Fairbanks, effectively "poke through" the inversion layer located in the flats.

The snow cover lying within the altitude range spanned by the inversion layer is subject to negligible winds, often through the entire winter. It is also subjected to very low temperatures at its upper surface for several months. However, the ground beneath the snow does not experience temperatures below -5° or -10°C, and strong temperature gradients prevail in the snow. This leads to extensive depth hoar development with average density generally less than 200 kg m^{-3}. In extreme cases, the snow pack becomes predominantly depth hoar (Trabant and Benson, 1972).

The dense air in the surface inversion layer is virtually detached from the air above (Benson, 1970), and winds in the upper air mass can be strong (Gotaas and Benson, 1964). Occasionally, the boundary between the dense, calm air in the valleys and windy air aloft may be seen in the form of a frost line on the forest. Delicate frost crystals cover the branches of trees below the boundary, while the trees above are free of frost. This might be explained partly by the fact that the lower temperatures below the boundary cause more condensation and crystal growth. However, the boundary has been observed to be very sharp following wind action at higher levels, while negligible winds occurred below. The boundary layer in the Fairbanks area lies slightly more than 100 m above the valley floor, just above the steepest inversion layer.

Hard-packed wind slabs develop on top of Ester Dome, about 600 m above the flats just west of Fairbanks. These slabs consist of fine grains (1 mm) which are firmly bonded. The density values generally range from 350 to 450 kg m^{-3}. At 200 m above the Tanana Valley, for example on top of Birch Hill, northwest of Fairbanks, the snow shows little wind packing, as in the valleys below. About 300 m above the valley floor, wind action on the snow becomes noticeable, and significant wind packing occurs every winter at altitudes in excess of 400 m above the valley floors. The snow density in these windy places is twice as great as it is in the valley bottoms. Above the altitude where wind acts on the snow, the taiga snow becomes tundra snow, with wind-packed layers overlying depth hoar layers. In the Delta Junction area, wind packing occurs in valley bottoms wherever forests are absent because of the strong winds from Isabel Pass in the Alaska Range (Benson, 1972).

The land south of the Brooks Range is forested, and the forest cover prevents taiga snow from exercising the same dominant control on the albedo that tundra snow does on the Arctic Slope. The boreal forest has about one-half the albedo of clear snow-covered areas within it, such as lakes and bogs (McFadden and Ragotzkie, 1967). In general, south of the Brooks Range, the albedo is lower and more variable than it is on the North Slope.

Physical Processes in the Snow

Physical processes which depend on wind action and on vapor transport within the snow lead to two extreme physical types of snow strata which will be briefly discussed.

Wind-Packed Snow. Wind action on snow may produce wind crusts, 1 or 2 mm thick, or wind slabs which vary in thickness from a few centimeters to several decimeters. Wind slabs consist of rounded, firmly bonded, fine (0.5 to 1.0 mm) or very fine (<0.5 mm) grains. Maximum values in the ram-hardness profiles are associated with wind slabs or icy layers in the snow strata. Even though very hard, wind slabs rarely exceed densities of 500 kg m^{-3}. The mechanism of forming wind slabs depends on bonding of the many small grains by deposition of water vapor at their points of contact. The early description of wind packing by Seligman is still reasonable. He concluded

> ...that wind-packing consists of the compacting of snow grains by the condensation of water vapour among them when subjected to the action of a moisture bearing wind. It is practically certain that at any rate some of this moisture is derived from the grains themselves. We can therefore define wind-packing as a special form of firnification accelerated by a wet wind. The mechanism of the processes is probably one of wind-accelerated diffusion which may or may not be influenced by the pulsations or pressure variations of the wind. (Seligman, 1936.)

Formation of Depth Hoar. Depth hoar is the coarsest grained snow structure that can form in the absence of the liquid phase (Bader, 1939). It consists of large, well developed skeletal crystals which are weakly bonded together so that depth hoar layers are fragile. It forms in seasonal and perennial snow strata as a result of upward vapor transport along vapor pressure gradients produced by temperature gradients in the snow.

The development of depth hoar in interior Alaska is extreme. It has the lowest density (less than or equal to 200 kg m^{-3}) of depth hoar formed anywhere. This is the result of the very steep temperature gradients which exist in the snow for long periods of time, up to five months. Not only are the gradients strong, but they also include relatively high temperatures of about -5°C at the base. A comparison between the top 50 cm of snow on the Greenland ice sheet and that of the Fairbanks area is revealing. Assume that both have a surface temperature of -45°C. If we go 50 cm below the snow surface in the Greenland case, we find a temperature of about -40°C, while in the Fairbanks case, the soil-snow interface at the same depth would have a temperature of -5°C. In this example, the vapor pressure difference in the Alaskan case is 70 times greater than the Greenland case (3.943 mb compared with 0.056 mb).

An experimental arrangement was set up in the Fairbanks area to observe depth hoar formation. The apparatus consisted simply of a set of tables, painted white, upon which snow could be deposited. The lack of wind in this region made it possible to carry out this experiment. Thus, one can observe two adjacent snowpacks with identical depositional history but with a drastically different thermal environment. The snow on the table is subjected to negligible temperature gradients because air is in contact with the bottom of the table as well as with the top of the snowpack. On the other hand, snow resting on soil has ambient air temperature at its top but the much higher soil-snow interface temperature at its bottom.

Temperature, density, and stratigraphy profiles of the adjacent snowpacks bave been made approximately once a week for nine years. By comparing densification rates in the two cases, an upward flux of water vapor has been determined to be 0.025 g H_2O cm^{-2} day^{-1} (Trabant, 1970; Trabant and Benson, 1972). This is an order of magnitude greater than flux rates calculated by pure diffusion models developed by Bader (1939), Yosida, et al. (1955), de Quervain (1958), Giddings and La Chapelle (1962), and others. The large flux is apparently due to air convection in the snow.

The upward flux of water vapor in the snow also exerts a significant and measurable drying action on the soil and vegetation below. The flux of water vapor from the top 5 cm of soil is an order of magnitude less than the flux measured in the overlying snow. These studies are discussed in greater detail by Trabant and Benson (1972) and Benson and Trabant (1973).

Combined Wind Action and Vapor Transport. When wind action and upward flux of water vapor occur together, they contribute to the simultaneous formation of depth hoar and wind slab. Part of the mass removed from the depth hoar layer is deposited in the overlying wind-packed snow and serves to bond it as described by Seligman (1936). This is the basic mechanism involved in forming the tundra snow structure on the Arctic slope. This is of extreme importance in the perennial snow of glaciers. It produces a reference datum in snow strata, in the form of a discontinuity between depth hoar layers and an overlying wind slab, during the short autumn season at the onset of winter each year. This enables one to measure the annual accumulation by interpreting the snow stratigraphy. Snow strata of the Greenland ice sheet have been correlated at 16-40 km intervals for 1800 km by identifying these stratigraphic discontinuities (Benson, 1962).

Caribou-Poker Creeks Research Watershed

The Caribou-Poker Creeks Research Watershed, about 50 km north of Fairbanks in the Yukon-Tanana Uplands (figure 1), is typified by taiga snow with small patches of tundra snow on the higher hills which go above timber line. The Watershed spans an area of 105.6 km^2 (40.8 mi^2) and is covered by a fire-patterned forest of black spruce, birch, aspen, and white spruce with a dense moss and lichen growth on the forest floor. The forest is present on the hill slopes and valley bottoms with treeless tundra areas on two windswept hill tops, Haystack Mountain (770 m, 2525 ft) and Caribou Peak (773 m, 2537 ft). The bedrock geology is primarily Birch Creek schist with a variable cover of aeolian silt. The maximum altitude of 826 m (2710 ft) lies on the northern boundary of the Watershed, and the minimum altitude of 200 m (656 ft) occurs where Poker Creek joins the Chatanika River.

The snow cover in the Caribou-Poker Creeks Research Watershed was studied during the 1974-75 and 1975-76 winters. Our main study area was centered on the top of Caribou Peak. Most of the detailed examinations of snow structure and the determinations of snow drift distribution were done there. Traverses extended downward from the Caribou Peak summit in 1976. A series of measurements on snow drift distribution was also carried out at the summit of Haystack Mountain. The evolution of the snowpack was studied in detail at a test site close to the University of Alaska, Fairbanks, where observations could be made more frequently than in the Watershed. Aerial photographs were made during the late winter and spring in order to follow the details of snowmelt on a regional scale. Both Poker and Caribou Creeks are subject to extensive aufeis formations. The interaction between aufeis and snow cover was observed near the junction of Caribou and Poker Creeks, and the area and volume of the aufeis was estimated with the aid of plane table mapping and aerial photographs.

Measurements on the snow cover included:

1. Snow depth determinations by probing along lines surveyed from the bench marks "Carib" on Caribou Peak and "Glo" on Haystack Mountain.

2. A series of pit studies in which temperature, density, grain size, and hardness profiles were measured from snow surface to the soil-snow interface at selected points along the survey lines. These were done at the test site near Fairbanks as well as in the Watershed.

3. Hardness profiles, measured with a ramsonde penetrometer at selected points along the survey lines.

4. In addition to the snow depth determinations at the summit and along the slopes, special attention was paid to the contacts between snow and aufeis in the valley bottoms.

5. Aerial photographs were taken on 21 April and 10 May 1975.

6. The distribution of snow drifting was mapped on Caribou Peak in detail; the directional distribution patterns on Haystack Mountain were similar.

7. In order to obtain a better measurement of total precipitation, both in the form of rain and snow, two specially shielded snow gages were established in the Watershed during October 1976.

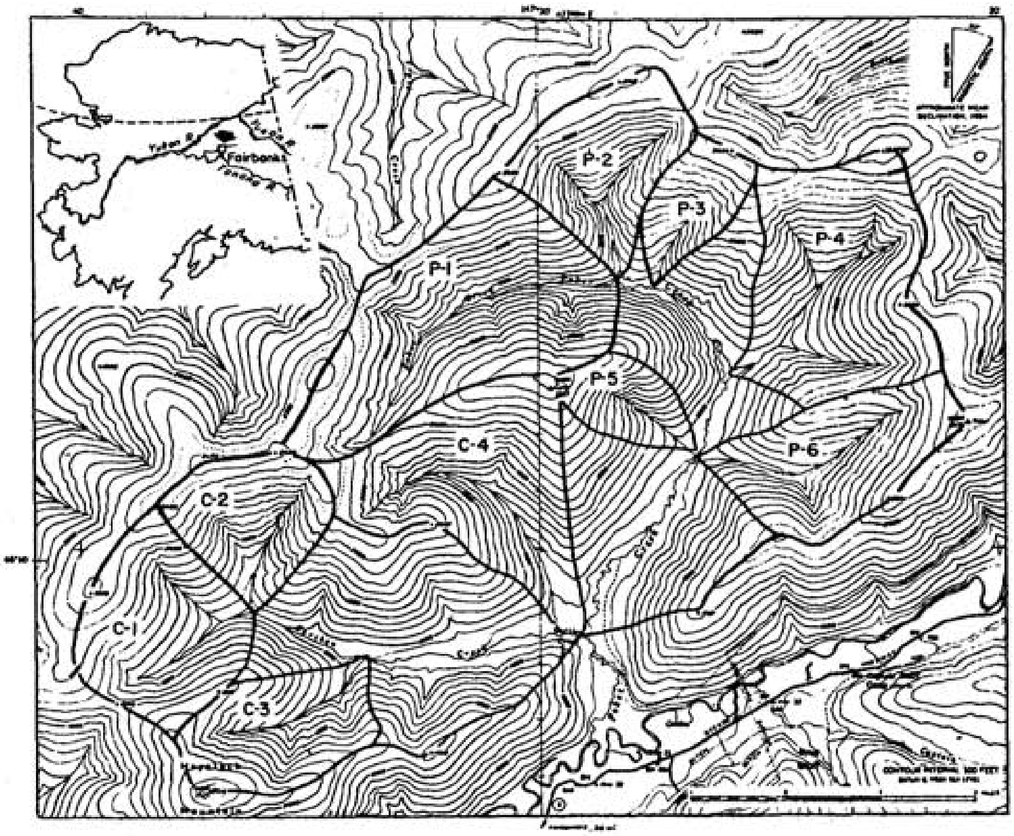

Figure 1. Caribou-Poker Creeks Research Watershed, Tanana River Basin, Alaska, showing subdrainages.

Summary of Results. Snow in the Caribou-Poker Creeks Research Watershed consists mainly of taiga snow with small areas of tundra snow above tree line. The taiga snow has low density with well developed depth hoar. The wind-packed tundra snow is harder and its density is about twice that of the taiga snow (200 and 400 kg m^{-3}, respectively).

The amount of snow precipitation in the Watershed from 1970 to 1977 averaged 1.2 to 1.7 times more than the long-term average value of 10 cm water equivalent recorded at Fairbanks. The long-term total precipitation, rain and snow, at Fairbanks is 28 cm water equivalent. Snow precipitation in the Watershed appears to increase with altitude at rates comparable with rates in the entire Chena Basin. However, the rates vary with aspect, and rates along the southwest slopes are closest to the rates in the entire Chena Basin.

Stream aufeis covers about 1 percent of the Watershed area in spring. When aufeis advances into the tundra snow, the junction between ice and snow is often complex and underlain by water. The main melting of aufeis occurs during the 2 to 3 weeks after snowmelt is completed.

The Research Watershed is an excellent place for establishing long-term research programs on snow and ice because the continuity of experiments can be assured for many years. This should be done because snow constitutes one-third of the total precipitation, and snow and ice dominate the hydrological regime of the Watershed for more than one-half of the year.

Available Data. The National Weather Service has maintained an office in Fairbanks since 1929. It is the only source of long-term climatological data in interior Alaska. Its precipitation record is complete from 1930 to the present and shows an average of 28.7 cm water equivalent per year, of which 10.4 cm comes as snow, and the remaining 18.3 cm as rain. Roughly, the annual precipitation is 30 cm water equivalent with one-third as snow and two-thirds as rain.

In addition to the Weather Service data, three snow courses in the Research Watershed have been measured since 1970. They are part of the Alaskan network of snow courses operated by the Soil Conservation Service. These three snow courses are included in the data base for the Chena Basin which is adjacent to the Research Watershed. The Chena Basin, with an area of 5220 km^2 (2040 mi^2), is 50 times larger than the Caribou-Poker Creeks Research Watershed. It is

> ...in terms of hydrometeorological data, one of the most highly instrumented basins within the entire state. In terms of station-years of data, the available record for the Chena Basin far surpasses that for any other basin, including the research Watersheds such as Caribou-Poker Creeks and Washington Creek.... The primary data base for the Basin includes records from four streamflow locations, four recording precipitation gages, and 17 snow courses located within and adjacent to the Basin. In addition to these primary data, storage precipitation gages are operated during the summer months at five of the snow courses, six-hourly and/or daily precipitation are available from three other precipitation stations, and there are two additional recording precipitation gages with very short periods of record.... The period of record is generally short with most of the summer data limited to the 1970 through 1975 seasons. The winter data generally covers the 1965-1966 through the 1975-1976 seasons, yet a number of the stations were not in existence prior to the 1969-1970 season (Santeford, 1976).

Of the 17 snow courses within and adjacent to the Basin, five are adjacent, with three of these being in the Caribou-Poker Creeks Research Watershed. Data from these three are summarized in table 1.

From the above considerations we see that the Caribou-Poker Creeks Research Watershed is well located with respect to available hydrologic data. More data are available for this region than for any other basin in Alaska.

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Snow Survey of Great Britain

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History

During the Edinburgh Geophysical Assembly in 1936, some of the British members attending the Snow and Ice Commission agreed to form an "Association for the Study of Snow and Ice" under the chairmanship of Mr. Gerald Seligman. It was noted that remarkably little information was available with regard to the frequency with which the higher uplands of Britain are covered with snow. A simple scheme was drawn up by which a number of observers in mountainous districts were asked to send in postcards giving daily reports of snow cover. The first observations were collected in 1938 by Professor Manley, who prepared a summary report covering the seasons 1938/39 and 1939/40.

The survey could not be made during the war years. In 1946, the Association became the British Glaciological Society, now the International Glaciological Society, and the survey was begun again under the directorship of Professor Manley. Full reports were prepared by Messrs. Hawke and Champion for the seven seasons from 1946/47 to 1952/53. Responsibility for the Snow Survey was then, by agreement, passed to the Meteorological Office, whose staff has prepared reports for the 24 seasons from 1953/54 to date.

Organization of the Snow Survey

The original concern of the survey was exclusively with snow conditions over the higher uplands of Britain, and observers were specially recruited from locations where there was a good view of high ground nearby. During the postwar reorganization and over the next few years, a very considerable expansion took place. With Meteorological Office cooperation, many official climatological stations were added to the survey network, and by 1951, contributions were being received from more than 300 observers, scattered over most parts of Britain. Since then numbers have declined, and currently only some 160 stations submit returns; however, with the aim of making the coverage truly representative of all upland and lowland areas of Britain, steps are now being taken to recruit observers to fill all significant network gaps.

Forms to record observations are supplied to each station for each calendar month from October to May inclusive; a few stations (mostly in Scotland) complete forms also for the months of June to September. Days (00-24 Gmt) on which snow or sleet is known to have fallen in the vicinity of the station are noted, and observations are made (preferably at about 09 Gmt) of the depth of undrifted snow covering more than half of the ground nearby. Using suitable hill features which can be identified from the station, observers also record to the nearest 150 m (500 ft), the level down to which snow is lying. There is space for daily remarks and observers are encouraged to note additional information, such as depths of snow drifts near the stations. General comment on the character of snowfall and snow cover during the months is also invited.

