Relationships Between Climate and Regional Variations in Snow-Cover Density in North America

Michael A. BILELLO
U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, N. H., U.S.A.

Abstract

Snow-cover observations made during November through March at 27 stations in Alaska, Canada and the northern United States for a 2 to 11 year period were analysed. The analysis showed that the average snow density can be classified in four general categories: Category 1 (density 0.20 to 0.23 g/cm^3), inland stations reporting light winds; Category 2 (0.24 to 0.27 g/cm^3), stations generally reporting moderate winds; Category 3 (0.28 to 0.30 g/cm^3), inland and coastal locations with stronger winds; Category 4 (0.32 to 0.36 g/cm^3), cold and windy stations of the North American Arctic. Skewness coefficients computed for each station showed bias toward lower densities for categories 1 and 2, and bias toward higher densities for categories 3 and 4.

A nomograph was developed in which the average winter air temperature and wind speed are the independent variables. This nomograph makes it possible to estimate the average snow-cover density for any location in the Arctic, Subarctic and North Temperate Zones. A comparison between observed and estimated densities for 10 other test stations yielded a correlation coefficient of 0.91 with a standard error of estimate of 0.016 g/cm^3.

An average snow density map of North America was drawn using observed densities from the 27 original stations and the 10 test stations, and estimated densities for 61 other locations. The continent was then divided into areas based on the four categories.

I. Introduction

Knowledge of the regional distribution of snow-cover density would contribute materially toward the solution of numerous winter problems. For example, the density-dependent thermal conductivity of the snow cover has a great influence on the rate of penetration of ground frost and the growth of ice on lakes and rivers. Trafficability of men and vehicles depends strongly upon the density of the snow cover. Snow may be dense enough to support a wheeled vehicle; excessive sinkage in snow of low density seriously impedes, or may prevent, movement. Studies in hydrology and in snow removal also require knowledge of the density of the snow pack during the winter.

This study investigates the regional variations of snow-cover density in the North American Arctic, Subarctic and Temperate Zones for the non-melting period only. This permits direct association of regional variations in snow density with observed air temperatures and wind speeds, and the development of a method by which average snow-cover densities can be estimated where the influence of melting on density may be disregarded. The purpose of this correlation was to make use of available climatological data to determine snow density in areas where such measurements had not been taken.

An investigation of this type requires concurrent measurements of snow-cover density and the meteorological elements. To obtain such measurements, a systematic snow observation program began during the winter season of 1952–53 at various locations in Canada, Greenland and the United States including Alaska. The observations were made at weather stations supported by the United States Air Force, United States Weather Bureau and the Meteorological Branch of the Canadian Department of Transport.

Two to eleven years of snow-cover data have been compiled for nine locations in Canada, ten in Alaska, seven on the United States mainland and one in Greenland. The Greenland station, Sondrestrom, although not on the North American continent, was included because of its proximity to the network.

The snow observations, made weekly and sometimes biweekly in accordance with standard procedures described in USA CRREL Instruction Manual No. 1 (USA CRREL, 1954) provide density, temperature, and hardness, data on the layers of snow in vertical profile. The different layers of snow are delineated by structural or textural variations identifying periods of major snow accumulation or metamorphism.

Previous studies (Wengler, 1914; Rikhter, 1945; Formozov, 1946; Klein, 1950) show that there are important regional differences in the density of the snow cover throughout the cold regions of the Northern Hemisphere. In an earlier study (Bilello, 1957), it was found that the snow cover during the winter months is denser in the Canadian Archipelago than in the interior of Alaska. Since publication of the first report, additional data have become available which permit extension of the analysis to other parts of North America.

II. Regional Variations in Density

In the analysis of the new data a weighted mean of snow-cover density for each observation was used (as was done in the earlier study, *op. cit.*), thus:

	Thickness of each layer (cm)	% of total depth	Observed snow density (g/cm³)	Weighted snow density (g/cm³)
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	30	100		0.255

This method of computation was used to allow for the variations in thickness and density of the different layers of snow.

