Research Report 39

NOVEMBER, 1957

A Survey of Arctic Snow-Cover Properties as Related to Climatic Conditions

by M. A. Bilello

U. S. ARMY SNOW ICE AND PERMAFROST
RESEARCH ESTABLISHMENT
Corps of Engineers
Wilmette, Illinois

PREFACE

The data used in this report were made available through the combined efforts of personnel associated with the Meteorological Division of the Canadian Department of Transport, the U. S. Weather Bureau, and the U. S. Air Force Weather Service. Mr. Bilello, meteorologist, Climatic and Environmental Research Branch, analysed the data and prepared the preliminary report. Mrs. Genevieve Jones assisted with the computation and tabulation of the data. The work was conducted under the general supervision of Mr. Marvin Diamond, assistant chief, Climatic and Environmental Research Branch.
This paper constitutes a progress report on Project 22.5-1, Snow cover studies.

Manuscript submitted 25 September 1957

Department of the Army Project 8-66-02-004

CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY

An analysis of snow-cover density, temperature, and hardness data, measured over a period of several years at five stations in Alaska and six stations in the Canadian Arctic, shows the snow cover in the Canadian Archipelago to be colder, denser, and harder than in the interior of Alaska.

A series of nomographs were developed to estimate average monthly snow-cover density from mean monthly air temperature and wind velocity. The nomographs are applicable for the months November through March, for the Alaskan and Canadian area north of 62°N latitude, and for elevations below 1500 ft. A comparison of observed snow-cover densities with those derived from the nomographs indicates that the method will provide a reliable regional estimate of snow-cover density.

Studies of the relation between snow-cover temperature and air temperature from November through March disclosed the snow to be on the average from 4C to 9C warmer than the air at the Alaskan stations and 4.5C warmer at the Canadian Archipelago stations.

An investigation of snow-cover hardness revealed regional variations similar to that for density. Measured snow hardness during the period of no melting was found to be related to densities between 0.15 and 0.36 g/cm^3.

A SURVEY OF ARCTIC SNOW-COVER PROPERTIES AS RELATED TO CLIMATIC CONDITIONS

by

Michael A. Bilello

INTRODUCTION

This report covers one phase of a USA SIPRE research program on the relationship between the characteristics of a snow cover and the meteorological conditions to which it has been subjected. The objective is to provide information which could increase the efficiency of military operations or civilian activities in an environment dominated by a snow cover and low temperatures for much of the year.

This study is an investigation of the regional variations of snow cover properties in the Arctic, and the development of methods for forecasting these properties from meteorological conditions.

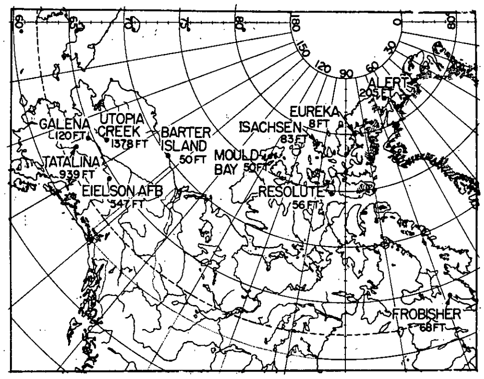

Figure 1. Location and elevation of stations covered in the study.

A study of this type requires concurrent measurements of both snow cover properties and meteorological elements. To obtain such measurements, a systematic snow observation program was initiated during the winter season of 1952-53 at various locations in Alaska and in the Canadian Arctic Archipelago (recently given the official name, Queen Elizabeth Islands). The observations were made at weather stations in Alaska operated by the U. S. Air Force and at the Joint Arctic Weather Stations in the Canadian Archipelago operated cooperatively by the U. S. Weather Bureau and the Meteorological Division of the Canadian Department of Transport.

Two to four years of snow cover data have been compiled for five stations in Alaska, five stations in the Canadian Archipelago, and for two locations at Frobisher on Baffin Island, Northwest Territories of Canada (Fig. 1).