Layout of Annual Report

Each Annual Report includes an explanatory introduction, and a map showing the location of all contributing stations (figure 1). Appendix I lists the stations by districts, along with their altitude and the grid reference. Summary texts are given concerning mountainous areas for each of the summer months of June to September, and for Britain as a whole, covering the snow season from October to May. Each of these latter months is then described in more detail, with separate paragraphs on temperature/precipitation, sequence of snowfall, number of days of snowfall, and number of days of snow cover.

The main body of the Report is then presented in tabular form. Table 1 summarizes the total annual number of days of snowfall and of lying snow at 10 representative stations or station pairs over the years since the first full survey in 1946/47. Table 2 presents daily depths of snow at a selection of stations on both low and high ground in all parts of Britain. Table 3 lists all the contributing stations together with their locations (map references) and altitudes. For each month at each station, figures indicate the number of days of snowfall and snow cover, the maximum depth during the month, and the date on which this occurred. Table 4 summarizes observations made at 12 stations of snow lying on the summits of nearby hills and at heights of 750 m on the sides of the hills.

Availability of the Annual Reports is listed in Appendix II.

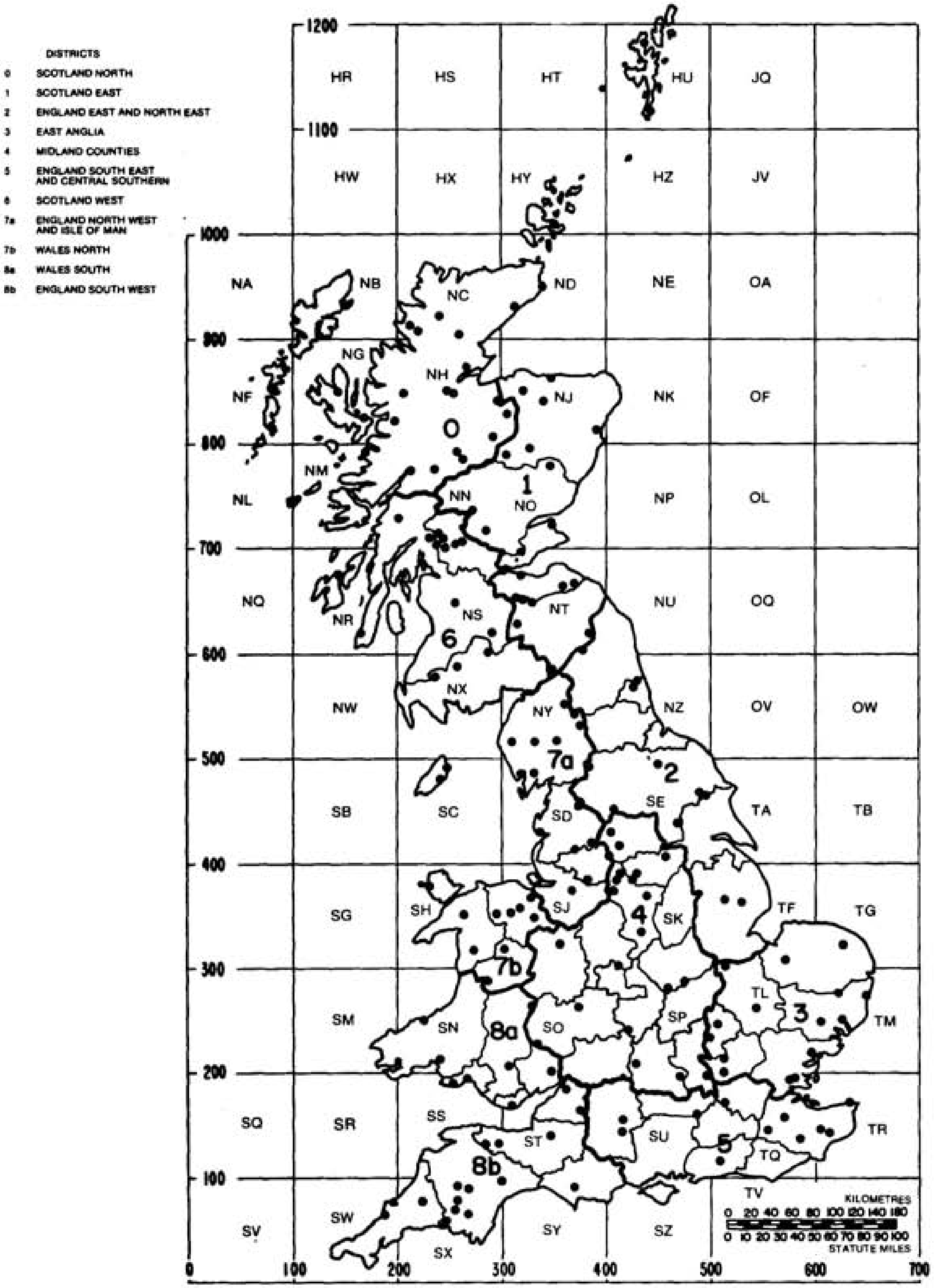

Figure 1. Snow survey stations in Great Britain.

Note: This map grid is based on the National Grid of Great Britain. It is a reference system that has a point of origin southwest of Land's End. The coordinates are parallel and at right angles to an approximate north-south line through the point of origin so as to form a grid square 100 km on a side.

Table 1. Number of days with snow or sleet falling, and snow lying, during each snow season.

number of days with snow or sleet falling											*number of days with snow lying*									
Fort Augustus/Corpach	Balmoral/Braemar	West Linton	Eskdalemuir	Huddersfield Oakes	Buxton	Woburn	Boscombe Down	Exeter	Lake Vyrnwy	Season	Fort Augustus/Corpach	Balmoral	West Linton	Eskdalemuir	Huddersfield Oakes	Buxton	Woburn	Boscombe Down	Exeter	Lake Vyrnwy
4	31	42	65	51	46	34	37	22	42	1946/47	5	72	66	59	64	71	58	42	10	63
26	30	34	49	25	23	13	14	9	33	1947/48	8	53	25	22	15	33	5	11	2	25
–	23	24	31	19	13	7	5	5	20	1948/49	–	23	10	14	10	12	2	1	0	11
–	45	28	46	30	11	7	5	7	23	1949/50	–	29	20	18	10	7	1	1	1	11
–	92	75	79	70	59	29	30	18	72	1950/51	–	102	65	61	31	48	12	10	10	47
23	61	41	45	37	38	20	22	13	40	1951/52	38	52	38	41	22	38	7	8	1	30
19	51	44	44	25	32	26	23	10	34	1952/53	12	61	34	32	11	25	25	4	2	32
24	45	31	36	26	26	14	12	10	23	1953/54	12	40	26	32	24	29	7	15	7	22
28	71	43	52	47	42	28	31	29	40	1954/55	32	82	58	57	37	52	27	16	6	38
31	74	50	54	42	40	23	28	19	34	1955/56	18	59	46	44	39	40	20	12	8	34
17	37	27	34	26	15	12	12	3	22	1956/57	13	14	15	10	10	12	5	2	0	17
36	51	40	48	31	25	19	19	19	27	1957/58	27	61	32	22	23	23	12	6	6	32
15	29	22	25	15	12	7	8	7	21	1958/59	23	60	29	26	19	26	13	9	3	22
20	31	39	38	29	31	13	11	14	30	1959/60	22	40	29	26	20	30	11	8	5	24
14	35	22	33	20	22	7	8	6	20	1960/61	2	31	8	10	6	10	0	0	0	14
36	56	41	67	38	26	17	17	19	39	1961/62	30	88	43	40	25	29	13	5	2	36
26	58	42	62	44	47	42	40	32	43	1962/63	29	90	86	82	70	74	69	64	40	78
18	29	19	40	20	20	14	17	11	19	1963/64	1	35	12	8	12	17	7	2	2	14
28	65	34	63	36	40	20	20	14	43	1964/65	13	71	31	34	20	34	10	15	2	48
28	84	46	87	53	37	18	18	11	42	1965/66	18	93	46	37	39	38	9	13	1	42
22	64	25	82	26	28	4	9	10	27	1966/67	13	53	19	20	7	14	1	1	0	11
26	48	35	66	30	39	23	24	11	32	1967/68	27	78	43	51	22	44	14	10	4	31
21	74	24	71	51	34	24	29	20	39	1968/69	25	83	32	35	53	50	18	5	11	56
28	69	32	96	63	53	34	42	25	57	1969/70	36	96	25	35	40	50	25	16	3	62
6	34	21	46	25	16	17	27	16	20	1970/71	3	28	22	19	10	23	6	14	2	20
10	32	20	52	34	27	11	15	9	25	1971/72	1	29	12	16	12	12	1	2	0	21
22	38	19	54	28	23	9	11	12	25	1972/73	11	44	12	27	15	17	2	2	2	22
22	57	20	58	27	28	8	16	9	36	1973/74	21	49	10	17	9	13	0	2	0	20
11	38	21	56	30	31	18	21	12	42	1974/75	3	37	5	15	3	6	3	3	0	18
10	50	11	63	26	31	9	10	12	29	1975/76	4	38	6	12	2	11	4	0	1	15
26	46	30	72	46	51	19	18	15	51	1976/77	5	67	42	47	31	43	7	4	1	34
27	54	34	70	46	36	21	33	22	48	1977/78	10	75	29	34	23	31	8	9	8	43

Table 2. Daily depth of snow, in centimeters, at selected stations.

Day	Wick	Knockanrock	Inverawe	Whitehillocks	Crammond	Eskdalemuir	Alston	Lanthwaite	Belmont	Riccall	Buxton	Martley	Marham	Penshurst	Dolgellau	Lake Vyrnwy	Merthyr Tydfil	Swansea	Exeter	Okehampton	Day
1																					1
2																					2
3		5	1	1	3	1	1														3
4		5	1	1												5					4
5				T												1					5
6																					6
7																					7
8																					8
9																					9
10		5	1	1	5	6	2		T												10
11		11	1	1	7	6	11		T	1						T				1	11
12		13	1	2	6	5	13				3					T					12
13			1		5		8				2										13
14					3		7														14
15							6														15
16		1					6			T							T				16
17		1				T	9	1	1		2		1		1	1	T				17
18		12				T	9		1	1	2		4		1	1	T			T	18
19		14	1		5	6	15	13	10	T	15	4	3	1		14	11				19
20		14		5	4	7	11		T	T	T	3	3	1		8	11				20
21		12		5	3	5	5		T		T		1			4	9				21
22		5		T			2		T												22
23		3		1		1	3														23
24		*		T																	24
25																					25
26			1			4	3		3		1					1					26
27						11	9		4		3					3					27
28		6		21		6	1				3										28
29		40		25			3				3					3					29
30		40		25		1	3			1						10					30
31		45	4	27	1	9	3	4	T	1	1	3				14	9				31

T indicates snow depth less than 0.5 cm
** indicates snow lying but depth not available*
+ indicates no information available

Table 3. Number of days with snow falling, snow lying, and maximum depth, in centimeters, with the date, during each month and during the season.

			1977			1978					
Station	grid reference	altitude (metres)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Season
DISTRICT O — SCOTLAND, NORTH											
Shetland											
Mossy Hill	HU 396203	229	0 0 — —	5 3 2 20	3 1 1 7	17 8 41 28	15 14 3 15	1 0 — —	7 4 1 10	1 0 — —	49 30 41 28/1
Ollaberry	HU 333836	226	2 0 — —	17 6 11 20	11 1 T 8	20 12 10 29	22 19 23 17	10 4 4 5	11 5 2 14	2 0 — —	95 47 23 17/2
Orkney											
Kirkwall #	HY 483076	26	1 0 — —	11 1 2 20	7 1 1 8	22 4 5 10	13 10 6 18	11 0 — —	8 0 — —	0 0 — —	73 16 6 18/2
Western Islands											
Benbecula#	NF 782555	6	0 0 — —	9 0 — —	4 0 — —	17 2 4 12	8 0 — —	3 0 — —	8 1 2 10	0 0 — —	49 3 4 12/1
Stornoway	NB 459332	3	0 0 — —	10 1 T 16	2 0 — —	16 4 5 31	9 5 3 18	7 0 — —	7 1 T 10	0 0 — —	51 11 5 31/1
Highland											
Achnagoichan	NH 913082	305	0 2 — —	12 11 25 22	2 4 T 9	9 20 120 28	10 23 120 1	11 9 10 16	8 7 8 11	0 0 — —	62 74 120 28/1
Achnashellach	NH 038492	67	0 0 — —	8 5 3 20	5 0 — —	18 14 32 31	8 10 30 1	10 2 5 21	8 3 4 10	0 0 — —	57 34 32 31/1
Ardross	NH 629737	171	0 0 — —	2 3 14 20	2 3 D —	18 16 D —	8 27 54 1	5 9 5 20	9 9 5 10	0 0 — —	44 67
Braemore	ND 074297	155	0 0 — —	10 4 4 20	4 4 2 8	16 12 53 31	12 24 50 1	10 3 1 20	9 6 17 10	0 0 — —	61 53 53 31/1
Broadford	NG 649228	30	0 0 — —	6 1 3 20	1 0 — —	11 7 8 10	2 2 1 12	6 0 — —	5 3 3 11	0 0 — —	31 13 8 10/1
Cassley	NC 396232	99	0 0 — —	7 4 T 20	2 1 1 30	12 14 26 31	11 26 26 1	6 1 3 20	5 4 5 13	0 0 — —	43 50 26 31/1
Corpach#	NN 080764	8	0 0 — —	3 1 • 20	0 0 — —	15 9 5 11	4 0 — —	2 0 — —	3 0 — —	0 0 — —	27 10 • •
Dalwhinnie	NN 634841	362	3 0 — —	15 14 13 17	6 2 1 7	17 16 33 31	14 22 30 1	16 7 13 21	9 2 1 10	1 0 — —	81 63 33 31/1
Fairburn	NH 455528	152	0 0 — —	1 2 1 20	0 0 — —	• • • •	• • • •	• • • •	• • • •	• • • •	• • • •
Fersit	NN 351782	259	0 0 — —	16 8 5 20	3 1 1 30	29 18 46 30	14 22 46 1	4 4 8 20	10 7 1 12	0 0 — —	76 60 46 30/1
Fort William (Br. Al.)	NN 130751	27	0 0 — —	2 2 3 20	0 0 — —	8 11 11 12	2 3 1 13	1 1 1 21	4 4 3 10	0 0 — —	17 21 11 12/1
Glenferness	NH 937430	213	0 0 — —	10 8 23 20	5 0 — —	14 9 8 26	1 1 15 10	11 11 10 19	• • • •	• • • •	• • • •
Glenshero Lodge	NN 562929	268	0 0 — —	15 14 15 20	3 2 T 28	21 19 D —	9 26 D —	18 15 13 20	9 8 4 10	0 0 — —	75 84 • •
Grantown-on-Spey#	NJ 039285	229	0 0 — —	9 12 • •	4 9 • •	17 15 63 30	11 28 67 18	10 8 22 1	8 5 15 10	0 0 — —	59 77 • •
Inverpolly	NC 074134	14	0 0 — —	4 0 — —	1 0 —	12 5 13 31	3 8 10 1	1 0 — —	5 3 9 11	0 0 — —	26 16 13 31/1
Knockanrock	NC 187088	244	0 0 — —	14 5 8 21	6 4 3 8	17 18 45 31	12 21 40 1	14 6 7 21	8 3 14 12	0 0 — —	71 57 45 31/1
Lairg#	NC 578055	107	0 0 — —	12 4 6 20	4 3 • •	20 14 29 31	14 18 30 1	12 1 2 21	8 2 T 10	0 0 — —	70 42 • •
Morar	NM 688922	16	0 0 — —	2 1 2 20	0 0 — —	9 4 8 17	1 0 — —	3 0 — —	4 0 — —	0 0 — —	19 6 8 17/1

The values are arranged in a pattern of four thus: a b
c d

where a *is the number of days on which snow occurred,*
b *is the number of days on which half or more of the ground in the immediate neighbourhood was snow covered,*
c is the greatest depth of accumulated and undrifted snow,
d is the date on which c first occurred

The entry D indicates that no snow depth was measured because of excessive drifting : the entry T indicates that the depth of snow was less than 0.5 cm.

Table 4. Number of days with snow observed to be lying in the mountains.

				1977				1978			
Peak and station	Altitude (metres)	Level	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Highland		a	1	30	31	30	28	31	30	0	181
Ben More Assynt	998	b	1	26	28	30	28	31	28	0	172
Cassley	99	c	0	4	1	14	26	1	4	0	60
Highland		a	3	30	28	31	28	31	30	31	212
Creag Meagaidh	1128	b	1	25	10	28	28	30	26	4	152
Fersit	259	c	0	8	1	18	22	4	7	0	60
Grampian		a	4	30	31	31	28	31	30	21	206
Ben Macdui	1310	b	2	29	31	31	28	31	29	10	191
Derry Lodge	427	c	0	19	18	28	28	18	9	2	122
Central		a	0	23	13	28	26	22	17	9	138
Ben Vane	916	b	0	22	8	27	26	22	17	9	131
Loch Arklet	146	c	0	1	0	20	25	3	5	0	54
Strathclyde		a	0	15	4	24	21	13	6	0	83
Beinn An Oir	784	b	0	15	4	24	21	13	6	0	83
Rhuvaal	20	c	0	0	0	2	0	0	0	0	2
Dumfries and Galloway		a	0	14	4	21	20	9	7	0	75
Merrick	845	b	0	14	4	21	20	9	7	0	75
Bargrennan	110	c	0	1	0	15	1	1	2	0	20
Northumberland		a	0	4	0	24	28	3	4	0	63
Carter Bar	579	b	—	—	—	—	—	—	—	—	—
Catcleugh	250	c	0	2	0	22	28	3	3	0	58
Cumbria		a	0	17	15	22	28	31	15	12	140
Cross Fell	893	b	0	17	15	22	28	31	15	12	140
Alston	287	c	0	2	1	21	16	6	5	0	51
Cumbria		a	0	14	8	26	20	12	8	0	88
Helvellyn	950	b	0	7	4	26	20	8	7	0	72
Dale Head	189	c	0	1	1	15	8	2	5	0	32
Gwynedd		a	0	18	15	26	27	10	12	0	108
Snowdon	1085	b	0	18	11	21	24	10	10	0	94
Bryn Gwynant	95	c	0	0	0	7	12	0	2	0	21
Gwynedd		a	0	12	8	20	18	5	8	0	71
Cader Idris	892	b	0	12	8	20	18	5	8	0	71
Dolgellau	27	c	0	0	0	2	3	0	1	0	6
West Glamorgan		a	0	10	1	8	11	8	2	0	40
Brecon Beacons	879	b	0	10	1	8	11	7	2	0	39
Penmaen	87	c	0	0	0	0	8	1	0	0	9

(a) near the summit, (b) at about 750 m, (c) at station level

See Figure 2 for days when mountains were obscured

The name of the peak is set in italic, the station in roman type

Appendix I

SNOW STATIONS OF GREAT BRITAIN

Note: The first three digits of the grid reference are eastings; the last three are northings. The locations are correct to within 100 m.