The average "seasonal" (November-March) snow-cover density for each station (Table 1) is the arithmetic mean of all the weekly mean weighted values based on a total of over 2 500 observations. The number of years of record for each station is also shown in Table 1. For some low latitude stations November and/or March was excluded because the observed average monthly air temperatures were above freezing and some melting may have occurred. Periods of above-freezing temperatures that may have occurred during the other winter months were assumed to be brief and effective only in raising the temperature of the snow without causing melt and, therefore, were disregarded. The effect of one day of freezing rain or thaw during midwinter would

Table 1. Summary of snow-cover densities and climate for 27 stations in North America and Greenland

Station	Years of record	Average seasonal snow density (g/cm^3)	Standard deviation	Skewness	Average seasonal temperature (°C)	Average seasonal wind speed (m/sec)
Category 1						
Eielson (Fairbanks), Alaska	6	0.199	0.053	+0.145	−20.3	1.3
Tatalina, Alaska	9	0.203	0.047	+0.014	−15.5	2.1
Hill (Ogden), Utah	8	0.219	0.083	+0.248	− 1.7	3.6
Galena, Alaska	10	0.233	0.060	−0.106	−20.7	2.2
Category 2						
Utopia Creek, Alaska	9	0.241	0.069	+0.154	−19.1	2.8
Naknek, Alaska	2	0.244	0.035	+0.361	− 9.2	4.3
Saglek, Labrador	6	0.249	0.091	+0.591	−10.6	3.8
Griffiss (Rome), N. Y.	9	0.252	0.052	+0.153	− 4.3	3.1
Malmstrom (Great Falls), Montana	8	0.252	0.046	+0.240	− 2.2	5.4
Elmendorf (Anchorage), Alaska	7	0.253	0.081	+0.100	− 8.6	2.5
Ernest Harmon (Stephenville), Newf.	9	0.255	0.102	+0.310	− 4.9	5.1
Sondrestrom, Greenland	5	0.262	0.038	+0.522	−17.6	3.1
Goose Bay, Labrador	2	0.268	0.068	−0.414	−10.9	4.1
Category 3						
Sparrevohn, Alaska	9	0.279	0.045	−0.065	−11.5	2.7
Sault Ste Marie, Mich.*	10	0.290	0.057	+0.063	− 8.4	4.4
Frobisher, NWT	4	0.292	0.066	−0.423	−22.8	4.8
Fargo, North Dakota*	2	0.294	0.050	−0.101	− 9.4	6.6
Loring (Caribou), Me.	11	0.294	0.080	−0.036	− 9.2	5.3
Northeast Cape, Alaska	2	0.296	0.033	−0.186	−10.2	5.9
Wurtsmith (Oscoda), Michigan	8	0.297	0.073	−0.091	− 5.1	4.5
Category 4						
Cape Lisburne, Alaska	2	0.320	0.051	+0.227	−16.2	5.5
Barter Island, Alaska	3	0.325	0.059	−0.730	−25.3	5.9
Eureka, NWT*	11	0.326	0.050	−0.325	−35.3	2.6
Resolute, NWT*	10	0.342	0.044	−0.016	−30.2	5.4
Alert, NWT*	10	0.345	0.061	−0.044	−30.5	2.7
Mould Bay, NWT*	7	0.354	0.050	−0.041	−32.2	4.3
Isachsen, NWT*	11	0.363	0.051	−0.057	−33.2	4.4

* U. S. Weather Bureau and Canadian Department of Transport stations. All others are U. S. Air Force, Air Weather Service stations.

have little influence on the snow cover and would not be reflected in the monthly average density.

The concurrent average seasonal air temperature (°C) and wind speed (m/sec) for each station are also given in Table 1. This information came from various sources, *e.g.*, U. S. Air Force (1952–63), Department of Transport, Canada (1952–63) and U. S. Weather Bureau (1952–63).