The observations, which were made in accordance with standard procedures described in SIPRE Instruction Manual 1 (Snow Ice and Permafrost Research Establishment, 1954), provide data on certain properties of each layer of snow in a vertical profile. The different layers of snow could be visually delineated by structural differences, such as size and shape of the snow grains, or textural variations identifying periods of major snow accumulation. The properties measured weekly were density, temperature, hardness, and crystal size.

Some preliminary studies on data from these stations indicated that there are important regional differences in the physical properties of the snow cover. In this report, an effort has been made to associate these regional differences in the properties of the midwinter arctic snow cover with specific climatic conditions.

CLIMATIC PARAMETERS WHICH MAY AFFECT ARCTIC SNOW-COVER DENSITY

As shown in Figure 2, arctic snow-cover density varies both regionally and seasonally. It is a snow property that appears to be affected by the meteorological environment.

Meteorological elements which may affect the density of arctic snow cover and are regularly measured at weather stations are air temperature, wind velocity, relative humidity, and cloud cover.

The objective of this particular phase of the study was to determine the effect of the above climatic parameters on the density of winter snow. Since melting results in rapid and large changes in density, the study was confined to the non-melt period in the area north of 62°N latitude. This period generally extends from November through March.

The average amount of cloudiness during the winter season (Table I) indicates that the Alaskan stations have almost 50% more cloudiness than the Canadian stations. The increase in cloud cover reduces the heat loss due to long-wave radiation and accounts in part for the higher temperatures of the snow cover at the Alaskan stations (Table II).

Table I. Mean monthly cloud coverage.
(1.0 = overcast; 0.0 = clear).

Alaskan stations	Period of record	Nov.	Dec.	Jan.	Feb.	Mar.	Mean
Galena	1946-53	0.7	0.7	0.5	0.5	0.6	0.6
Eielson AFB	1953-55	0.6	0.6	0.6	0.5	0.5	0.6
Tatalina	1952-55	0.8	0.7	0.5	0.6	0.6	0.6
Utopia Creek	1951-55	0.7	0.6	0.5	0.6	0.6	0.6
Barter Island	1947-53	0.8	0.6	0.5	0.5	0.6	0.6
							0.6
Canadian Archipelago stations							
Alert	1950-53	0.5	0.4	0.4	0.4	0.5	0.4
Eureka	1947-53	0.4	0.3	0.3	0.4	0.4	0.4
Isachsen	1948-53	0.5	0.4	0.4	0.5	0.5	0.5
Mould Bay	1948-53	0.5	0.4	0.4	0.4	0.4	0.4
Resolute	1947-53	0.6	0.4	0.3	0.4	0.4	0.4
							0.4

Table II. Mean monthly snow-cover temperatures (C).

Alaskan stations	Period of record	Nov.	Dec.	Jan.	Feb.	Mar.	Mean
Galena	11/53-3/56	-8.4	-15.7	-14.4	-13.2	-9.5	-12.2
Eielson AFB	11/52-3/55	-8.3	-14.4	-16.5	-11.7	-6.2	-11.4
Tatalina	11/53-3/56	-7.1	-11.7	-10.3	-13.8	-6.1	- 9.8
Utopia Creek	12/53-3/55	Msg.	-15.6	-13.2	-16.6	-12.2	-14.4
Barter Island	11/52-3/55	-9.0	-17.2	-20.8	-22.7	-21.2	-18.2
							-13.2
Canadian Archipelago stations							
Alert	11/54-3/56	-22.6	-28.5	-31.4	-34.6	-33.8	-30.2
Eureka	11/52-3/56	-26.8	-29.6	-32.6	-32.5	-32.7	-30.8
Isachsen	11/52-3/56	-23.3	-26.6	-30.0	-32.8	-33.6	-29.3
Mould Bay	11/53-3/56	-22.3	-27.6	-28.2	-31.7	-31.4	-28.2
Resolute	11/52-3/56	-19.0	-23.2	-27.1	-31.1	-27.4	-25.6
							-28.8

It is generally recognized that the values of relative humidity at temperatures below 0C as obtained with the sling psychrometer may be in considerable error. During periods when air temperatures were below -37C, relative humidity was not measured at the Canadian Arctic stations. For these reasons it was not possible to undertake a study of the effect of relative humidity on snow-cover density.