DISTRICT 0 - SCOTLAND NORTH

Station	Grid reference	Altitude (meters)
SHETLAND		
Mossy Hill	HU 396203	229
Ollaberry	HU 333836	226
ORKNEY		
Kirkwall	HY 483076	26
WESTERN ISLANDS		
Benbecula	NF 782555	6
Stornoway	NB 459332	3
HIGHLAND		
Achnagoichan	NH 913082	305
Achnashellach	NH 038492	67
Ardross	NH 629737	171
Braemore	ND 074297	155
Broadford	NG 649228	30
Cassley	NC 396232	99
Corpach	NN 080764	8
Dalwhinnie	NN 634841	362
Fairburn	NH 455528	152
Fersit	NN 351782	259
Fort William (Br. Al.)	NN 130751	27
Glenferness	NH 937430	213
Glenshero Lodge	NN 562929	268
Grantown-on-Spey	NJ 039285	229
Inverpolly	NC 074134	14
Knockanrock	NC 187088	244
Lairg	NC 578055	107
Morar	NM 688922	16
Muir of Ord	NH 527500	46
Prabost	NG 418501	67
Ratagan	NG 919197	4
Wick	ND 364552	36

DISTRICT 1 - SCOTLAND E

Station	Grid reference	Altitude (meters)
GRAMPIAN		
Balmoral	NO 260946	283
Derry Lodge	NO 036932	427
Drummuir	NJ 372441	189
Dyce	NJ 883125	58
Glenlatterach	NJ 200546	151
Rochomie	NJ 441633	94
TAYSIDE		
Ardtalnaig	NN 702394	130
Drummond Castle	NN 841178	113
Whitehillocks	NO 448800	258
FIFE		
Leuchars	NO 468208	10
Loch Leven	NT 158988	122
LOTHIAN		
Cramond	NT 180758	26
Hopes	NT 551622	247
Hungry Snout	NT 665633	218
BORDERS		
Baddingsgill	NT 126554	335
Broughton	NT 123296	226
Newcastleton	NY 479870	105
Portmore	NT 260507	305
Sourhope	NT 843203	221
West Linton	NT 150520	244

Station	Grid reference	Altitude (meters)
DISTRICT 2 - ENGLAND E and NE		
NORTHUMBERLAND		
Catcleugh	NT 749032	250
TYNE and WEAR		
Burradon	NZ 269721	67
Gosforth	NZ 240680	52
NORTH YORKSHIRE		
Chelker	SE 051517	223
High Mowthorpe	SE 888685	175
Moorland Cottage (Sedbergh)	SD 807923	343
Osmotherley	SE 458967	147
Riccall	SE 608373	5
HUMBERSIDE		
Sledmere	SE 933648	121
LINCOLNSHIRE		
Revesby	TF 303634	38
Southrey	TF 140664	6
DISTRICT 3 - EAST ANGLIA		
NORFOLK		
Coltishall	TG 262229	17
Marham	TF 726094	23
CAMBRIDGESHIRE		
Cambridge	TL 434604	24
Etton	TF 142048	11
SUFFOLK		
Melton	TM 281506	9
Wingfield	TM 235782	49
Wattisham	TM 025514	89
BEDFORDSHIRE		
Cardington	TL 081464	28
Woburn	SP 964358	89
HERTFORDSHIRE		
Garston	TL 123017	78
Rothamsted	TL 132134	128
ESSEX		
Langham	TM 018339	12
Layer-de-la-Haye	TL 965196	44
Rayleigh	TQ 805910	73
DISTRICT 4 - MIDLAND COUNTIES		
WEST YORKSHIRE		
Huddersfield Oakes	SE 113177	232
Thornton Moor	SE 051334	363
SOUTH YORKSHIRE		
Doncaster	SE 576040	9
Hall Broom	SK 267891	320
Redmires	SK 262857	338
DERBY		
Buxton	SK 060725	307
Edale	SK 097855	293
Howden	SK 168924	258
Littleover	SK 334339	71
Wingerworth	SK 378665	116
Wood Cottage	SK 128896	310
STAFFORDSHIRE		
Hednesford	SK 123017	235
LEICESTERSHIRE		
Market Harborough	SP 732879	96
Stanford	SP 596804	112
Salop		
Shawbury	SJ 553220	72
WARWICKSHIRE		
Shipston-on-Stour	SP 213407	111
HEREFORD AND WORCESTER		
Longtown	SO 322291	172
Martley	SO 743598	53
OXFORDSHIRE		
Brize Norton	SP 289060	84
Shirburn	SU 695971	108
Buckinghamshire		
Little Chalfont	SU 988968	130

Station	Grid reference	Altitude (meters)
DISTRICT 5 - ENGLAND SE AND CENTRAL SOUTHERN		
GREATER LONDON		
Charlton Park	TQ 433745	46
Eastcote	TQ 110881	53
Twickenham	TQ 158718	13
WILTSHIRE		
Boscombe Down	SU 172403	126
Upavon	SU 162552	179
SURREY		
Camberley	SU 867600	66
KENT		
Biddenden	TQ 850362	52
East Malling	TQ 708571	32
Lyminge	TR 138405	182
Manston	TR 335666	44
Penshurst Place	TQ 528440	40
Wye	TR 057469	56
WEST SUSSEX		
Washington	TQ 118135	23
DISTRICT 6 - SCOTLAND W		
STRATHCLYDE		
Inverawe	NN 021316	23
Lanark	NS 875434	152
Leadhills	NS 888153	388
Loch Sloy	NN 293105	204
Machrihanish	NG 663226	10
Rhuvaal	NR 426792	20
South Moorhouse	NS 529508	249
Tiree	NL 999446	9
CENTRAL		
Brig o'Turk	NN 537063	84
Couligarton	NN 454007	49
Glengyle	NN 388133	122
Loch Arklet	NN 376096	146
Loch Vennachar	NN 598063	84
Stronachlachar	NN 401103	117
DUMFRIES AND GALLOWAY		
Bargrennan	NX 361789	110
Drumlanrig	NS 852001	107
Eskdalemuir	NT 235026	242
Forrest Lodge (Dalry)	NX 555866	152
DISTRICT 7A - ENGLAND NW AND ISLE-OF-MAN		
CUMBRIA		
Alston	NY 717471	287
Dale Head	NY 313175	189
Ennerdale	NY 085153	117
Geltsdale	NY 575537	229
Hawes Water	NY 503159	213
High Nibthwaite	SD 294898	54
Lanthwaite	SD 165851	44
Moor House	NY 758328	556
LANCASHIRE		
Bacup	SD 847198	404
Belmont	SD 692142	247
Slaidburn	SD 717547	192
Squires Gate	SD 316317	10
GREATER MANCHESTER		
Ringway	SJ 818850	75
Strinesdale	SD 975066	244
CHESHIRE		
Northwich	SJ 656729	14
ISLE OF MAN		
Maughold Head	SC 498914	70
Snaefell	SC 397880	614

Station	Grid reference	Altitude (meters)	Station	Grid reference	Altitude (meters)
		DISTRICT 7B - WALES N			
GWYNEDD			Cae Lywyd	SJ 269482	280
Bryn Gwynant	SH 642513	95	Clawdd Newydd	SJ 078521	300
Dolgellau	SH 732177	27	Mount Pleasant (Mold)	SJ 256663	153
Valley	SH 310758	10			
CLWYD			POWYS (NORTH)		
Alwen	SH 956528	335	Lake Vyrnwy	SJ 017188	303
Bwlch Tunnel	SJ 164580	277	Moel Cynnedd	SN 843877	358
		DISTRICT 8A - WALES S			
DYFED			WEST GLAMORGAN		
Aberporth	SN 242521	133	Penmaen	SS 531889	87
Towy Castle	SN 406141	84	Swansea	SS 655925	23
POWYS (SOUTH)			MID GLAMORGAN		
Evancoyd	SO 261630	227	Merthyr Tydfil	SO 048071	235
SOUTH GLAMORGAN			GWENT		
Barry	ST 077668	210	Crumbland	SO 474024	245
		DISTRICT 8B - ENGLAND SW			
AVON					
Bath	ST 751638	118	Chagford	SX 661866	381
Filton	ST 598802	59	Exeter	SY 001933	32
SOMERSET			North Hessary Tor	SX 585735	427
Exton	SS 962338	335			
Hawkridge	SS 877327	314	Okehampton	SX 593943	240
Glastonbury	ST 503400	15	Plymouth	SX 514529	49
DORSET			Yalland	SX 690628	264
Dorchester	SY 697900	6	CORNWALL		
DEVON			Bastree	SX 244765	232
Burrator	SX 553680	230	St. Mawgan	SW 871642	103

Appendix II

AVAILABILITY OF SNOW SURVEY REPORTS

Snow season	Published in
1938/39 and 1939/40	*Royal Meteorological Society. Quarterly Journal*, January 1941.
1946/47 to 1952/53	*Journal of Glaciology*, no. 3, 5, 7, 9, 11, 13, and 15.
1953/54 to 1955/56	*Meteorological Magazine*, December 1954, December 1955, and December 1956.
1956/57 to 1967/68	*British Rainfall*, 1957 to 1968.
1968/69 to 1975/76	Not published; limited number of copies available from the Meteorological Office* at £1 per copy.
1976/77 onwards	Published by the Meteorological Office* from whom they be obtained at £2 per copy or £5 for a 3-year subscription.

* Meteorological Office (Met 0 3b), London Road, Bracknell, Berkshire RG12 2SZ, England.

Snow Investigations in Norway

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Snow Investigations in Norway

The western part of Norway has a fairly steep topography with mountains reaching far above the tree line. The population, however, is concentrated in areas at sea level or close to it. In many places, avalanches run almost every year, and roads and railways are, in many cases, placed so that they will normally not be hit by these fairly well known avalanche tracks. However, unusual snow conditions during single winters may cause avalanches to run along "unusual" tracks and cause damage to roads, railways, telephone lines, power lines, or inhabited areas. History can tell about the loss of many lives in western and northern Norway, where such avalanches are relatively frequent. Avalanches are also quite common in high mountain areas elsewhere in the country, but most of them occur in relatively remote and uninhabited areas and are hardly noticed by anyone.

The first snow investigations in Norway cannot be referenced here, because single researchers have dealt with the problem locally for a long time. The first official step was made in 1951 when the Department of Agriculture created a position for a consultant in avalanche protection. The first person in this position started the valuable work of mapping all known avalanche tracks. He also proposed defense structures in places of great avalanche risks. However, after some years, this activity was terminated and no snow investigations or avalanche work were carried out for a few years.

In 1963, several government institutions felt that it was regrettable that nothing had been done to develop defenses against avalanches; and it was understood that research would be necessary to give better advice regarding new settlements and the design of proper protection constructions. A committee was created and at the end of 1964 a snow researcher was appointed. In 1968, he got an assistant engineer, and they worked together in various parts of the country up to 1971. Then it was decided that the Norwegian Geotechnical Institute should take over all snow investigations and practical arrangements regarding avalanches, whereas the Norwegian Water Resources and Electricity Board should be responsible for the hydrology of snow, since snowmelt water is an invaluable resource in water power production.

During the years 1964 to 1971, a great number of snow observation stations were created in Norway, most of which were in the southern part of the country, which has the highest population density. A relatively simple daily observation program and a somewhat larger biweekly observation program was designed to provide data for a general study of the development of the snowpack during the winter. All observations were made by local people, but inspections were regularly made by one of the two government snow researchers.

The following daily observations were made: air temperature, wind direction and velocity, precipitation, snow depth, and snow temperature at the surface and at depths of 10 and 30 cm. The strength of the snow surface was also measured by a special device.

The biweekly observations consisted of more comprehensive pit studies. The thickness of various snow layers, snow density, temperature, grain size, etc. were observed. A complete ramsonde profile was also made.

The data from these stations were used both for general studies of variations in the various parameters throughout the winter and to predict avalanche danger. However, the small size of the research group made it impossible to produce avalanche forecasts on a regular basis, although they were made on certain occasions. Much of the research group's time was used to meet requests from various agencies for advice, particularly with regard to road construction and settlement developments in areas where steep topography indicated risk of future avalanches. This kind of service is now provided by the Norwegian Geotechnical Institute, where an increasing staff of researchers and technicians have started a more extensive avalanche study. A substantial field observation station has been built in Grasdalen, Western Norway, where good accomodation and laboratory facilities are available.

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Focus on U.S. Snow Research

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I. Introduction

In the past decade, several reports (see bibliography) have mentioned the impact of snow on society and have stressed the need for basic research on the properties and processes associated with all forms of snow. Most of these reports have recognized the importance of snow in the environment, but have not attempted to quantify the economic impact of snow. Due to the fact that snow influences so many facets of our environment, an accurate economic evaluation of its impact is, at best, difficult and, for this reason, this omission is understandable. For example, it is widely recognized that the seasonal veneer of snow is an important factor in the heat budget and climate of the earth, but placing a dollar value on this factor is very difficult. This paper provides several examples which attempt to demonstrate the economic effects of snow, thereby giving an economic justification for both increasing snow research support and developing a more coordinated, broad scale approach to problems caused by the presence of snow.

II. Impact of Snow

The widespread impact of snow on the U.S. economy is illustrated here in five categories - agriculture, energy production, floods, transportation, and recreation. The dollar values given for each of these categories only provide a sense of the financial impact of snow, because no simple summation of snow's financial impact is possible. For example, the use of salt on highways causes about $3 billion in obvious damages each year (Water Information Center, 1976). To this value should be added other costs that are much more difficult to appraise, such as those resulting from the disruption of the natural ecological balance along roadways and costs from increased hypertension caused by higher levels of sodium in local water supplies. Thus, while we recognize that the economic impact of snow is substantial, only a lower limit of the overall impact will be suggested by the monetary figures given here. However, even these minimum estimates indicate the need for a thorough review of the nation's commitment to snow research and data collection.

Agriculture. Snow can be both beneficial and harmful to the agricultural industry. For example, water, originating as mountain snow, is utilized in irrigation in the semi-arid Western States. To alleviate the water supply problem in the Northern Great Plains, attempts are made to keep the snow well distributed over cultivated fields and pastures. Snow is very harmful to the agricultural community when, for example, spring blizzard conditions and blowing snow damage cattle and sheep ranching. In the fruit growing areas of the Great Lakes, snow damage to trees occurs frequently. In other Central States, heavy seasonal snowfalls or late snowfalls often cause wet soil conditions which delay planting and reduce the growing season and harvest.

In the Northern Great Plains, 6-9 cm of precipitation in the form of snowfall comprise about 20 percent of the total annual precipitation. This amount of snow is important to agriculture in this region for several reasons: 1) it provides protection against the winterkill of wheat and other plants; 2) it reduces soil freezing; and, 3) it helps replenish water in the soil. The latter is particularly important to grain production in the Northern Great Plains. The normal climate of this area is conducive to the growth of small grains and cool-season grasses. However, a good grain yield is dependent on having some stored soil water in addition to the precipitation received during the growing season. Hence, above a threshold of about 15 cm soil water, wheat yields are increased by 7800-13,500 kg per km for each additional cm of soil water available. Considering that over 40,500 km of wheat were harvested in North Dakota during 1974 (U.S. Department of Agriculture, 1975), and over 60,750 km were harvested in Saskatchewan (Canadian Grain Council, 1974), the economic effect of additional soil water is apparent. Using 1974 market prices, each additional centimeter of water above the threshold value represents a potential return of at least $75 million from the North Dakota wheat crop alone.

Management of the snow could increase crop production in the Great Plains by causing the snow to be trapped and held where needed. Without management, the snow tends to drift into coulees or draws where the resulting meltwater is carried away without contributing to the effective soil water on the agricultural fields. Also, the sparse snow cover may melt and run off before the soil is sufficiently thawed to permit infiltration. Would the control of the aerodynamic roughness of these fields by plowing or cropping practices cause maximum deposition and retention of snow on the field itself? Perhaps so, but conclusive research on this problem is severely handicapped by our limited understanding of the basic dynamics of snow distribution processes.

The impact of snow on irrigation farming of the Western States is also large. Of the 3.1×10^{10} m^3 of irrigation water used annually in the Central Valley of California, some 1.6×10^{10} m^3· originate as snowmelt. Using the 0.97×10^{-2} dollar per m^3 value established by the Kings River Water Association, this snowmelt water alone has a value of $156 million per annum. Similar monetary results have been found for irrigation projects in all of the Western States. The gross and net values of stream irrigation water in dryland areas of 10 Western States have been estimated as $521 and $129 million, respectively (1973 dollar value, Earth Satellite Corporation, 1974); more than half of this water is probably derived from melting snow.