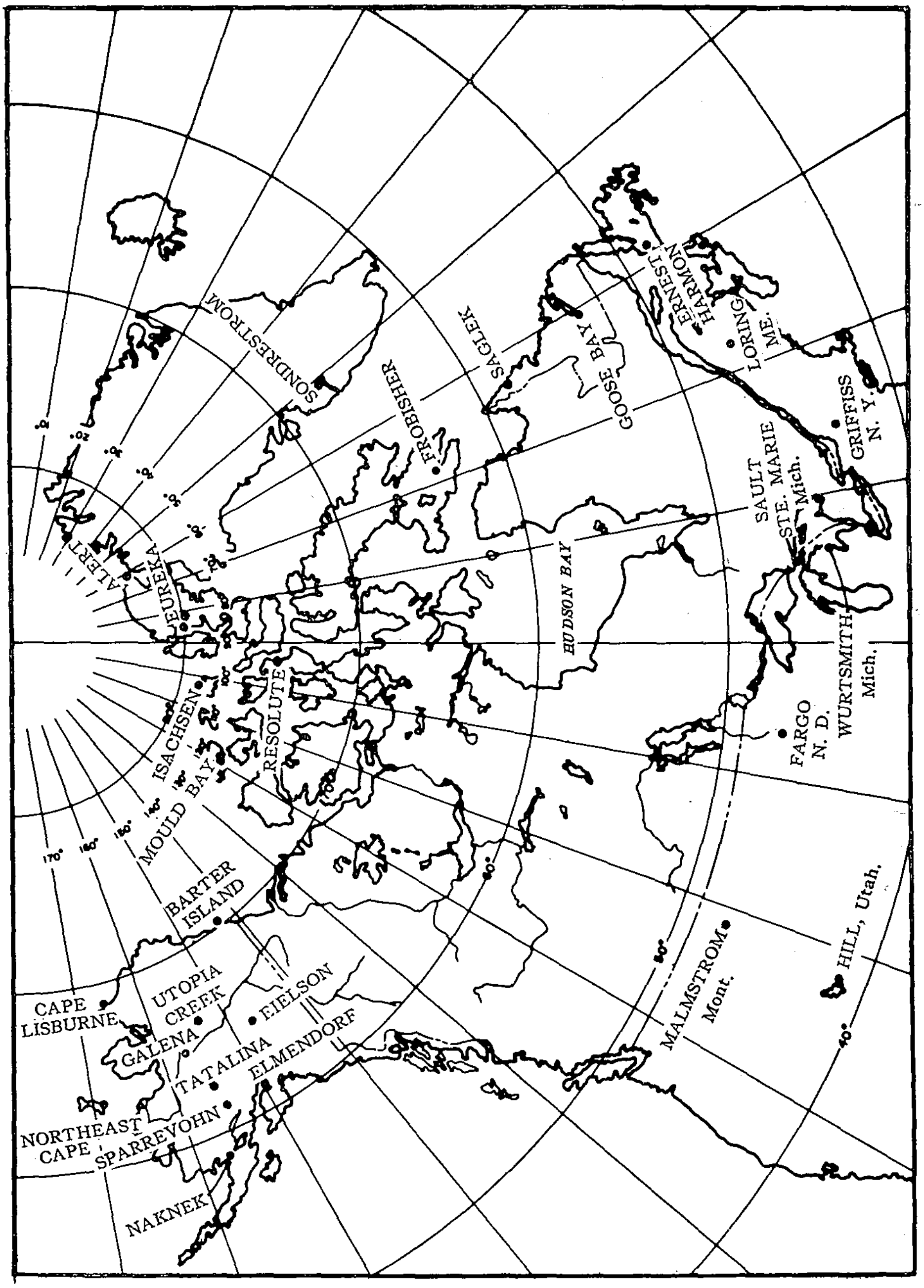

Fig. 1. Locations of stations

Analysis indicated that the stations could be classified into four general categories based upon the observed densities, climatic factors and to some extent on geographical location (Fig. 1). These categories were grouped in such a way as to emphasize regional, rather than point, variations in snow-cover density. Category 1 included the four stations with lowest observed densities (between 0.199 and 0.233 g/cm^3). These stations are located in the interior of Alaska and western United States, and have, in general, light winds. The second group comprises nine stations with average densities of between 0.241 and 0.268 g/cm^3 most of which are near coastlines. The seven stations in Category 3 have densities between 0.279 and 0.297 g/cm^3. This group does not have a geographic entity; the stations are located both inland and near coasts. Category 4 consists of seven arctic stations where the highest densities (between 0.320 and 0.363 g/cm^3) and the lowest seasonal temperatures were observed. Frequency curves, one for each of the four categories, are shown in Fig. 2. The figure shows clearly how the four categories fall into a series of increasing densities. Naturally, the local topography and vegetation create differences in the density from point to point within a categorically defined region. Deviations from the average value for each region can also be expected from month to month and year to year. The standard deviations from the average values (Table 1) show the extent of these monthly and yearly variations.

Skewness (departure from symmetry) coefficients, based on the quartile method (Mode, 1948), were computed for each station and are shown in Table 1. All but two stations in Categories 1 and 2 show positive skewness, *i.e.*, the peak of the frequency curve is toward lower densities, and all but two of the stations in Categories 3 and 4 show negative skewness, *i.e.*, the peak of the frequency curve is toward high densities.