Additional processes not directly attributable to current meteorological phenomena could affect the properties of a snow cover. The temperature gradient and thermal conductivity of the soil, for example, determines the heat flow from soil to the snow, which influences the metamorphic processes within the snow cover. Soil conditions which may have an influence on the snow cover, e.g. water content and depth of freezing, may be related to meteorological phenomena which occurred prior to the development of the seasonal snow cover. Except for some near-surface soil temperatures measured at Resolute, no observations were made on soil conditions at the arctic stations.

Air temperature and wind velocity were measured with sufficient accuracy and frequency to permit the evaluation of their effect on the density of the arctic snow cover.

RESULTS OF STUDY

Regional variations in snow-cover density

A weighted mean of snow-cover density for each weekly observation was derived in the following manner:

	Thickness of each layer (cm)	% of total depth	Observed snow density (g/cm^3)	Weighted snow density (g/cm^3)
Layer 1 (bottom)	6	20	0.205	0.041
Layer 2	15	50	0.290	0.145
Layer 3 (top)	9	30	0.230	0.069
Total depth =	30 cm	100%		0.255 g/cm^3 weighted mean

This method of computation was used to allow for variations in thickness of the layers forming the snow cover. The density samples were taken at the midpoint of each layer, and were assumed to be representative for that layer.

Mean monthly densities (Table III) are the arithmetic means of the weekly values.

Table III. Mean monthly snow-cover densities.

Station	Location		Years of record	Nov.	Dec.	Jan.	Feb.	Mar.
Tatalina, Alaska	62°54'N	155°59'W	3	0.136	0.186	0.212	0.223	0.229
Galena, Alaska	64°43'N	156°54'W	3	0.167	0.221	0.217	0.246	0.275
Eielson AFB, Alaska	64°39'N	147°04'W	3	0.198	0.187	0.212	0.218	0.229
Utopia Creek, Alaska	66°03'N	153°45'W	2	Msg.	0.235	0.257	0.258	0.269
Barter Island, Alaska	70°07'N	143°40'W	3	0.319	0.332	0.324	0.326	0.329
Frobisher 1 (Weather Station Site) N. W. T.	63°44'N	68°33'W	2	0.284	0.288	0.284	0.298	0.317
Frobisher 2 (Runway Site) N. W. T.	63°44'N	68°33'W	2	0.286	0.282	0.304	0.270	0.305
Resolute, N. W. T.	74°41'N	94°54'W	4	0.306	0.330	0.333	0.339	0.350
Mould Bay, N. W. T.	76°16'N	119°28'W	3*	0.378	0.367	0.348	0.350	0.354
" "	"	"	1954-55	0.428	0.413	0.397	0.396	0.397
Isachsen, N. W. T.	78°47'N	103°32'W	4	0.359	0.376	0.386	0.388	0.393
Eureka, N. W. T.	79°59'N	85°57'W	4	0.348	0.359	0.352	0.361	0.367
Alert, N. W. T.	82°30'N	62°20'W	2	0.359	0.358	0.355	0.375	0.348

* Including 1954-55.

A plot of these snow-cover densities (Fig. 2) reveals that the interior Alaskan stations (Eielson Air Force Base, Tatalina, Galena, and Utopia Creek) differ from the Canadian Archipelago stations (Resolute, Eureka, Isachsen, Alert, and Mould Bay) and Barter Island on the Alaskan north coast. The stations are grouped to emphasize that the study is of regional rather than point variations in snow-cover density. The surrounding or local topography and forest conditions may cause some differences in particular areas.