Water for irrigation is currently managed through the operation of reservoirs and water distribution systems. The reservoirs are used to hold snowmelt runoff until it is needed for the growing crops, but many of the reservoirs are also used for flood control and hydroelectic power, providing specified river flows according to legal agreements, etc. Because of these competing uses, the amount of water which can be made available for agriculture at the right time depends critically on the accuracy of reservoir inflow forecasts. Could the forecast accuracy be substantially improved through the use of new snow distribution and snowmelt runoff models? Could the snow accumulation, transport by wind, and melt in the drainage basin source areas be managed to increase and delay the runoff, thereby diminishing the constraints on reservoir operation? These tasks seem to be possible, but increased knowledge of the physics of snow accumulation and the energy balance of melting or evaporating snowpacks as well as an improved snow monitoring system are required before major advances can be made.

Energy Production. The impact of snow on energy production is extremely important, but highly diverse. It is most significant in the Western States where most of the water used in the production of electrical energy originates in the mountain snowpacks. There are many public and private power projects in this region, as well as in the Northeast and Upper Great Lakes Region, which utilize snowmelt runoff for the production of electrical power. Although the benefits are difficult to quantify, some valuable insights can be gained if we briefly examine one river system.

The Columbia River Basin has 159 hydroelectric power plants with 21×10^6 kW of power-generating capacity (as of 19 December 1974) which supply about 80 percent of the electric energy needs of the Pacific Northwest (Limpert, 1975). The system employs 81 reservoirs with 50.4×10^9 m^3 of usable storage. However, the annual runoff at the downstream station has varied between 149 and 316×10^9 m^3 with an average of 228×10^9 m^3 (Limpert, 1975). This low storage-to-runoff ratio and the large differences in annual flow show that accurate runoff forecasting is needed in order to make optimum use of storage for flood regulation and power generation.

In the Upper Missouri Basin, the Pacific Northwest, and other Western States, much of the runoff is supplied by snowmelt. The fact that the snow on the ground can be measured, and thus the runoff predicted, permits more efficient management of these river systems. The energy value of forecasts lies in the "reduction in hedge", i.e., in the absence of accurate forecasts, some of the runoff water must be wasted by spilling it over dams instead of running it through turbines in order to satisfy a safety factor (hedge) required for flood control and other competing requirements. If this wastage of water can be reduced or eliminated through more accurate forecasts, additional electrical energy can be generated.

A recent analysis shows that a modest improvement in streamflow forecast accuracy, obtained, for instance, by improved monitoring of snow-covered area, would result in large economic savings as well as increased generation of power. Reduction from 20 percent to 15 percent in the error of the 1 April forecast of runoff into Hungry Horse Reservoir, Montana, for instance, would yield hydropower benefits at that reservoir alone of $1.5 million per year. Total benefits in the system including this and four reservoirs downstream of $4.5 million per year (Earth Satellite Corporation, 1974,). The same modest reduction in forecast error in all major hydropower systems would lead to total benefits for 11 western states, ranging from $9.3 million in 1977 to $14.8 million in 1976 (Earth Satellite Corporation, 1974).

Additional benefits would accrue through increased power generation, reduction in flood damage, improved environmental protection, more efficient delivery of irrigation water, and decreased need for oil imports.

Can an operational snow monitoring program provide this increase in forecast accuracy? Because those remote sensing methods which have been shown to be useful for monitoring snowpacks from satellites cannot penetrate a cloud cover, active or passive microwave techniques will undoubtedly have to be used. Unfortunately, the electrical properties of snow, especially the volume scattering characteristics, are not yet sufficiently understood, and an all-weather, efficient remote sensing system has not yet been designed. As in the case of providing water for irrigation, new numerical models could be developed to improve forecasts. Or, direct snow management techniques might be considered to improve runoff water availability, if increased knowledge were available.

Not only does snow play a direct role in energy production, but it is also indirectly responsible for helping to provide some of our energy requirements. In the development of the northern oil and gas reserves, snow is useful as a building material for roads, airstrips, and construction pads. Current practices in Petroleum Reserve-4, Alaska, require the "harvesting" of large quantities of snow for the construction and maintenance of numerous roads and drilling pads used throughout the winter months (Francis, 1977). Through the use of snow as a construction material, the initial impact on the environment is greatly reduced and the impact of a gravel roadway is eliminated completely. At the same time, snow has been the cause of higher costs in the development of the trans-Alaskan oil pipeline. For example, it has proven necessary to design buildings specifically to minimize the adverse effects of drifting snow.

A last example of the impact of snow on our energy resources is the effect that snow has on the transmission of electrical power from the generating plant to the user. Snow is often the cause of damaged power lines and disrupted service. For example, during a single snowstorm in 1974, the transmission system of Ohio Edison Power Company suffered $4.5 million in damages. The cost of repairs, cost of purchasing replacement power, and loss of income from reduced generating capacity caused a loss in annual earnings of 42 percent (Ohio Edison Company, 1974). These figures do not include the losses to customers resulting from power outage, nor the discomfort experienced by residential customers left without heat during the outage.

Floods. One of the major harmful results of snow is river flooding due to rapid snowmelt. Estimates of property damage due to floods show that flood losses are increasing to values above the average annual loss of $1 billion experienced during 1951 to 1965 (U.S. Congress, 1966). During that same period, over 70 persons per year were killed by floods (U.S. Department of Commerce, 1969), despite forecasting and protection systems.

An example of the value of good snowmelt forecasts in providing adequate flood forecasts can be obtained by examining data from the Kansas City River Forecast Center (RFC) of the National Weather Service (NWS). The RFC experiences problems caused by snowmelt flooding every year in some part of its region of responsibility. During March and April of 1973, it was estimated that flood forecasting from the Kansas City RFC prevented $450 million in property damage (Mondschein, 1974). The spring snowmelt flood of 1969 in the Upper Midwest caused an estimated $100 million in damage, killed 10 people, and forced 25,000 people to leave their homes in spite of early flood forecasting that permitted advance action, preventing an additional $250 million in damages and saving an unknown number of lives (Paulhus, 1971).

The snowmelt flood not only causes problems with riverside development, but also has an adverse effect on river transportation. The U.S. Army Corps of Engineers reported a delay of 800,000 tons of shipping for 12 days on one stretch of the Mississippi during one flood period. This represents a loss of nearly $6 million to the tug operators alone (Hanson, 1975).

Forecasting of snowmelt floods could be made more efficient, timely, and precise if the relation between energy-balance processes at the snow surface and larger-scale atmospheric conditions were well established. This, however, cannot be done until the complex processes of energy exchange at the snow surface are better understood.

Transportation. Snow brings many benefits to the recreational, hydroelectic, and agricultural industries, but is a source of cost and inconvenience to the average traveler. The heavily traveled highways of the United States are maintained by state and local governments under the "bare roads" policy. The rationale behind this policy is easily understood if one considers how heavily this nation's roads are used. For example, 82 percent of the commuters living in or near our major cities use automobiles. In the city of Chicago alone, it has been estimated that snow removal prevents 15,250 accidents each year. These accidents represent potential losses of over $4 million, not to mention the suffering due to death and injury (Minimizing Deicing Chemical Use, 1974). It has also been shown that only 2 in of snow on Chicago's highways increased fuel consumption by 50 percent and caused millions of commuters an average delay of 30 minutes each, representing a substantial economic loss (Claffey, 1972).

While the benefits of the "bare roads" policy are obvious, the national expenditures for salt, plows, fuel, and labor, as well as the countering of the effects of pollution and corrosion are enormous. For instance, the national expenditure for salt alone is about $200 million per year; in addition, the salt-related highway damage is about $500 million per year. The economic value of the salt-kill of trees and the salt-induced deterioration of water supplies, although hard to estimate, have both been thought to cost at least $200 million per year (Water Newsletter, 1976). Automobile deterioration caused by salt also offsets the benefits of bare roads. In Boston, Anderson and Auster (1974) estimated salt-induced deterioration of automobiles at $44 per car per year or $119 million per annum for the Greater Boston area. While public opinion tends to force decrease in the use of salt for road maintenance because of the high costs of pollution and vehicle corrosion, the effects of reduced mobility are unacceptable in our society. The economic loss in any of our major cities would reach hundreds of millions of dollars per year. It is clear that an immense effort is needed to develop better ways of preventing the bonding of compacted snow to pavements, while at the same time reducing the usage of salt.

The problems of snow removal on highways seriously affect both rural and long distance travel. For example, when a 27 km (17 mi) stretch of Interstate Highway 80 west of Laramie, Wyoming, was opened to traffic during the winter of 1970-71, one or more lanes of the highway were blocked by snowdrifts during almost every snowstorm and/or period of high winds. Conventional snow removal techniques were expensive and inadequate to keep the road open. Steep snowbanks were left along the road causing reduced visibility and aggravating the snowdrift situation. For the first winter, the snow removal cost was about $310 per kilometer of roadway per centimeter of precipitation (Tabler, 1973). Then, the Wyoming State Highway Department and the U.S. Forest Service devised and installed a series of snow fences to reduce the adverse effects of blowing snow. The results of this effort were a general reduction in the snow removal cost such that during the 1974-75 season, the cost was reduced to $117 per centimeter of precipitation per kilometer of roadway. This was less than 40 percent of the cost prior to the research study and the implementation of corrective actions. The accident rate was also reduced, and the general roadway visibility greatly increased (Tabler, 1973).

High snow removal costs are not limited to the Mountain States, but are common throughout the entire northern tier of states. In fiscal year (FY) 1969, the Ohio Department of Highways calculated the annual direct cost for snow and ice control on its Interstate routes at $753 per centerline kilometer. The total direct expenditure for Ohio during FY 1969 amounted to $6.2 million, while the FY 1970 expenditure increased to nearly $14 million. These figures do not include the additional cost for snow and ice removal from county and township roads, from highways and streets within cities, nor from the Ohio Turnpike, all of which are the responsibility of other agencies or organizations (Miller, 1970).

Airports also incur great expenses due to snow removal. Although highly variable from year to year, the three major airports in the New York City area have had snow removal costs in excess of $4 million per season per airport (Flagg, 1975). Airport safety is also affected by the presence of snow. During FY 1974, there were 60 snow-related interruptions of airport glide slope devices, and many more snow-related outages of other aircraft navigation devices (Barkalow, 1975).

When extrapolated to a national scale, these statistics on snow-related transporation accidents are very impressive. Could the negative impacts of snow on our transportation systems be diminished through new, innovative management techniques? Better understanding of the mechanics, thermal characteristics, and adhesive properties of snow and of the dynamics of snow drifting would undoubtedly permit more efficient snow plowing and snow and ice melting with less environmental impact, as well as improved tire traction on snow, better design of highways to alleviate snow and ice problems, and more efficient prediction and monitoring of snow drifting and deposition.

Recreation. Many recreational facilities and industries rely heavily on snow for success. The sale of ski equipment, snowmobiles, transportation to and from recreational areas, user fees, lodging and meals, special clothing, fuel for operating recreational vehicles, etc., are all contingent upon the quality of the snow cover. In addition, large expenditures, both private and public, are made to improve recreational conditions and thus increase the net returns from the operation of snow-related recreational areas. These expenditures include such items as snow grooming, snow making, avalanche control, and construction of snowmobile trails and race tracks.

During the 1973-74 season, there was an average of 113,598 skier-days per ski area or nearly 45 million skier-days nationally (Goeldner and Dicke, 1974). The average capital investment at each ski area is $2.34 million, representing nearly $1 billion nationally. During the 1973-74 season, snow conditions were poor and 53 percent of the areas of the National Ski Area Association lost money, even though the average gross income per ski area was $1.22 million, or nearly $500 million nationwide. The areas which showed a profit were almost exclusively those which had good natural snow conditions. Virtually all of the areas which had snowmaking facilities did not show a profit. This demonstrates that the skier is highly responsive to snow conditions and, therefore, small variations in snow conditions and snow management could result in large changes in the local economy.

In addition to the cost of lift tickets at the ski areas, related expenditures for equipment, transportation, lodging, and meals are also significant. Typical expenditures for equipment, skis, boots, bindings, poles, and clothing, could total \$400 to \$600 per skier and be amortized over a 2- to 5- year period. If a skier drives 56 km to the recreational area at a cost of \$0.09 per kilometer, then the cost of getting to and from the ski area is close to the \$10.75 average daily expenditure that he would make at the ski facility. From these examples, it is clear that the \$500 million spent at the ski areas per se is only a small fraction of the total money spent in the ski industry. Because the ski industry is so enormous and yet so dependent on the quality and quantity of snow available, the intensification of snow research could benefit the economy enormously.

The impact of snow on recreation is not limited to activites such as skiing or snowmobiling. Hunting is another recreational pastime which is affected by snow conditions. In many areas of the country, snowfall has a direct influence on the number of hunters, the size of the game harvest, and the total expenditures made during a hunt. For example, Colorado had an above average snowfall during the winter of 1972-73. The presence of this heavy snow cover was believed to be a major contributing factor in the estimated winterkill of 11,000 deer in the Piceance Basin, an area of 4144 km^2 (1600 mi^2) and 1,400 deer in the Parachute Creek Basin, 518 km^2 in area (200 mi^2). Using the Colorado Division of Wildlife's estimate of \$700 per deer, the loss in potential income resulting from the snow-related winterkill in these two small areas alone represents nearly \$9 million. Assuming that the value of \$700 per deer is a resonable estimate of the value of all big game animals, such as deer, elk, antelope, moose, and caribou, it is obvious that the effect of snow on the big game industry on a national scale is highly significant. Increasing the snowfall by weather modification, therefore, could have serious consequences on the hunting industry.

Unfortunately, the loss of life directly attributable to snow is not limited to game animals. As activity increases in the back country during the winter months, the potential for injury and death from avalanches, exposure, hypothermia, and frostbite also increases. The statistics on avalanche deaths are a good example of the national trends. For the winters of 1950-51 through 1963-64, there were an average of four deaths per winter, of which 56 percent were recreation related; for the winters of 1964-65 through 1969-70, the average number of deaths increased to five, and 75 percent were recreation related; for the winters of 1970-71 through 1974-75, the average had increased to 12, of which 90 percent were recreation related; and for the last two winters, the average has jumped to 18, with 97 percent recreation related (Williams, 1975). These statistics demonstrate the increasing need for snow data collection, an expanded avalanche forecast network, and especially, an expanded program for educating the public about the hazards of avalanches.

Snow, thus, has major positive and negative impacts on recreation in the United States. Techniques for generating artificial snow and managing snow properties to benefit recreation are used in certain ski areas. Also, hazard prediction, coupled with protective structures, is now being used in some ski areas and travel corridors to minimize loss of life and property due to snow avalanches. The snow-related or snow-impacted recreation industries are so large and diverse, however, that the present snow management tools used in ski areas must be considered as just a beginning. Many other management techniques could be used to increase the recreationists' enjoyment of snow-covered terrain, such as control of snow distribution or hardness. In wilderness areas of pristine natural beauty, direct management of the snow is not desired; however, the prediction or knowledge of snow conditions may still be useful. Very few of the possible techniques for snow management or the prediction of snow conditions have been identified and exploited. This apparently is due to a lack of general background knowledge of snow physics, snow mechanics, and snow climatology, which must serve as a foundation for the development of practical, snow engineering advances.

Many other impacts of snow on society could be mentioned. Those listed above deal only with certain aspects of food, energy, protection from flooding, transportation, and recreation. Common to all of these discussions is an obvious hierarchy connecting the impact of snow on society to the research needed to alleviate or optimize that impact:

1. Impact of snow on society (problem or opportunity)

2. Management possibility (to alleviate the problem or optimize the opportunity)

3. Specific research application (to evaluate and develop the management possibility)

4. Fundamental principles and processes (to provide the background information required for the specific research application)

The impacts of snow on society, the management possibilities, and the specific research applications illustrated in the previous section are highly diverse. Much of the existing research on snow has been equally diverse and uncoordinated, yet the underlying principles and processes are common to all. Strengthening this basic, fundamental pool of knowledge and intercommunicating the separated research application efforts could result in a more rapid and efficient solution of snow-related problems that affect our society.

III. Existing Research Efforts

The far-reaching effects of snow on the U.S. economy, as well as the multidisciplinary nature of the problems caused by snow, were illustrated in the previous section. With these ideas in mind, it is not surprising that research related to snow has evolved into a highly diverse set of specific studies oriented towards solving specific problems. Often the understanding of snow and its interaction with the problem under study has been lost in the overall objectives of the project. For example, we are now able to obtain images of the snow cover at microwave frequencies, but we lack the basic physical understanding of the electromagnetic properties of snow that is required to make a proper interpretation of these images. As a result, the problems of understanding the properties and processes associated with the snow, per se, have commonly not been attacked directly, and much research has been repetitive and unproductive. The magnitude and varied nature of the current research effort concerning snow-related problems is indicated by the diverse list of current snow research projects in the United States (U.S. Army. Cold Regions Research and Engineering Laboratory, 1975).

Table 1 is a listing of the federal agencies and state governments which participate in snow research either through direct research or through funding of research efforts performed by others. If the list of agencies and/or organizations involved with snow research were expanded to include those groups that use snow data and information in a direct application, the list would include virtually all agencies within the Federal Government, most State Governments, and numerous private organizations and companies. For example, the Federal Housing Administration uses snow data to set design criteria for snow loads on buildings. The Bureau of Indian Affairs and the Public Health Service use snow data to design water and sewage facilities for native villages in Alaska.

The centers for snow research shown in table 2 are the only ones known to have two or more full-time professional staff charged with the primary responsibility of conducting snow research. It is apparent from these tables that the current snow research effort involves many small projects widely dispersed throughout the public and private sectors. Most of these projects are oriented toward examining specific applied problems with only very limited support being given to the basic research necessary to develop a fundamental understanding of the physical properties and the processes affecting the behavior of snow. This does not imply that most of the past and/or present snow research has been a waste of time and effort, but only that the maximum return from the research has not been achieved because of the lack of a central focus and coordination among the various projects.