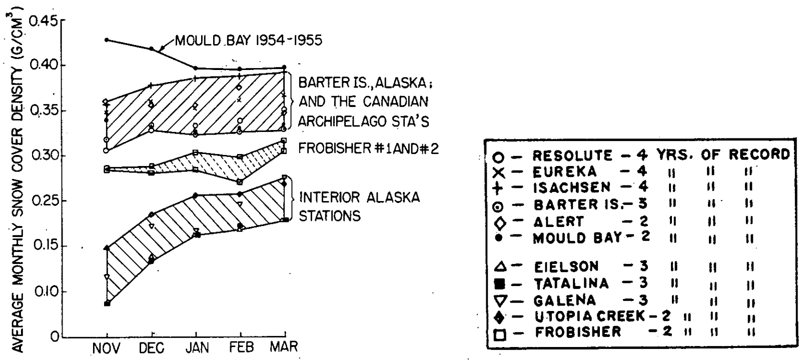

Figure 2. Regional and seasonal variations in snow-cover density.

The range of values for the interior Alaskan stations is approximately 0.13 to 0.20 g/cm³ in November and 0.23 to 0.27 g/cm³ in March. The densities at Barter Island, Alaska, and the five Canadian Archipelago stations range from approximately 0.30 to 0.36 g/cm³ in November, and 0.33 to 0.39 g/cm³ in March. Snow-cover densities measured at the two sites at Frobisher, Northwest Territories, range from approximately 0.27 to 0.32 g/cm³. Unusually high densities reported from Mould Bay during 1954-1955 are treated and shown separately in Figure 2. They range from approximately 0.43 g/cm³ in November to 0.395 in March. As shown later these observations coincided with high values in snow hardness. No extreme values of air temperature or wind velocity appeared to be associated with these high densities.

Prediction of average monthly snow-cover density in the arctic from air temperature and wind velocity

Mean daily air temperatures at each station were computed from the daily maximum and minimum temperatures.

Average monthly air temperatures for these stations, computed from the mean daily temperatures, are presented in Table IV. The period of record is the same as for the average monthly snow-cover density (Table III).

Table IV. Mean monthly air temperatures (C).

Station	Nov.	Dec.	Jan.	Feb.	Mar.
Galena, Alaska	-13.5	-24.2	-24.6	-23.3	-13.5
Eielson, Alaska	-12.5	-23.0	-24.8	-19.4	-12.2
Tatalina, Alaska	-12.8	-19.8	-19.1	-20.0	-10.2
Utopia Creek, Alaska	-12.5	-23.6	-20.0	-26.4	-14.4
Barter Island, Alaska	-14.5	-25.4	-26.8	-29.4	-25.2
Frobisher, Canada	-15.8	-26.1	-26.4	-26.2	-19.7
Alert, Canada	-25.9	-31.2	-32.0	-34.9	-34.6
Eureka, Canada	-29.6	-35.8	-36.4	-36.9	-38.5
Isachsen, Canada	-28.2	-32.1	-34.2	-37.3	-36.8
Mould Bay, Canada	-26.3	-33.9	-33.2	-37.1	-34.1
Resolute, Canada	-24.0	-29.6	-32.4	-33.8	-32.3

A plot of the average monthly snow-cover density vs air temperature for all the stations for the period November through March is shown in Figure 3. The linear relationship based on least squares computation yields a correlation coefficient of -0.77 with a standard error of estimate of 0.04 g/cm³.