IV. Future Direction of Snow Research and Data Collection

Although it is clear that the economic costs and benefits of snow are enormous, the current effort on the subject is highly fragmented and could benefit from serious evaluation and coordination. Some recommendations that are considered essential in order to solve the problems associated with the effective utilization of the snow resource are the following:

1. Snow Data System. The existing snow data gathering systems have developed through the needs of the various organizations and interest groups using the data. Many organizations, the Cooperative Snow Survey, Soil Conservation Service, National Weather Service, state agencies, ski resorts, and a host of other private "user" organizations, are involved, but their objectives are usually quite different.

While it is not reasonable to suggest that one government agency can provide all of the data needed by all the various user groups, some elimination of duplication and improved data collection is clearly possible. A group of snow experts should be established to review existing data collection programs and requirements. Once the overlaps and gaps in the existing data collection networks have been identified, the task of eliminating costly duplication and improving the quality and generality of the data collection techniques could begin. Also, a thorough review of the methods used to gather snow data is necessary. Existing methods can probably be improved by introducing space-age technology. New devices necessary for the collection of the snow data must be identified, and the research and design necessary for their manufacture initiated.

2. Glaciological Provinces. Although it is known that snow conditions vary rather systematically between different geographic regions, little has been done to quantify these changes. Because of the lack of information on this subject, many cases which, at first sight, appear to be "duplication of effort", actually turn out to be similar measurements performed on quite different types of snow. Snow is a highly dynamic material which varies greatly from one environmental setting to another. The application of basic scientific principles must be made in all settings but, for a specific engineering problem, the pertinent material properties of the snow must be determined at the specific site and time

Table 1. Summary of agencies involved in snow research.

- U.S. Department of Agriculture
    - Agriculture Research Service
    - Cooperative Extension Service
    - Soil Conservation Service
    - Forest Service
- U.S. Department of Commerce
    - National Oceanic and Atmospheric Administration including the National Weather Service
- U.S. Department of Defense
    - Air Force
    - Army
    - Navy
- U.S. Environmental Protection Agency
- U.S. Federal Energy Administration
- U.S. Department of Interior
    - Bureau of Land Management
    - Bureau of Outdoor Recreation
    - Bureau of Reclamation
    - Fish and Wildlife Service
    - Geological Survey
    - National Park Service
    - Office of Water Resources Research
- U.S. National Aeronautics and Space Administration
- National Science Foundation
- U.S. Department of Transportation
    - Federal Aviation Administration
    - Federal Highway Administration
- State Governments (Including Universities)

Alaska
Arizona
California
Colorado
Connecticut
Florida
Hawaii
Idaho
Illinois
Indiana
Iowa
Kansas
Maine
Maryland
Massachusetts
Michigan
Minnesota
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New York
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
South Dakota
Texas
Utah
Vermont
Washington
Wisconsin
Wyoming

Table 2. Centers for snow research[*]

- U.S. Army
    - Cold Regions Research and Engineering Laboratory
      Hanover, New Hampshire
- U.S. Forest Service
    - Pacific Southwest Forest and Range Experiment Station
      Berkeley, California
    - Rocky Mountain Forest and Range Experiment Station
      Fort Collins, Colorado
- U.S. Geological Survey
    - Project Office - Glaciology
      Tacoma, Washington

[*] Research stations with two or more full-time professional staff specifically assigned to snow research projects.

of the problem. Moreover, snow data and study results can not be blindly transferred from one geographic area to another. Rather, in transferring information from one location to another, consideration must be given to the similarities and differences between the sites and the relative importance that one process may have over another.

It is currently believed that there are at least 12 major "glaciological provinces" in the United States where the snow cover has distinctly different characteristics. These distinguishing characteristics should be identified and documented in each province. The environmental factors and physical processes affecting the snow in that province should also be described, such that typical values of snow depth, water equivalent, stratigraphic horizons, temperature, etc., are available. Furthermore, since each of these characteristics is presumably highly variable on seasonal and yearly bases, the development and decay of the snow cover during a typical season should be studied. Special characteristics such as avalanche activity, avalanche forecasting requirements, snow drifting problems, snow removal requirements, snowmelt flood probabilities, agricultural requirements, and hydroelectric requirements, should be identified. The potential for managing the snow resource within each of the provinces should be assessed, and current practices by local agencies identified.

3. Snow Research. The diverse nature of snow-related problems has resulted in many research activities aimed at answering specific management needs. Accordingly, there is not a good fundamental understanding of the physical characteristics of snow, the change of these physical characteristics with different environmental conditions, and the effect of various processes on these physical characteristics. One example is the response of various snows to the application of a mechanical load, either static or dynamic. The physical condition of the snow, such as its temperature, liquid water content, depth, entrained air, impurity content, and grain size, all affect the response of the snow to the applied load. However, it is not always possible to predict the response of snow to an applied stress, especially when the snow contains some liquid water. This lack of basic knowledge is amazing, since wet snow on highways causes substantial economic loss every year and retards the development of safer snow tires for automobiles, better equipment for snow grooming of ski slopes, more efficient snow removal techniques, and less expensive methods of constructing airstrips and roadways.

Some obvious research needs relating to the physical properties of snow are as follows:

a. The interaction between the winter snow cover and climate has often been cited because the albedo and areal coverage of the snow cover is an important criterion in the earth's energy balance. It has been suggested that the U.S. economy is directly affected by the areal extent of the winter snow cover (To feed the world: What to do with changing climate, 1974) through the effect that snow's high albedo has on the earth's energy budget. In spite of this obvious link with the energy budget and possible coupling with the general circulation of the atmosphere, very little is known about the optical properties of snow. Basic theoretical and experimental studies are necessary to define the optical properties, especially the albedo, under the wide variety of conditions common in natural snow covers. This information is particularly lacking for wet snow, in spite of the fact that snow covers in the temperate regions experience repeated melting each season.

b. The recent development of remote sensing techniques provides new opportunities for making rapid advances in snow research. The ability to survey large areas of snow cover to determine water equivalent, for example, would not only make a major improvement in our ability to forecast snowmelt runoff, but would eliminate much of the expensive and inaccurate point-by-point measurements which are made at this time. The development of this capability for all areas of the country could be a major goal of a well coordinated national program with the participation of many government and state agencies.

c. Recent advances in electromagnetic sensing suggest that important improvements could be made in snow cover surveying to determine snow depth, density, free water content, areal variability, grain size, and layering. Some work has been done to develop the appropriate techniques, but much remains to be learned about the electromagnetic properties of snow. Since snowmelt runoff is of primary economic importance, the techniques must also be developed for sensing the status of a melting snow cover. These developments will have to be preceded by theoretical and experimental studies of the electromagnetic properties of both dry and wet snow.

d. Even if we can accurately determine the quantity of snow on the ground at the onset of spring runoff, the percentage of meltwater infiltrating the soil cannot be predicted a priori because of the highly variable soil conditions which exist from location to location and year to year. The soil-snow system needs to be studied as a coupled porous medium and techniques must be developed to assess the permeability of the soil at the onset of snowmelt runoff. The possibilities of soil water replenishment during a year of unfrozen soil, or of rapid runoff with flooding during a year of frozen soil, justifies quite extensive investigations into the fundamental nature of the snow-soil system.

e. The snow cover of the temperate regions is a unique porous medium in the sense that it changes phase and infiltrates through itself. Once this movement of meltwater begins, rapid changes occur in the material properties which control the mode of infiltration and subsequent runoff. Rapid grain growth, density increases, and ice layer decomposition occur, and the response of the snow cover to surface melt or rain becomes quite rapid. The nature of this "ripening" process varies with location and year, and it must be understood in order to construct a realistic model of water runoff during the ripening period. The model must include such effects as the development of meltwater channels within the snow, ice layer decomposition, albedo changes, grain size changes, and undersnow stream development. In some glaciological provinces, such as the Midwest where the snow cover is thin and rapid melting can occur, rapid changes in the important material and geometrical properties of the snow cover can occur throughout the complete melt period.

4. <u>Focal Point</u>. There is a pressing need for a focal point to help provide overall direction and coordination at the national level for the study of both seasonal and perennial snow. Because sn is incidental to the principal missions of various interested user agencies, no agency has a responsibility for generating information of basic scientific value on snow. As a result, much of the information needed to utilize our snow resources more effectively is not available. The focal point should consist of a group of snow experts charged with the following responsibilities:

a. To speak for the problems of snow research activities within the United States

b. To identify the most important applied research problems of national importance that can only be solved by effective multi-agency cooperation

c. To suggest ways for improved coordination among the various agencies and organizations which are currently performing snow research and data collection

d. To identify those areas of basic snow research which would provide the most immediate benefits

e. To provide synthesis reviews of the current status of snow research and knowledge

V. Conclusions

The snow cover in the temperate regions of the United States is one of its most important, renewable resources. The use of snow as a ground insulator, for soil water replenishment, for the generation of hydroelectric power, for winter recreation, and for municipal water supplies is well established. Future management of the snow resource could limit future agricultural capacity, oil shale processing, and strip mine revegetation. The competition for the use of snowmelt runoff will increase in the future, and our ability to predict and control snow runoff should increase accordingly. The disadvantages of snow, such as decreased mobility, snowmelt floods, soaked fields, and collapsed roofs are also well known and deserve more research attention.

There is a vital need to focus our research efforts on snow through:

1. an effective planning and coordinating body that will take a broad view of snow problems in general,

2. improved inter-agency programs and procedures,

3. further programs designed both to advance our utilization of snow as resource and to alleviate the problems caused by its presence.

Examples of specific problem areas that should be studied and specific research recommendations which can be made at this time are as follows:

1. To develop advanced techniques for determining the water equivalent of the snow-cover over large areas in order to more efficiently utilize snowmelt runoff.

Some specific research objectives are:

a. To increase knowledge of the electromagnetic properties of snow in order to facilitate the development of active microwave sensors.

b. To improve understanding of the factors affecting snow albedo and improved methods of areal measurements.

c. To develop satisfactory techniques for measuring snow-water equivalent under widely varying conditions. Both point and areal measurement techniques are needed.

d. To develop short-term methods of measuring precipitation at remote sites.

2. To study the regional characteristics of the snowcover in the United States, in order to separate the country into a number of glaciological provinces within which there is only a limited variation in the various distinguishing parameters. The availability of such a classification would greatly facilitate the meaningful transfer of data from one province to another. The work leading to the development of the classification would also help to clearly identify data gaps.

3. To increase knowledge of the properties of snow in relation to the problem of its removal from roadways, the following research objectives are of particular importance here:

a. To increase knowledge of the material properties of snow wetted by saline water. This requires both theoretical studies of the physical chemistry of the eutectic mixture and experimental investigations of the response of wetted snow to high rates of loading.

b. To investigate the bonding of both wetted and dry snow to pavement surfaces.

c. To increase knowledge of the propagation of stress waves through snow to aid in the design of better highway plows.

4. To improve methods of hydrological forecasting in order to allow better predictions of steamflow during periods of intense snowmelt or rain-on-snow. Specific research objectives are:

a. To increase knowledge of the interaction between the snow and the underlying soil to improve methods for adjusting for water infiltrating into the soil. This aspect of runoff also has important agricultural implications.

b. To make detailed studies of the changes which occur in a snow cover following the onset of liquid infiltration and an increased knowledge of the interaction between the properties of the snow and movement of water.

c. To increase knowledge of the energy fluxes to a melting snow surface especially in forested areas, as well as improved methods for extrapolating point energy flux measurements to values representative of large areas.

5. To study the basic physical and chemical properties of snow needed to provide basic information which can be used for a variety of applications. Some of the most important research needs are:

a. To increase knowledge of the basic mechanical properties of snow, including failure criterion for avalanche studies, snow adhesion for snow removal, and stress wave propagation for high speed loadings.

b. To make electromagnetic and optical studies in order to improve areal measurements of snow properties. Small scale measurements of energy exchange and liquid water content also require increased knowledge in this same area.

c. To study the thermal and thermodynamical properties of snow in order to provide a better understanding of the metamorphism and heat flow in snow.

Advanced nations generally spend about 3 percent of their gross national product on research and development activites (Wade, 1975). If all of the benefits and costs of snowfall in this country were totaled, we would find that even at greatly expanded levels of activity, the amount of effort devoted to developing knowledge about our snow resources is substantially less than 3 percent of the impact of snow in our economy. The significance of snow will clearly continue to increase during the late 1970's and the 1980's because of the increased need for agricultural and energy production. Accordingly, needs for the snow research described here are immediate and should be pursued vigorously.

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Snow and Ice Research at the Goddard Laboratory for Atmospheric Sciences

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The overall objective of the Hydrospheric Sciences Branch is to do research that will improve our understanding of the hydrosphere and our ability to monitor, utilize, or manage the components of the hydrosphere that affect our balance of natural resources and human activities. In particular, there are specific objectives being pursued in the Hydrospheric Sciences Branch that are pertinent to snow and ice research. Efforts in the Branch are divided between snow research over land surfaces, primarily hydrologically oriented, and cryospheric research on sea ice and the continental ice sheets, primarily directed toward climate and ocean operations applications. One objective, common to both hydrologic and cryospheric studies, is to develop models of radiative transfer processes in snow and ice and from underlying surfaces for use in employing remotely sensed information for characterizing snow and ice properties. The basic activities include the development of data inversion techniques to extract quantitative snow and ice parameters from various sets of remotely sensed radiances, microwave brightness temperatures, and radar backscatter coefficients.

In snow-over-land studies, attempts are being made to improve remote observations of snow extent, depth, water equivalent, structure, and grain size for snowmelt runoff prediction purposes. In this context, a demonstration project on snow extent mapping applications is being conducted in cooperation with six federal agencies (U.S. Geological Survey, U.S. Soil Conservation Service, U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, U.S. National Oceanic and Atmospheric Administration, and the Bonneville Power Administration), and three state agencies (California Department of Water Resources, Colorado Division of Water Resources, and Arizona Salt River Project). In addition, the interaction and usefulness of remotely sensed data in snowmelt runoff models is being tested. Such a project is being conducted cooperatively with the Swiss Federal Institute for Snow and Avalanche Research.

In the cryospheric discipline, the primary objective is to improve the understanding of sea ice and ice sheet processes, their effects upon the earth's climate and ocean operations, and resource extraction in the polar regions. For sea ice, a specific objective is to quantify the role of sea ice processes in terms of parameters observable from space. For example, the fraction of open water within the pack ice is obtained from satellite passive microwave sensors; but additional measurements and studies are required to relate this to desired quantities, such as the heat exchange between the atmosphere and ocean. For the ice sheets, specific objectives are to obtain accurate ice sheet elevation, ice volume change, surface temperature, and ice accumulation rate from radar altimetry. Microwave radiometry is used for studies of ice sheet mass balance and surging potential. Sea ice and ice sheet dynamics models are being adapted to utilize remote sensing data. The primary data sources for this research are the passive microwave data from Nimbus 5 and 6, radar altimetry data from GEOS 3, data from polar aircraft missions, and the passive and active microwave data to be obtained from Nimbus 7. The requirements for remotely sensed ice information and various satellite sensor capabilities are being reviewed with the scientific community as part of the planning and definition of an ice satellite mission for the mid-1980's.

Recent progress in several of these areas is highlighted below. It has been demonstrated that snow-covered areas observed from space are a significant parameter in improving seasonal snowmelt-runoff predictions. Additionally, the remote sensing data have been successfully employed in snowmelt models for daily streamflow prediction. To improve description of snowpack conditions, sets of multifrequency active and passive microwave data over varying snowpack conditions (such as depth, water equivalent, and free water content) have been acquired and initial analysis has begun. Landsat and airborne active and passive microwave studies of the North Slope of Alaska have been completed, showing the freeze/thaw cycles on lakes and rivers, aufeis extent, and variations in ice thickness. In a complementary fashion, successful experiments with improved models describing the microwave radiative transfer process in varying ice and snowpack conditions have been accomplished, and further development is continuing. Nimbus 5 microwave data were used to compile a time series data set showing the dynamics of large scale snow and ice features. A review was published (Zwally, Gloersen, 1977), describing the information content and significant insights provided. Radiative transfer modeling, combined with observations of the microwave emission from ice sheet firn, have shown that for a range of microwave wavelengths, the emission is controlled mainly by the granular structure of the firn.

These results provide a physical basis for the measurement of the ice accumulation rate through its effect on grain size. Other results obtained in collaboration with various investigators include the mapping of the Greenland ice sheet south of 65° N by satellite radar altimetry to an estimated accuracy of 2 m.

Members of the Hydrospheric Sciences Branch will continue to work in these areas of snow and ice research in the future. Emphasis will shift to a more total characterization of snow and ice conditions and processes using modeling and microwave data. Cooperative research with other interested agencies and scientific collaborators is strongly encouraged and will continue to be undertaken by the Hydrospheric Sciences Branch.

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Snow and the Organization of Snow Research in the United States

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After the winter of 1976-77, residents of the temperate regions of North America are well aware of the importance of the seasonal snow cover. In an unfortunate display of the fickle nature of snowfall, Californians were rationing precious snowmelt runoff while nine snowbound counties in New York were declared "Major Disaster Areas" and the National Guard was mobilized to help restore some resemblance of normality. Memories of these experiences tend to fade during the warm summer months, and generous snowfalls in the Western and Rocky Mountain States did begin to rebuild the storage in ground water, reservoirs, and snowpacks. However, heavy snows returned to the Northeast during the winter of 1977-78 where hundreds of roofs failed, including a large sports arena, a large auditorium, numerous industrial buildings, and retail stores. The city of Boston was hit by a major snowstorm that closed down all but emergency transportation and services and kept the city paralyzed for a week. The economic loss for Boston alone from that single storm was hundreds of millions of dollars, due to snow clearance costs and property loss but, most important of all, loss of individual, business, and tax incomes.