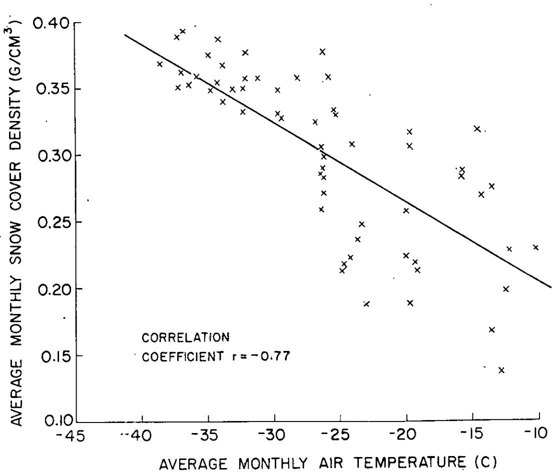

Figure 3. Relation between air temperature and snow-cover density.

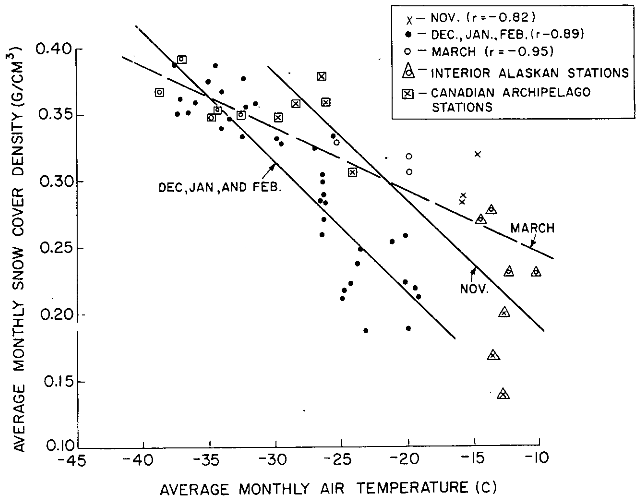

Figure 4. Relation of air temperature to snow-cover density on monthly basis.

Examination of the data on a month to month basis revealed that the lines of best fit varied for different periods of the snow season. One line fitted the data for November, another for March, and a third for December, January, and February (Fig. 4).

The November line incorporates the low snow densities and relatively high temperatures of the interior Alaskan stations and the high snow density and lower air temperature of the Canadian Archipelago stations. At lower latitudes, the snow accumulation season has just started by November. The newly fallen snow, not having been subjected to severe temperature changes or wind action, forms a soft snow cover of low density. At the Canadian Archipelago stations, the snow season is more advanced by November and the snow cover has been exposed to meteorological influence for a longer period of time.

The slopes and intercepts of the regression lines for December, January, and February were practically the same, indicating a similarity of response of the snow cover to climatic factors at all stations during that period. The three months, therefore, were combined into one group.

During March, the total daily direct solar radiation is greater at lower latitudes so that, at the interior Alaska stations and at Frobisher on the southern end of Baffin Island, the upper layers of the snow cover undergo a net gain in radiational heat. The absorbed radiation increases the rate of metamorphism, which increases the density of the pack. Oda and Kudo (1941) observed similar changes in the snow cover in Japan. Since the metamorphic process has not reached this stage in the higher latitudes during March, the regression line for snow density in the more northern stations remains relatively unchanged.

The following equations represent the relationships between snow density and air temperatures shown in Figure 4.

For November: $\rho_s = -0.0098T_A + 0.090$

For December, January, February: $\rho_s = -0.010T_A + 0.016$

For March: $\rho_s = -0.0048T_A + 0.197$

where ρ_s = average monthly snow cover density (g/cm³),

and T_A = average monthly air temperature (C).

An investigation of possible causes for departures of the actual snow-cover density from values estimated from the regression equations indicated that high snow densities frequently were associated with strong winds and low densities with light winds.

These departures are plotted against the corresponding average monthly wind velocity in (Fig. 5). Wind velocity appears to be more influential in November than in February and March. This seasonal decrease in the apparent effect of wind velocity on snow-cover density is associated with (1) the period when most of the snow has accumulated and (2) the seasonal increase in snow-cover density. In the area under discussion, 50% of the midwinter snow is deposited by November 30 and 80% by January 31; and the snow cover density increases from an average of 0.28 g/cm³ by the end of November to 0.32 by the end of March.

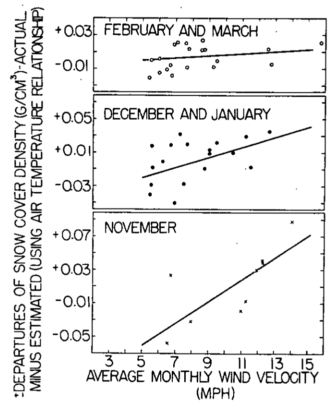

Figure 5. Difference between observed and estimated snow-cover density in relation to wind velocity. (Densities estimated using air temperatures).

Since both air temperatures and wind velocity affect the snow density, these variables were used to develop a method for graphically computing average monthly snow-cover densities. The nomographs (Fig. 6A-D) for November through March are applicable to the Canadian and Alaskan regions north of 62°N latitude, and for elevations below 1500 ft.

Comparison of observed snow-cover density with density computed from the nomographs

Figure 7 shows observed and estimated snow-cover densities for the 1956-1957 season. (The 1956-57 observed densities were not included in data previously used in this study.)

For Resolute, Eureka, and Alert (Canadian Archipelago stations), meteorological data for the 1956-57 season were used to compute densities from the nomographs. For Tatalina and Utopia Creek (interior Alaskan stations), climatological data from weather records published by the Air Weather Service (1951-1955) were used to compute densities, as weather data for 1956-57 were not available.

There is fair agreement between the actual and estimated snow-cover densities on the basis of regional variations. However, for individual locations within regions, the prediction accuracy decreases.

Relation between snow-cover temperature and air temperature

The mean snow-cover temperature for each observation was computed by weighting the temperature of each layer by the ratio of the layer thickness to the snow-cover thickness. The procedure was similar to that described earlier for computing the mean density of the snow cover. The mean monthly snow-cover temperatures, computed arithmetically from the weekly means, are listed in Table II. The relationship between monthly snow-cover temperatures and air temperatures (Table IV) is shown in Figure 8.

The distribution of points in this figure indicates that the data used in this study probably were derived from two separate populations. Line A appears to define a climatic regime in which the snow temperatures are about 4.5C higher than the air