The inevitable melt following a heavy winter's snow accumulation produces mixed responses in our society. Highway departments and public officials are relieved of the tremendous costs and responsibilities of snow clearance, roofs are relieved of their extra burdens, and automobile corrosion disappears along with deicing chemicals. However, depending on how much snow has accumulated and how fast it runs off, spring flooding is likely to take a heavy toll somewhere across the country, while ski areas from California to Maine count the blessings they had during the snowy winter months. Winter wheat crops are nourished, in part, by the melting of the snow which had provided insulation earlier. Also, snowmelt runoff across the country provides high quality water for residential and industrial, as well as agricultural, use.

The uses of snow or abuses caused by snow are very different phenomena which have different consequences across the country. The common denominator in all of these situations is the snow itself. It comes as the solid form of precipitation which, once deposited, undergoes various transformations depending on the prevalent environmental forces acting through the laws of nature. In fact, snow takes many forms and has widely varying properties depending on such factors as its age, temperature, density, and liquid content. It is a fascinating material for study, and its importance in society cannot be denied. In view of this, it is interesting to examine the level of research effort addressing snow or snow related problems. The basis for the review given here is an online computer search of the Smithsonian Science Information Exchange (SSIE) data base of funded research projects involving seasonal snow on the ground. Snow is a secondary or incidental factor in many of these projects, and the level of funding is not usually known. Furthermore, it is very clear that not all funded projects appeared in the survey and that good research is often "bootlegged". In spite of these limitations, the information given here should provide a measure of both the level of support for snow research and the attitude of state and federal governments regarding the generation of new and potentially useful information about seasonal snow.

The SSIE survey disclosed 40 to 50 funded research projects involving snow in each of three fiscal years (1974/75 to 1976/77). This level of support is equivalent to about 25 professional researchers per year with projects ranging in scope from full scale research programs with a team of investigators to miniprojects with less than $1000 in total support. The itemized list of reported projects shown in table 1 is typical of the three years surveyed.

Table 1. Fiscal Year 1976/77 Projects

Projects	Sponsor	Recipient	Number of Projects
A. Biological, Environmental, Land Use, and Soil Erosion	State of California	University of California	1
	U.S. Army	U.S. Army	2
	State of Oregon	Oregon State University	1
	State of Minnesota	University of Minnesota	2
	State of Washington	University of Washington	1
	U.S. Department of Agriculture	U.S. Department of Agriculture	5
	National Science Foundation	University of Wisconsin	1
	State of Michigan	Michigan State University	1
	U.S. Air Force	U.S. Air Force	1
	National Science Foundation	University of Chicago	1
			16
B. Avalanches, Military, Transportation, Hydrological, and Blowing Snow	State of Wyoming	U.S. Department of Agriculture	1
	National Aeronautics and Space Administration	National Aeronautics and Space Administration	2
	Department of Transportation	Utah Highway Department	1
	U.S. Department of Agriculture	U.S. Department of Agriculture	9
	U.S. Army	U.S. Army	4
	U.S. Department of Agriculture	Montana State University	1
	U.S. Department of Agriculture	Cornell University	1
	Thiokol Chemical Corporation	Utah State University	1
	Michigan Technological University	Michigan Technological University	1
	State of Oregon	Oregon State University	1
			22
C. Physical and Mechanical Properties	U.S. Army	Montana State University	1
	U.S. Army	University of Colorado	1
	U.S. Army	U.S. Army	8
	National Oceanic and Atmospheric Administration/ National Environmental Satellite Service	Energy Research & Technology Inc.	1
	National Aeronautics and Space Administration	University of California	1
	National Bureau of Standards	National Bureau of Standards	1
			13

The importance of snow in each project varies widely. Biological, land use, soil erosion, and environmental problems are addressed with only minor reference to snow as one of many factors. These projects, about one-third of the total, are primarily concerned with another subject and include snow only as a secondary parameter. Avalanche, military, hydrological, and transportation research projects (about two-fifths of the total) involve snow directly, but usually without developing any new information about the snow itself. These projects are generally users of information about the properties of snow. The largest number of these projects are hydrological in nature and are concerned with such things as snow storage and snow measurement. About one-quarter of the research projects are designed to generate new information about snow's physical and mechanical properties. The majority of these are supported by the U.S. Army, but the National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and the National Bureau of Standards also make contributions. The optical and electromagnetic investigations are generally motivated by the desire to develop better remote sensing capabilities, a fact which greatly influences the nature of each study (e.g., spectral region investigated) and the kind of results obtained. For the three fiscal years cited, the SSIE survey identified two National Science Foundation (NSF) projects, one project dealing with avalanches, and one project dealing with thickness measurements of various materials (including snow) using a pulsed radar. These two projects over a period of two years received an average of less than $20,000 per project per year (including overhead), a level of NSF support for research in snow which seems totally inadequate in view of the problems and benefits of the seasonal snow cover. Without the Army support of both its own laboratory and university research, and without the interest in the remote sensing of snow cover, there would be very little U.S. research dealing with the basic physical and mechanical properties of snow.

During fiscal year 1976/1977, six states supported eight research projects dealing with snow, although these projects often dealt with snow as an incidental factor in the project, and none of them dealt with the fundamental properties of snow. The Federal Government supported four-fifths of the projects (see table 2) mostly through in-house research, but also through seven university, one state, and one privately operated project. Of course, these projects cover the spectrum of those dealing with snow and, as stated earlier, all of the projects generating new information about the physical and mechanical properties of snow are federally funded.

Table 2. Fiscal Year 1976/77 Sponsors and Recipients

Sponsor	Recipient	Number of Projects
Federal	Federal	32
Federal	University	7
State	University	7
Miscellaneous		5
		51

The type of research conducted does not usually reflect the problems of the location of research. For example, in the case of the New York/New England area, the majority of the projects are not necessarily designed to meet local needs because more than three-fourths (see table 3) of the projects are conducted at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) which serves as both a national center for snow and ice research and a center for military projects. The major exceptions are the U.S. Department of Agriculture (USDA) laboratories which conduct two-thirds of the snow research projects in the Rocky Mountain States. These laboratories do concentrate on regional problems, for example, snow entrapment for better soil protection and meltwater availability, avalanches, and blowing snow. One surprising result is the lack of any reported research projects in the state of Alaska, although some work certainly exists. Another interesting result shown in table 3 is that only the Western, Rocky Mountain, and Midwestern States appear to support snow research projects, although New York and the New England states have had some severely damaging and expensive snow conditions in recent years.

Table 3. Geographical Distribution of Projects

Region	Number of Projects	Locally Supported
Western	8	4
Rocky Mountain	18 (12 USDA)	2
Midwestern	6	4
New York/New England	17 (13 CRREL)	-
Miscellaneous	2	-

The results of increased snow research efforts would have a wide range of payoffs if the research were done on a basic level. For example, information about the basic rheological properties of snow is needed for improved avalanche forecasting, improved snow removal techniques, and improved trafficability over snow in a variety of situations. Such basic knowledge of the physical properties of snow can also have a wide range of applications to the understanding of other materials, since monomineralic snow undergoes metamorphism in the same manner as other materials but at temperatures and pressures more convenient for study.

The importance of increased knowledge of the basic properties of snow can readily be illustrated by the following example. Developing the ability to measure the depth, density, and liquid water content of the snow cover over a large area would have profound implications for flood forecasting, water supply forecasts, and hydroelectric power production. In principle, these measurements could be made by active microwave systems, such as those soon to be introduced in satellites, but long available for aircraft or surface carriers. However, the interpretation of the return signal requires a sophisticated understanding of the complex interactions of electromagnetic signals with the liquid content, grain size, density, and depth, as well as the layering of the snow and the properties of the underlying material. A basic understanding of the electromagnetic properties of snow can only be achieved through well financed efforts involving experts from several different disciplines. Although the need for such investigations was stated in Polar Research: A Survey (National Academy of Sciences, 1970), little progress has been made in that direction. This situation is very unfortunate in view of the growing importance of snow in agriculture, transportation, recreation, and other industries.

Since snow is involved in a wide variety of our activities, it is not surprising that a wide variety of federal and state agencies are concerned with it. Local and state governments are responsible for snow removal, while federal agencies deal with problems of water supply, military preparedness, and others. The problem of water supply alone impacts directly on the responsibilities of the Environmental Protection Agency, the National Weather Service, the Geological Survey, the Soil Conservation Service, the Army Corps of Engineers, the Bureau of Reclamation and others. Other agencies are trying to develop improved data collection techniques, and still others are concerned with transportation or energy problems. Because each agency's reason for being involved with snow is related to its own mission, no single agency takes responsibility for a comprehensive approach to snow research. Accordingly, there is a lack of emphasis on developing a fundamental knowledge of snow, knowledge which would be of benefit to many aspects of our society.

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

SNOTEL: An Operational Data Acquisition System Using Meteor Burst Technology

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Introduction

The U.S. Soil Conservation Service (SCS) is presently developing a data collection, transmission, and processing system, designated SNOTEL. The SNOTEL system will eventually collect snow and other hydrometeorological data from some 500 remote data sites, transmit the data to a central computer where it is stored and validated, and provide the data in near-real-time to a variety of cooperating users. The system uses the reflection of very high frequency (VHF) signals by ionized meteor trails to accomplish communications between remote data sites and two master polling stations. This paper briefly reviews the SNOTEL system requirements, discusses the system architecture, and describes the status of the project and the anticipated performance of the system.

System Requirements

In general, the architecture of a data collection and transmission system is influenced by five major factors: types of data to be collected, geographical coverage, system responsiveness, characteristics of the users, and data processing requirements. The SNOTEL requirements are characterized by an advancing state of the art in sensors, coverage of a vast geographical area, system responsiveness requirements which will vary according to circumstances, users with a variety of regional interests and technical backgrounds, and decentralized and nonstandardized data processing facilities.

The types of data collected by SNOTEL will change as the sensor state of the art advances. The sensor technologies, as applied to snow and other hydrometeorological data, are far from stabilized. Therefore, it is a continuing requirement that SNOTEL be responsive to changes in sensor characteristics, and even to changes in the types of physical parameters which are collected. For this reason, the SNOTEL design approach strives to separate sensors from the other system components to the greatest extent possible. Quantitatively, the system must accomodate up to 16 of any mix of analog and digital sensors. Although it is recognized that some digital sensors will pose special interfacing problems, the modular design will accommodate unforeseen sensor requirements with a minimum of retrofitting.

The SNOTEL system is required to provide coverage to a large geographical area. It will serve the data collection needs of 10 western states. A map depicting the 160 sites operational as of January 1978 is shown in figure 1. (Appendix I contains a complete listing of sites, including those to be installed). The data site locations extend from northwestern Washington to western New Mexico, a distance of some 1900 km. The area ultimately covered by SNOTEL is extimated at over 2,000,000 km . In addition to the large area coverage, the SNOTEL system must also provide flexibility of coverage. That is, the data site locations should not be constrained by communication system considerations, as they might be in the case of land lines or some other rigid system. The system must accomodate data site population growth without requiring any redesign of the system.

The need for system responsiveness is a factor which weighs heavily in any system design. In the synthesis of data collection systems, response time alone will typically narrow the field to just a few alternative designs, and SNOTEL is no exception. The SNOTEL service requirements include the ability to sample selected sites, on demand, with a response time of about 1 hour. To complicate matters, the quickest response times are essential only for a limited portion of the season, and only for a small and unpredictable subset of the relatively vast total population of some 500 sites. Therefore, a system with a preset periodic sampling rate, which offers the needed responsiveness for the proper

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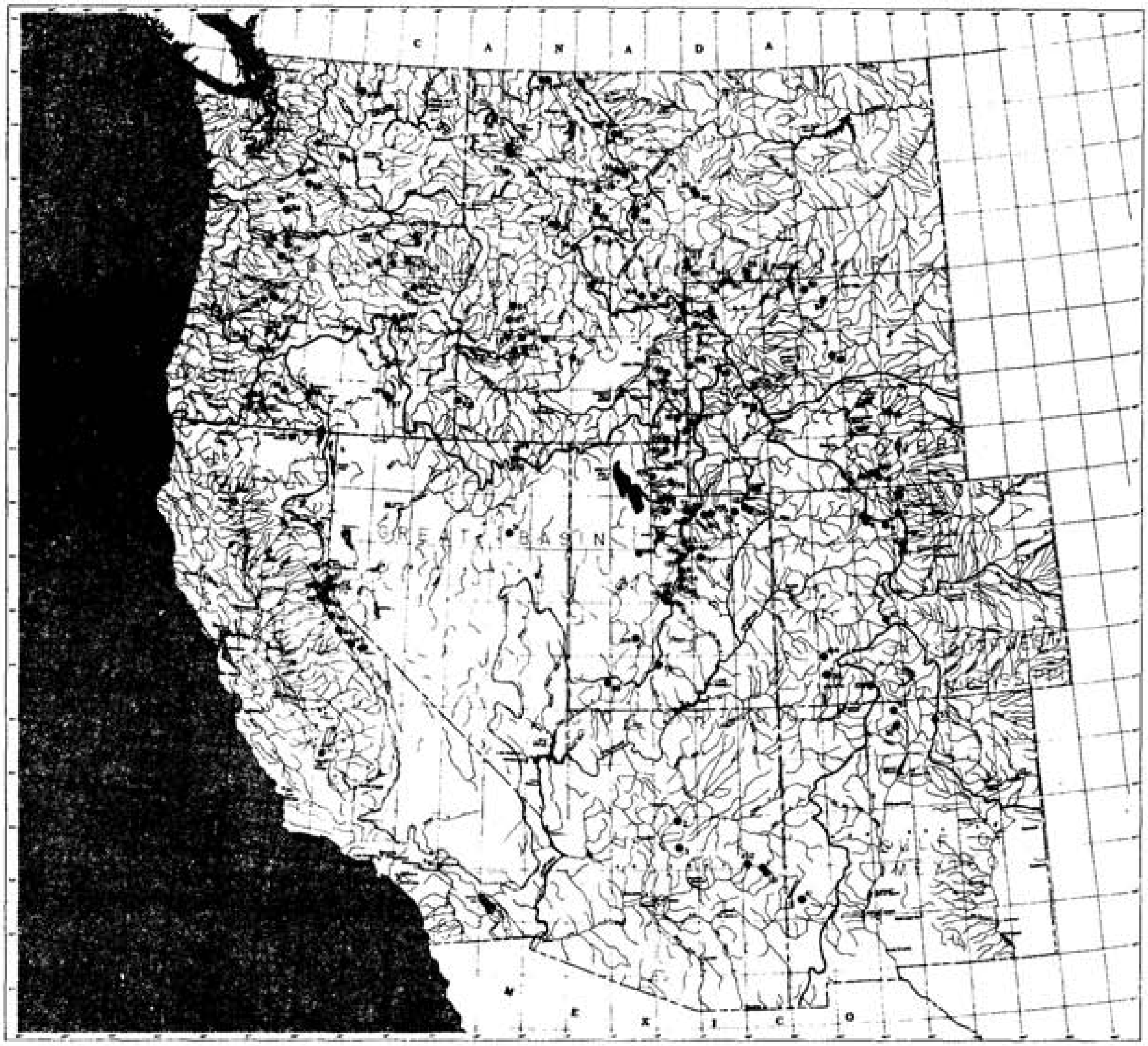

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155	CASCADE, CO
156	MORSE LAKE, WA
157	BIG BOULDER CREEK, WA
158	GRAHAM GUARD STA., ID
159	TEX CREEK, ID
160	SHEEP MTN., ID

50 0 50 100 150 MILES
SCALE 1:12,500,000

Source:
Base map prepared by SCS, WTSC Carto Staff from USGS, Water Resource Development, May 1969.
Thematic detail prepared by Water Supply Forecast Staff.
U.S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE

M7-OL-21506-2

Figure 1. SNOTEL sites operational as of January 1978.

sites at the proper times, would necessarily be collecting superfluous data most of the time from most of the sites. Because of this inherent "overkill" associated with a self-timed or periodic system, the SNOTEL requirements clearly dictate some form of interrogation capability.

The SNOTEL system must also provide access to a variety of types of users. Areas of expertise and depth of computer and communication knowledge vary significantly, even within the relatively homogeneous snow survey community of SCS. In cases where the users' technical backgrounds are similar, their forecasting and reporting methods may nevertheless differ. The mere presence of a common user data collection system does not permit the forcing of standards and procedures upon a group of users with individual requirements. The need for adaptability to user requirements has influenced the SNOTEL design approach, having given rise to a separate user access and control component. This component is the interface between the users and the rest of the system. It can be modified as new users are added, or as experienced users refine their requirements.

Data processing facilities are often not as easily shared among users as the data themselves. Each government, commercial, and educational establishment has its own data processing organization(s) and facilities. As the population of SNOTEL's cooperating users expands, and as their experience with the system grows, the direct linking of SNOTEL with users' computer facilities will become increasingly desirable. This inevitable trend has influenced the SNOTEL architecture. On one hand, the SNOTEL system does not include significant data processing software, other than what is necessary to move, store, validate, and provide access to the data in a reliable fashion. On the other hand, the user access component of the system has been designed to interchange data with computer systems as easily as with people. Therefore, as user population growth adds requirements for direct SNOTEL-to-computer interchange, these requirements can be met with minimum impact on the user access component, and with no impact on the transmission component of the system.

In addition to the five major factors discussed above, the SNOTEL design has been influenced by several other constraints. The remote site equipment is required to operate continuously for up to 1 year without attention. This specifically implies a power system which is self-sustaining for 1 year. The entire transmission component is required to operate without human attention, other than periodic maintenance. Also, the system is required to be as immune as possible to single element failures. The general reliability considerations need to account for the known severity of the environmental conditions associated with snow-related data sites. These and other factors have all influenced the SNOTEL design as it has evolved to date.