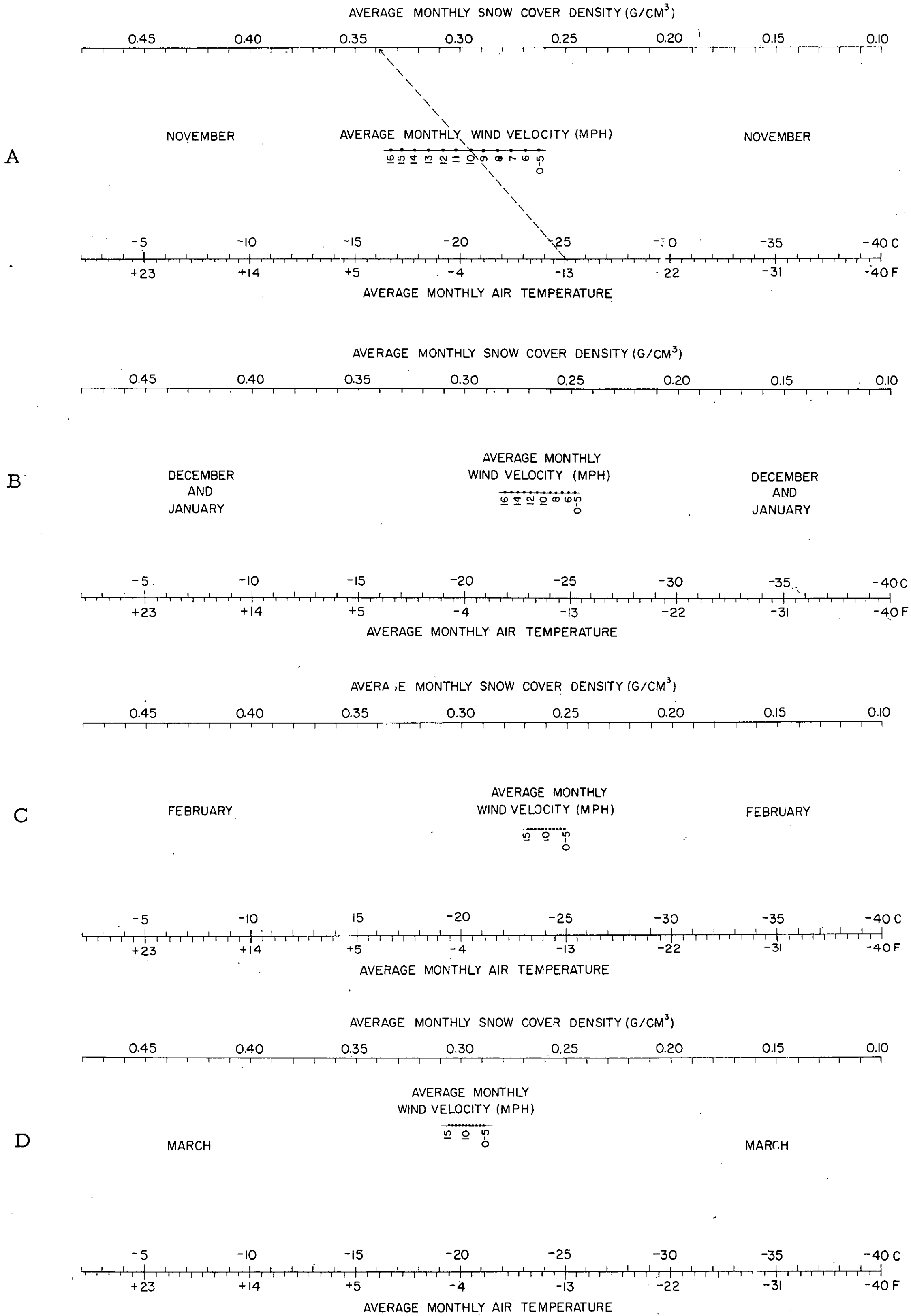

Figure 6. Nomographs to estimate average monthly snow cover density for the months November, December and January, February, and March.

Example: Assume average monthly air temperature for November is -25C and average wind velocity is 10 mph. In Fig. 6A, extend a straight line through these two points and read 0.34 g/cm on the average monthly snow cover density scale.

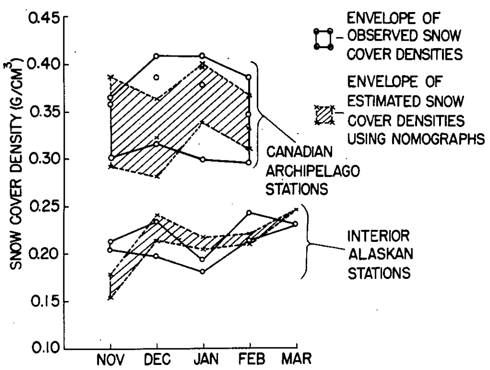

Figure 7. Comparison of observed snow-cover densities with densities computed from the nomographs, for 1956-1957.

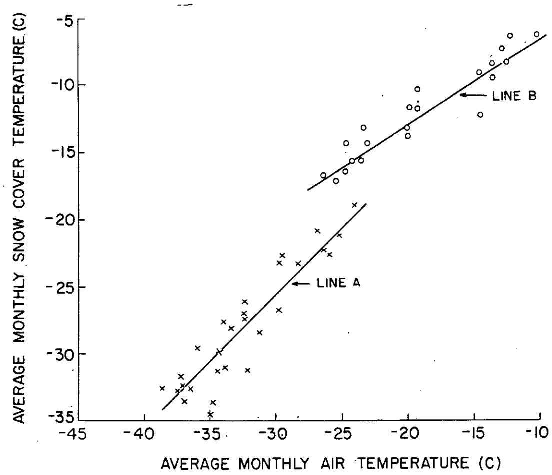

Figure 8. Relation between air temperature and snow-cover temperature.

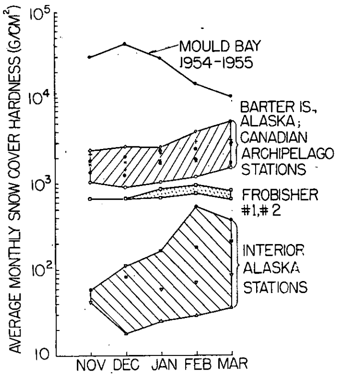

Figure 9. Seasonal and regional variations in snow-cover hardness. (Same symbols as Fig. 2.)

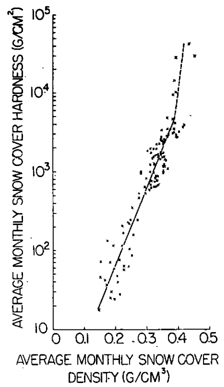

Figure 10. Relation between density and hardness of the snow cover.

temperature while line B defines a regime where snow temperatures are from 4C to 9C higher than the air temperature. The data to which line A has been fitted were all derived from stations located north of 70°N latitude, and with but two exceptions (Barter Island, Nov. and Dec.) all points assigned to line B were derived from records for stations located between 63° and 66°N latitude.

The difference between the two climatic regimes may be due in part to differences in the physical properties of the snow cover; in part to differences in soil properties and heat storage in the soil; and in part, as previously discussed, to the degree of cloudiness. The possible influence of soil temperature on the snow-cover temperature is indicated by the fact that the -0.2 to -0.4C geotherm is found at from 30 to 60 ft depth at Ladd, Alaska, near latitude 65°N, whereas a soil temperature of -9.5C is found at from 30 to 200 ft below the surface at Point Barrow, Alaska, latitude 70°N, and Thule, Greenland, 76.5°N. Sufficient data on soil temperatures are not available for the stations included in this report to determine differences in magnitude of heat flow between the earth and the snow cover. It appears, however, that differences in snow-cover temperatures may be due in part to differences in soil temperatures.

Relation between hardness and density of the snow cover

The geometric mean was used to compute mean snow cover hardness in order to reduce the effect of extreme values.

The regional and seasonal variation in mean monthly hardness of the snow cover (Fig. 9) is similar to that of the density (Fig. 2). This indicates an association between the hardness and density of the snow cover, as shown in Figure 10.

The line of best fit extends without change in slope to a hardness of 5000 g/cm^2. The plotted points above that value are for the hard and dense snow cover reported from Mould Bay during 1954-1955.

Increases in the hardness of the arctic snow cover may be attributed to two processes: (1) an increase in the number of snow grains per unit volume, which is accompanied by an increase in density, as indicated in Figure 10, for densities between 0.15 and 0.36 g/cm^3; (2) the development of ice bonds between the snow grains, which would not be accompanied by an increase in snow density. The instruments and procedures used in measuring hardness do not permit separate identification of the two processes. Consequently, it was not possible to establish relationships between snow hardness and the meteorological parameters identified with snow-cover density.

REFERENCES

Air Weather Service, Data Control Division (1951-1955) Uniform summary of surface weather observations, U. S. Air Force.

Oda, T., and Kudo, K. (1941) Setsushitsu to mitsudo (Properties of snow and its density), Seppyo, vol. 3 (text in Japanese). SIPRE Translation 32, 1954, 21p.

Snow Ice and Permafrost Research Establishment (1954) Instructions for making and recording snow observations, Instruction Manual 1, U. S. Army, Corps of Engineers, 10p.

GPO 808600—3