System Architecture

As implied in the above discussion, the SNOTEL system is designed around a modular or "building block" approach. The intent of this approach is to isolate, and thereby minimize, the impact of changes in the users' requirements, as well as to afford the users some latitude in their operation of the system.

A study of various users and their data collection and processing requirements resulted in a system architecture of three major components: sensors, transmission, and user access. The relationships among these components are depicted in figure 2.

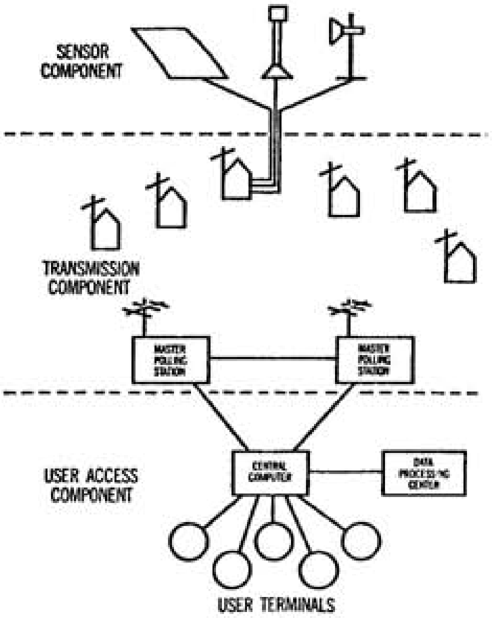

Figure 2. System architecture.

This approach accounts for the fact that the sensor types and characteristics and system access requirements are largely user oriented and relatively flexible, whereas the data transmission process is virtually transparent to the users and relatively rigid in its design.

Sensor Component

From the standpoint of system design, sensor characteristics are the hardest for which to plan. The rapid evolution and relative lack of standardization of sensors have rendered the sensor interface problem a difficult one. The initial phase of SNOTEL includes 160 remote stations with a standard mix of four sensors, all of which have analog outputs. The four parameters are temperature, snowpack water equivalent, precipitation, and remote station power system battery voltage. This relatively simple standard mix of sensors will facilitate the evaluation of the system in its first season of operation. Later, the system will accommodate additional sensors and sensor types, both analog and digital.

At the SNOTEL remote station, the sensor interface barrier strip is the boundary between the sensor component and the transmission component. Each additional sensor does require the addition of some sensor interface electronics; however, the modular remote station design permits these changes in the field, using vendor-supplied parts and simple modification procedures. Special interfacing problems, typical of some sophisticated digital sensors, will be handled on a case-by-case basis.

Transmission Component

The transmission component is the backbone of the SNOTEL system, and the most costly element within it. The SNOTEL system uses the meteor burst telemetry technique to gather data from the remote stations. This technique is based upon the use of a master polling station, which is capable of emitting a remote station probe in the lower VHF frequency range (in this case, 40.530 MHz). This frequency allows the exploitation of ionized meteor trails, billions of which occur every day in the upper reaches of the earth's atmosphere (80-120 km altitude). Such ionized trails reflect or re-radiate the master station probe back to the surface of the earth. These naturally occurring reflective media can establish usable communication paths at distances up to 2000 km. When a suitable probe is reflected by a meteor trail to a remote station's receiving equipment, the remote station is activated and transmits its data over the reciprocal path. The reciprocity of the path is assured in most instances, because the return frequency (in this case, 41.530 MHz) is selected sufficiently close to the probe frequency.

The occurrence of a meteor trail in the right geometric orientation, and of sufficient duration to allow a particular remote station to read its probe and transmit its data, is a random event. In the worst of natural circumstances, the successful polling of a particular site can be expected to occur several times per hour, assuming the remote station is probed continuously.

The meteor burst telemetry technique has many features which make it uniquely responsive to SNOTEL requirements. The long-range paths which it creates will allow coverage of the vast area populated by SNOTEL data sites. Also, the use of meteor trails for reflection creates, for each data site, an unlimited number of potential paths for transmission. This minimizes and, in most cases, eliminates blockage problems due to terrain obstacles. Meteor burst also affords great flexibility from the standpoint of expanding the data site population. The addition of a site requires only the installation of the remote station equipment and the updating of computer tables in the master polling station. No hardware changes of any kind are required.

Another facet of the meteor burst technique is that it allows complete control over which stations are probed at particular times. This control is effected by governing the scheduling and content of the master station probes.

The meteor burst transmission system consists of two master polling stations plus the remote stations. The purpose behind dual master stations is two-fold. First, the overall reliability of the system is enhanced. The system will collect data from all data sites, although significantly less efficiently, during an outage of either master station. The second purpose of two master stations is to provide better quality paths for communications. In cases where a data site location is disadvantageous relative to one master station, then the other master station, or a combination of both master stations, will yield the desired performance.

The master stations can poll any remote station or group of remote stations on command. In addition, the system will automatically perform systemwide polling once per day in the absence of any other instructions. Each master station can also store up to 3 days worth of data on-line, a backup feature which will be used if land line outages prevent the forwarding of data. The master stations are completely computer controlled and commanded over leased telephone circuits; they are designed for unattended operation.

The two master stations are located in Boise, Idaho, and Ogden, Utah. The general locations were determined by the transmission subsystem contractor, based on the required area of coverage. Within these general areas, the selection of the specific sites was based primarily on 1) the availability of enough land to accommodate four 40-foot guyed antenna towers, 2) the availability of utility connections, 3) the absence of detrimental electromagnetic noise, and 4) the absence of terrain obstacles higher than 3° above the horizon. The last consideration, an inherent necessity for a meteor burst system satisfying SNOTEL requirements, can rule out many superficially attractive candidate locations.

The remote stations contain all necessary equipment to detect, interpret, and respond to master station probes, plus analog-to-digital conversion, sensor interfacing, and data buffering electronics for sampling the sensors.

Each remote station has a unique address for probing purposes, so that the master stations may probe selectively. In that way, interference among remote stations can be minimized.

The remote stations are powered by batteries which are charged by solar panels. The power system is designed to be self-sustaining for at least 1 year.

The remote station uses a folded dipole antenna oriented for optimum communication with one or both master stations.

User Access Component

The user access component is designed 1) to provide SNOTEL users with access to the system and control over polling, 2) to isolate users from the complexities of radio frequency data communications, 3) to interface SNOTEL with users' data processing facilities, and 4) to perform routine functions associated with the operation and management of the SNOTEL system.

User access is provided through a real-time computer facility to be located at the Water Supply Forecasting Unit in Portland, Oregon. The computer is a Hewlett-Packard 9640A multiprogramming system operating under the RTE-II real-time executive software. The system includes 5 million bytes of disc storage and two magnetic tape drives for storing data. It also includes a line printer for printing reports. Two computer terminals are used as control consoles for the computer and for the transmission system. The peripheral equipment also includes an asynchronous multiplexor for interfacing with data communication circuits.

The central computer commands the two master stations and receives data from them over leased telephone circuits operating asynchronously at 1200 bits per second. In addition to initiating probes and receiving data, the central computer uses these circuits for assigning or re-assigning remote stations to one or both master stations for polling responsibility, updating the master station clocks, and transferring polling responsibility in the event of master station failure.

The users access SNOTEL by means of remote terminals located in their offices. The initial set of user terminals will consist of one in each of nine SCS Snow Survey Units. Each of these nine terminals includes a keyboard and cathode ray tube for input and output, as well as a thermal printer for permanent copy.

The user terminals access the SNOTEL system via dial-up telephone circuits operating asynchronously at 1200 bits per second. Once connected to the central computer, the user can log himself onto the system, using identification codes which control access, and issue requests to the computer.

The user may request on-line data in various combinations. In that case, the transmission system is not involved. The user may also request the polling of a site (within his jurisdiction) for new data. In that case, the appropriate master station(s) is commanded by the central computer to probe the site. If the user does not wish to remain on-line while awaiting the response, he may terminate the call, and the requested data will be provided when he again logs on.

The user may also schedule the periodic polling of a site or group of sites, if he does not wish to issue repeated requests, provided he is authorized to poll those sites. In that case, the central computer maintains an internal schedule of all required automatic commanding of the master stations.

The central computer performs certain routine functions associated with the operation of the system. Received sensor data are converted into engineering units, and preliminary validation checks are made on the data. The data are also logged in, formatted and stored in an on-line data base. The central computer can also interchange data with users' data processing systems. Presently, the software is configured to communicate with the UNIVAC 1140 at the Department of Agriculture Computer Center in Fort Collins, Colorado. This link, a dial-up link operating synchronously at 2000 bits per second, will initially be used for archiving data in Fort Collins.

Project Status

Work is presently in progress to establish the 160-remote-station system for initial operational evaluation. The sensors, transducers, equipment shelters, antenna masts, and other supporting equipment have been installed at the 160 remote locations.

The central computer software is completed and has been tested. In anticipation of the transmission system acceptance test, an automatic test driver is being developed for the central computer. These efforts are being performed by Systems Consultants, Inc., at their Emeryville facilities, under contract to SCS.

The contract for the transmission system was awarded to Western Union Telegraph Company in May 1976. The master stations have been fabricated and are undergoing installation and checkout. The remote stations are being fabricated, and the first units off the production line are being installed and checked out. After the 160 remote stations are installed, the formal acceptance testing of the transmission system will commence.

System Performance

The overall SNOTEL system performance will obviously depend most heavily upon the performance of the transmission component. The meteor burst system is required to satisfy quantitative performance criteria in two areas: scheduled systemwide polling, and on-demand polling of selected sites.

The requirement for systemwide polling calls for polling and obtaining data from all remote stations within 1 hour. To allow for the random nature of meteor trails, 2 percent of the responses can fall outside this 1-hour window. For on-demand polling, the requirement calls for receiving the data within 1/2 hour. To account further for the random nature of meteor trails, the systemwide time limit must be met 95 percent of the time, and the on-demand limit must be met 90 percent of the time.

Preliminary tests conducted by Western Union, using SNOTEL production prototype equipment, indicate that the system will perform better than the performance criteria for SNOTEL, even during February, the worst month for exploiting meteor trails.

Summary

The implementation of the SNOTEL system will bring together several of the recent advances in sensor technology, communications engineering, and data processing to provide a broad community of users with timely and reliable access to remotely acquired data. The system will also be a demonstration of a new communication technique, data transmission by meteor burst, which has been made possible only by the last few years' developments in digital electronics. Meteor burst will likely be responsive in several other data acquisition applications, especially where near-real-time data access requirements are combined with low data rates, and data are to be collected from isolated sites scattered over a large area.

Appendix I
SOIL CONSERVATION SERVICE SNOTEL SITES
WESTERN UNITED STATES

	Site Name and Number	Latitude	Longitude	Elevation (feet)
1	Baldy, AZ	33° 59'	109° 30'	9220
2	Mormon Mountain, AZ	34° 56'	111° 31'	7500
3	Baker Butte, AZ	34° 27'	111° 24'	7330
4	Silver Creek Divide, NM	33° 22'	108° 42'	9070
5	Joe Wright, CO	40° 31'	105° 51'	10120
6	Arrow, CO	39° 55'	105° 46'	9680
7	Berthoud Summit, CO	39° 48'	105° 45'	11320
8	Columbine, CO	40° 23'	106° 36'	9165
9	Willow Creek Pass, CO	40° 20'	106° 06'	9550
10	Porphyry Creek, CO	38° 29'	106° 20'	10750
11	Tower, CO	40° 32'	106° 40'	10560
12	Deadman Hill, CO	40° 48'	105° 45'	10220
13	Moores Creek Summit, ID	43° 56'	115° 40'	6100
14	Galena Summit, ID	43° 53'	114° 43'	8790
15	Somsen Ranch, ID	42° 57'	111° 22'	6830
16	Slug Creek Divide, ID	42° 34'	111° 18'	7230
17	Lookout, ID	47° 27'	115° 42'	5120
18	Mosquito Ridge, ID	48° 03'	116° 14'	5250
19	Vienna Mine, ID	43° 49'	114° 51'	8960
20	Above Burke, ID	47° 32'	115° 47'	4100
21	Swede Peak, ID	43° 37'	113° 58'	7640
22	Sunset, ID	47° 34'	115° 49'	5530
23	Fortynine Meadows, ID	47° 06'	115° 53'	4840
24	Deadwood Summit, ID	44° 33'	115° 34'	6800
25	Atlanta Summit, ID	43° 45'	115° 14'	7500
26	Cole Creek, MT	45° 12'	109° 21'	7850
27	Combination, MT	46° 28'	113° 24'	5600
28	Black Pine, MT	46° 25'	113° 26'	7100
29	Whiskey Creek, MT	44° 36'	111° 09'	6800
30	White Mill, MT	45° 03'	109° 54'	8700
31	Flattop Mtn, MT	48° 48'	113° 51'	6300
32	Northeast Entrance, MT	45° 00'	110° 00'	7350
33	Waldron, MT	47° 55'	112° 47'	5600
34	Mount Lockhart, MT	47° 55'	112° 49'	6400
35	Twelvemile Creek, MT	46° 09'	114° 27'	5600
36	Saddle Mtn, MT	45° 42'	113° 58'	7900
37	Twin Lakes, MT	46° 09'	114° 30'	6400
38	Deadman Creek, MT	46° 48'	110° 41'	6450
39	Spur Park, MT	46° 47'	110° 37'	8100
40	Independence Camp, CA	39° 27'	120° 18'	7000
41	Ward Creek #3, CA	39° 08'	120° 14'	7000
42	Marlette Lake, NV	39° 09'	119° 54'	8000
43	Hagan's Meadow, CA	38° 51'	119° 56'	8000
44	Sonora Pass, CA	38° 19'	119° 36'	8800
45	Virginia Lakes, CA	38° 05'	119° 15'	9500
46	Fallen Leaf, CA	38° 56'	120° 03'	6250
47	Mt. Rose, NV	39° 21'	119° 53'	9000
48	Ebbetts Pass, CA	38° 33'	119° 48'	8700
49	Bear Creek, NV	41° 50'	115° 27'	7800
50	Seventysix Creek, NV	41° 42'	115° 28'	7100
51	Corral Canyon, NV	40° 17'	115° 32'	8500
52	Bateman, NM	36° 31'	106° 20'	9160
53	Red River Pass #2, NM	36° 40'	105° 23'	9855
54	Hopewell, NM	36° 48'	106° 16'	10000
55	Blue Mountain Spring, OR	44° 15'	118° 30'	5900
56	Summit Lake, OR	43° 27'	122° 08'	5600
57	Bowman Springs, OR	45° 22'	118° 27'	4580
58	Taylor Butte, OR	42° 42'	121° 24'	5100
59	Mud Ridge, OR	45° 15'	121° 44'	4050
60	High Ridge, OR	45° 41'	118° 06'	4980
61	Arbuckle Mtn., OR	45° 11'	119° 15'	5800
62	Bourne, OR	44° 49'	118° 12'	5800
63	Irish Taylor, OR	43° 49'	121° 57'	5500
64	Snow Mountain, OR	43° 57'	119° 33'	6300

Appendix I (cont.)

	Site Name and Number	Latitude	Longitude	Elevation (feet)
65	Billie Creek Divide, OR	42° 25'	122° 17'	5310
66	North Fork, OR	45° 23'	122° 01'	3120
67	Fish Creek, OR	42° 42'	118° 38'	7900
68	Summer Rim, OR	42° 42'	120° 49'	7100
69	Trial Lake, UT	40° 51'	110° 58'	9800
70	Lakefork #1, UT	40° 36'	110° 26'	10200
71	Parley's Summit, UT	40° 46'	111° 37'	7500
72	Smith & Morehouse, UT	40° 47'	111° 05'	7600
73	Strawberry Divide, UT	40° 09'	111° 10'	8000
74	Beaver Divide, UT	40° 37'	111° 04'	8000
75	Widtsoe #3, UT	37° 50'	111° 53'	9720
76	Horse Ridge, UT	41° 17'	111° 26'	8270
77	Big Flat, UT	38° 18'	112° 21'	10300
78	Farmington, UT	40° 58'	111° 48'	8010
79	Pickle Keg, UT	39° 01'	111° 35'	9600
80	Kolob, UT	37° 31'	113° 02'	9250
81	Mammoth-Cottonwood, UT	39° 41'	111° 18'	8800
82	Monte Cristo, UT	41° 28'	111° 30'	8960
83	Bumping Ridge, WA	46° 47'	121° 20'	4600
84	Trough, WA	47° 14'	120° 19'	5300
85	Park Creek Ridge, WA	48° 27'	120° 55'	4600
86	Surprise Lakes, WA	46° 06'	121° 45'	4250
87	Lone Pine, WA	46° 16'	121° 58'	3800
88	Casper Mtn., WY	42° 44'	106° 19'	7900
89	Spring Creek Divide, WY	42° 32'	110° 40'	9000
90	Bald Mtn., WY	44° 48'	107° 51'	9375
91	Big Sandy Opening, WY	42° 38'	109° 16'	9100
92	Laprele Creek, WY	42° 26'	105° 52'	8375
93	Old Battle, WY	41° 09'	106° 58'	9900
94	Dome Lake, WY	44° 34'	107° 18'	8880
95	Middle Powder, WY	43° 38'	107° 11'	7760
96	Arrastre Lake, WY	41° 22'	106° 23'	10275
97	Lewis Lake Divide, WY	44° 12'	110° 40'	7860
98	Gros Ventre Summit, WY	43° 23'	110° 08'	8775
99	Salt River Summit, WY	42° 31'	110° 55'	7600
100	Phillips Bench, WY	43° 31'	110° 55'	8200
101	Hogg Pass, OR	44° 25'	121° 52'	4760
102	Santiam Jct., OR	44° 26'	121° 56'	3750
103	South Mtn., ID	42° 46'	116° 53'	6200
104	Tepee Creek, MT	44° 47'	111° 42'	8000
105	Ben Lomond Peak, UT	41° 22'	111° 55'	8000
106	St. Lawrence, WY	43° 02'	109° 12'	8950
107	Cozy Cove, ID	44° 16'	115° 39'	5400
108	Divide, MT	44° 48'	112° 03'	7800
109	Franklin Basin, ID	42° 04'	111° 35'	8200
110	Webber Springs, WY	41° 10'	106° 56'	9240
111	Trinity Mtn., ID	43° 38'	115° 26'	7760
112	Lemhi Ridge, MT	44° 59'	113° 26'	8100
113	Red Hill, OR	45° 28'	121° 42'	4380
114	Tony Grove Lake, UT	41° 54'	111° 38'	8200
115	North French Creek, WY	41° 20'	106° 22'	10130
116	Calvert Creek, MT	45° 53'	113° 20'	6430
117	Greenpoint, OR	45° 37'	121° 42'	3400
118	Dill's Camp, UT	39° 03'	111° 27'	9200
119	South Brush Creek, WY	41° 20'	106° 30'	8440
120	Black Bear, MT	44° 30'	111° 07'	7950
121	Fourmile Lake, OR	42° 24'	122° 13'	5920
122	Trout Creek, UT	40° 42'	109° 41'	9480
123	Lick Creek, MT	45° 30'	110° 58'	6860
124	Silvies, OR	42° 44'	118° 41'	6900
125	Clear Creek #1, UT	39° 51'	111° 17'	9200
126	Shower Falls, MT	45° 24'	110° 57'	8100
127	Lucky Strike, OR	45° 17'	118° 51'	5050
128	King's Cabin, UT	40° 23'	109° 33'	8730
129	N Fk Elk Creek, MT	46° 52'	113° 16'	6250

Appendix I (cont.)

Site Name and Number	Latitude	Longitude	Elevation (feet)
130 Lake Creek R.S., OR	44° 11'	118° 36'	5120
131 Mosby Mtn., UT	40° 37'	109° 54'	9500
132 Copper Bottom, MT	47° 03'	112° 36'	5200
133 Wolf Creek, OR	45° 04'	118° 08'	5700
134 Red Pine Ridge, UT	39° 26'	111° 16'	9400
135 Copper Camp, MT	47° 05'	112° 44'	6950
136 Jump Off Joe, OR	44° 23'	122° 10'	3400
137 Indian Canyon, UT	39° 52'	110° 46'	9040
138 Rocker Peak, MT	46° 22'	112° 15'	8000
139 Tipton, OR	44° 40'	118° 22'	5150
140 Seeley Creek, UT	39° 19'	111° 26	9920
141 Frohner Meadow, MT	46° 27'	112° 12'	6480
142 Buck Flat, UT	39° 08'	111° 26'	9360
143 Fisher Creek, MT	45° 04'	109° 57'	9100
144 Vernon Creek, UT	39° 56'	111° 25'	7400
145 Silver Run, MT	45° 09'	109° 21'	6630
146 Clear Creek #2, UT	39° 52'	111° 15'	8320
147 Stahl Peak, MT	48° 55'	114° 52'	6030
148 White River #1, UT	39° 59'	111° 01'	8620
149 Grave Creek, MT	48° 55'	114° 46'	4300
150 Brown Duck, UT	40° 36'	110° 35'	10820
151 Maverick Fork, AZ	33° 55'	109° 27'	9200
152 McNary, AZ	34° 05'	109° 53'	7225
153 Upper San Juan, CO	37° 29'	106° 50'	10200
154 Mineral Creek, CO	37° 51'	107° 43'	10300
155 Cascade, CO	37° 38'	107° 48'	8850
156 Morse Lake, WA	46° 54'	121° 29'	5400
157 Big Boulder Creek, WA	47° 26'	121° 02'	3200
158 Graham Guard Sta., ID	43° 57'	115° 16'	5690
159 Tex Creek, ID	43° 22'	111° 35'	6550
160 Sheep Mtn., ID	43° 12'	114° 40'	6510
161 White Horse Lake, AZ	35° 08'	112° 09'	7180
162 Heber, AZ	34° 19'	110° 45'	7640
163 Frisco Divide, NM	33° 44'	108° 56'	8000
164 Coronado Trail, AZ	33° 48'	109° 09'	8400
165 Hannagan Meadows, AZ	33° 39'	109° 19'	8960
166 Signal Peak, NM	32° 55'	108° 09'	8360
167 Workman Creek, AZ	33° 49'	110° 55'	6900
168 Promontory, AZ	34° 22'	111° 01'	7900
169 Fry, AZ	35° 04'	111° 52'	7200
170 Sugar Loaf, AZ	34° 37'	111° 31'	6120
171 Hawley Lake, AZ	34° 00'	109° 46'	8250
172 Lookout Mountain, NM	33° 22'	107° 50'	8150
173 Bonita Rock, AZ	33° 47'	109° 36'	8270
174 Burro Mountain, CO	39° 52	107° 37'	9400
175 Culebra #2, CO	37° 12'	105° 12'	10500
176 Fremont Pass, CO	39° 22'	106° 12'	11400
177 Independence Pass, CO	39° 04'	106° 37'	10560
178 Lake Eldora, CO	39° 56'	105° 36'	9700
179 Park Reservoir, CO	39° 02'	107° 52'	9960
180 Santa Maria, CO	37° 49'	107° 07'	9650
181 McClure Pass, CO	39° 07'	107° 20'	8750
182 Vail Mountain, CO	39° 22'	106° 37'	10300
183 University Camp, CO	40° 02'	105° 35'	10300
184 Copeland Lake, CO	40° 12'	105° 34'	8600
185 Copper Mountain, CO	39° 29'	106° 10'	10450
186 Elk River, CO	40° 50'	106° 58'	8650
187 Lake Irene, CO	40° 25'	105° 49'	10680
188 Bear Canyon, ID	43° 45'	114° 56'	7920
189 Howell Canyon, ID	42° 19'	113° 37'	7980
190 Mill Creek Summit, ID	44° 28'	114° 39'	8800
191 Sherwin, ID	46° 57'	116° 20'	3200
192 Hilts Creek, ID	44° 02'	113° 28'	7760
193 Boulder Mountain, MT	46° 34'	111° 18'	7950
194 Many Glacier, MT	48° 48'	113° 40'	4900

Appendix I (cont.)

	Site Name and Number	Latitude	Longitude	Elevation (feet)
195	Lubrecht Flume, MT	46° 53'	113° 19'	4680
196	Bloody Dick, MT	45° 10'	113° 30'	7550
197	Monument Peak, MT	45° 13'	110° 14'	8850
198	Lower Twin, MT	45° 30'	111° 55'	7900
199	Noisy Basin, MT	48° 09'	113° 57'	6040
200	Daly Creek, MT	46° 11'	113° 51'	5780
201	Skylark Trail, MT	47° 22'	113° 47'	6200
202	Kraft Creek, MT	47° 26	113° 46'	4750
203	Box Canyon, MT	45° 17'	110° 15'	6700
204	Porcupine, MT	46° 07'	110° 28'	6500
205	Warm Springs, MT	46° 16'	113° 10'	7800
206	Crystal Lake, MT	46° 48'	109° 30'	6050
207	Badger Pass, MT	48° 08'	113° 02'	6900
208	Clover Meadow, MT	45° 01'	111° 51'	8800
209	Nevada Creek, MT	46° 50'	112° 31'	6480
210	Lakeview Ridge, MT	44° 35'	111° 50'	7400
211	Skalkaho Summit, MT	46° 15'	113° 46'	7250
212	Nez Perce Camp, MT	45° 44'	114° 29'	5650
213	Pike Creek, MT	48° 18'	113° 20'	5930
214	Beagle Springs, MT	44° 28'	112° 59'	8850
215	Emery Creek, MT	48° 26'	113° 57'	4350
216	Hand Creek, MT	48° 18'	114° 50'	5035
217	Pickfoot Creek, MT	46° 35'	111° 16'	6650
218	Barker Lakes, MT	46° 06'	113° 08'	8250
219	Wood Creek, MT	47° 27'	112° 49'	5960
220	Poison Flat, CA	38° 31'	119° 38'	7900
221	Lamoille #3, NV	40° 38'	115° 24'	7700
222	Jacks Peak, NV	41° 30'	116° 01'	8420
223	Berry Creek, NV	39° 21'	114° 39'	9100
224	Truckee #2, CA	39° 18'	120° 12'	6400
225	Independence Lake, CA	39° 26'	120° 19'	8450
226	Echo Peak, CA	38° 51'	120° 05'	7800
227	Pole Creek R.S., NV	41° 52'	115° 15'	8330
228	Green Mountain, NV	40° 23'	115° 23'	8000
229	Goat Creek, NV	41° 50'	115° 09'	8800
230	Blue Lakes, CA	38° 37'	119° 55'	8000
231	Big Bend, NV	41° 46'	115° 43'	6700
232	Jack Creek, Upper, NV	41° 33'	116° 01'	7250
233	Laurel Draw, NV	41° 46'	116° 02'	6700
234	Lobdell Lake, CA	38° 26'	119° 22'	9200
235	Heavenly Valley, CA	38° 55'	119° 54'	8800
236	Rubicon #2, CA	39° 00'	120° 08'	7500
237	Cedar Pass, CA	41° 35'	120° 18'	7100
238	Dorsey Basin, NV	40° 53'	115° 12'	8100
239	Granite Peak, NV	41° 39'	117° 34'	7800
240	Lamance Creek, NV	41° 31'	117° 38'	6000
241	Independence Creek, CA	39° 30'	120° 17'	6500
242	Chamita, NM	36° 57'	106° 40'	8400
243	Gallegos Peak, NM	36° 12'	105° 33'	9700
244	North Costilla, NM	37° 00'	105° 16'	10600
245	Panchuela, NM	35° 50'	105° 40'	8300
246	Quemazon, NM	35° 55'	106° 24'	9100
247	Blazed Alder, OR	45° 25'	121° 52'	3650
248	Daly Lake, OR	44° 31'	122° 05'	3600
249	Seine Creek, OR	45° 31'	123° 17'	1750
250	Saddle Mountain, OR	45° 32'	123° 22'	3250
251	Sevenmile Marsh, OR	42° 41'	122° 08'	5725
252	Roaring River, OR	43° 54'	122° 02'	4900
253	Three Creeks Meadow, OR	44° 09'	121° 38'	5650
254	Ochoco Meadows, OR	44° 26'	120° 20'	5250
255	Peavine Ridge, OR	45° 03'	121° 56'	3500
256	Mt Hood Test Site, OR	45° 20'	121° 43'	5400
257	Taylor Green, OR	45° 02'	117° 32'	5740
258	Derr, OR	44° 27'	119° 56'	5700
259	Cold Springs Camp, OR	42° 32'	122° 10'	6100

Appendix I (cont.)

	Site Name and Number	Latitude	Longitude	Elevation (feet)
260	Marion Forks, OR	44° 36'	121° 58'	2600
261	Little Meadows, OR	44° 37'	122° 13'	4000
262	Ben Lomond Trail, UT	41° 23'	111° 55'	5680
263	Box Creek, UT	38° 32'	112° 01'	9300
264	Bug Lake, UT	41° 41'	111° 25'	7950
265	Castle Valley, UT	37° 40'	112° 47'	9580
266	Chalk Creek #1, UT	40° 51'	111° 04'	9100
267	Chalk Creek #2, UT	40° 54'	111° 04'	8200
268	Currant Creek, UT	40° 21'	111° 05'	8000
269	Daniels-Strawberry, UT	40° 18'	111° 15'	8000
270	Dry Bread Pond, UT	41° 25'	111° 32'	8350
271	Farnsworth Lake, UT	38° 46'	111° 41'	9600
272	Gooseberry R.S., UT	38° 48'	111° 41'	8000
273	Harris Flat, UT	37° 30'	112° 35'	7700
274	Hayden Fork, UT	40° 47'	110° 53'	9400
275	Kimberly Mine, UT	38° 29'	112° 23'	9300
276	Little Bear, Upper, UT	41° 24'	111° 49'	6550
277	Long Flat, UT	37° 31'	113° 24'	8000
278	Midway Valley, UT	37° 34'	112° 50'	9800
279	Steel Creek Park, UT	40° 55'	110° 31'	10100
280	Timpanogos Divide, UT	40° 26'	111° 37'	8140
281	Webster Flat, UT	37° 35'	112° 54'	9200
282	Blewett Pass, WA	47° 21'	120° 41'	4270
283	Harts Pass, WA	48° 43'	120° 39'	6500
284	Lyman Lake, WA	48° 12'	120° 55'	5900
285	Pope Ridge, WA	47° 59'	120° 34'	3540
286	Upper Wheeler, WA	47° 17'	120° 22'	4400
287	Corral Pass, WA	47° 01'	121° 28'	6000
288	Fish Lake, WA	47° 31'	121° 04'	3371
289	Olallie Meadows, WA	47° 22'	121° 26'	3625
290	Rainy Pass, WA	48° 35'	120° 43'	4700
291	Stampede Pass, WA	47° 17'	121° 20'	3000
292	Base Camp, WY	43° 56'	110° 26'	7030
293	Cloud Peak Reservoir, WY	44° 24'	107° 03'	9860
294	Blind Bull Sum, WY	42° 57'	110° 36'	8750
295	Bone Springs Div, WY	44° 41'	107° 35'	9350
296	Brooklyn Lake, WY	41° 22'	106° 14'	10220
297	Burgess Junction, WY	44° 47'	107° 32'	7875
298	Burroughs Creek, WY	43° 42'	109° 40'	8750
299	Canyon, WY	44° 43'	110° 32'	8090
300	Cottonwood Lake, WY	42° 31'	110° 49'	7670
301	Dinwoody, WY	43° 16'	109° 28'	10060
302	Grassy Lake, WY	44° 08'	110° 50'	7460
303	Hobbs Park, WY	42° 52'	109° 06'	10100
304	Kelley R.S., WY	42° 15'	110° 48'	8180
305	Little Warm, WY	43° 30'	109° 45'	9370
306	Loomis Park, WY	43° 10'	110° 08'	8240
307	Powder River Pass, WY	44° 10'	107° 08'	9475
308	Shell Creek, WY	44° 30'	107° 26'	9600
309	Sucker Creek, WY	44° 43'	107° 24'	8900
310	Sylvan Lake, WY	44° 29'	110° 09'	8400
311	Togwotee Pass, WY	43° 45'	110° 03'	9620

Addendum to Western Snow Conference Paper

Project Status Update (December 15, 1978)

Installation of the first 160 remote stations has been completed. The stations are being operated under lease pending a final acceptance test scheduled during mid January - mid February 1979. Additional communication equipment for 151 stations has been ordered. Sixty stations have been installed with the remainder scheduled to be completed by no later than September 1, 1979. At that time there will be at least 311 stations of the 511 station system in operation. In general, the data being collected appears to be of good quality. System performance has been fair to good with increasing overall improvement resulting from application of operational experience to the system.

SNOW COVER: A SELECTED BIBLIOGRAPHY

This bibliography covers areal snow cover extent, its temporal variations, and measurement techniques. The citations are divided into the following subject divisions for the reader's convenience:

1. GENERAL

   General works on snow cover; snow cover properties, including surface reflectance and energy fluxes; and snow cover-climate interactions.

2. SNOW COVER EXTENT:

   A geographic breakdown of snow cover extent, including regional to continental scale snow data on depth and distribution, operational snow cover products, atlases, and other related data reports.

   A. Global/Hemispheric
   B. Antarctica
   C. Arctic/Greenland
   D. Europe
   E. North America
   F. South America
   G. USSR/Asia

3. SNOW COVER MAPPING AND REMOTE SENSING APPLICATIONS

   Descriptions of operational satellite and snow mapping techniques, snowline mapping, snow cover detection and dynamics using various satellite sensors and platforms, snow/cloud discrimination, etc.

Except where a citation deals primarily with one of the above areas, the following topics have been excluded:

- snow cover models
- applications to streamflow forecasting and flood prediction
- vehicles and transportation on snow
- conventional snow survey techniques
- avalanches
- snow drifting
- sublimation and evaporation loss
- mechanical properties of snow
- snow crystallization
- transformation of snow to ice

Citations have been limited by date of publication (1969-79), with the exception of some earlier classical works which are included because they are still widely referenced.

The following printed and on-line computerized sources were used to compile the bibliography:

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Conference Papers Index, 1973-79
Dissertation Abstracts, 1861-1979
Geoarchive, 1974-79
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Meteorological and Geoastrophysical Abstracts, 1972-79
NTIS (National Technical Information Service), 1965-79
Scisearch (Science Citation Index), 1974-79
Miscellaneous bibliographies

Since less than 10 percent of the citations were duplicated among the above indexes, we feel that this bibliography is useful as a concise source for snow cover data.

In the bibliography, we assume that the language of publication is English unless otherwise stated. Because we do not have all of the original material in hand, we cannot be certain of the completeness of each citation, although every effort possible has been made to ensure accuracy. Since we realize that the maximum value of a bibliography lies in the availability of the original documents, we have marked each item owned by the World Data Center with an "*". Photocopies of any of these documents can be provided upon request to institutions and individuals. Lengthy publications are available on interlibrary loan to other libraries. Publications with an NTIS number are available in microfiche or photocopy form from: National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia, 22161, U.S.A. Prices vary according to length of the publication.

We urge you to acquire items not owned by the WDC through your regular library channels or from the publishing agency or author. If, however, these methods are unsuccessful, please feel free to call or write the WDC for assistance.

If any individuals or institutions see their publications in this list without an "*", the WDC would gratefully appreciate receiving copies of the ones which are still available.

Since we may update the bibliography in the future, we greatly appreciate your notifying us of any errors or omissions.

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