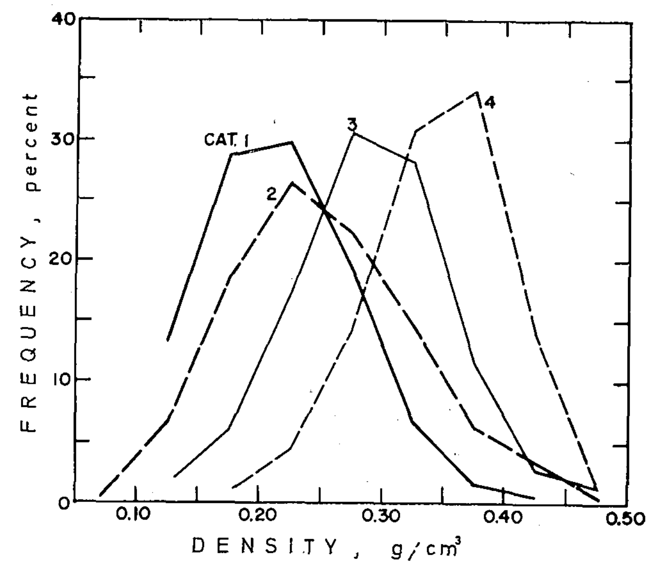

Fig. 2. Frequency curves for density Categories 1–4. Curves comprise line segments connecting midpoints of class intervals 0.10–0.15 g/cm^3, 0.15–0.20 g/cm^3, etc.

This difference supports the separation of Category 2 from 3, but since the computed values have not been analysed the results are used only as an indicator.

III. Monthly Increase in Density

The metamorphic processes which take place within a snow cover with time have been described by a number of investigators (*e.g.*, Bader, *et al.*, 1939; de Quervain, 1945; Kingery, 1960). It has been shown (*e.g.*, Shepelevsky, 1938; Work, 1948; Thornthwaite, 1950; Gold, 1958) that this aging process results in a gradual increase in the snow-cover density as the winter progresses.

This time-densification process was substantiated in this study on average monthly density values. The computed monthly values for the stations within each category were combined and the results are shown in Fig. 3. The density for the stations in Categories 1, 2 and 3 (except for 2 between November and January) increases by approximately 0.01 g/cm^3 each month. The decrease in density during December for Category 2 is believed due to the fact that the stations in this group are principally located in a region of heavy snowfall and that the new snow of lighter density that accumulates between November and December dominates the snow pack. The stations in Category 4 show little change throughout the winter because their densities are initially near maximum and because they are located at latitudes where the heat derived from solar radiation between December and March is known to be very small and of negligible effect on snow density.

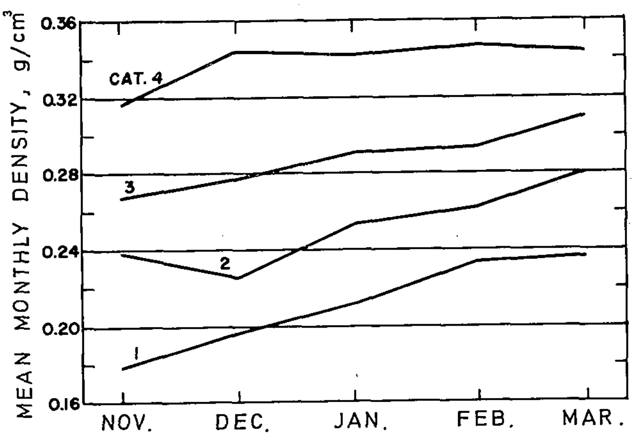

Fig. 3. Increase in density from November through March for Categories 1–4

IV. Nomograph to Estimate Average Snow-Cover Density

One of the main objectives of this study was to develop a nomograph from which the relationship between climatic parameters and the density of winter snow cover could be determined.

There are a number of fundamental conditions which determine the structure, and physical and mechanical properties, of a snow cover (Yosida, 1955). In addition to the meteorological environment, other processes directly or indirectly attributable to weather could affect the snow cover. For example, Kondrat'eva (1945) reports that the sublimation process in the snow cover can bring about a significant redistribution of snow mass and that a temperature difference of 11 °C in a snow pack caused the density in the lower layer to decrease by 0.08 g/cm^3 in 5 days. The heat flow from the soil and the soil conditions with respect to water content and depth of freezing also may influence the metamorphic processes within the snow pack. However, these subtle effects and their resultant changes in snow density are not within the scope of this report. These processes and such factors as humidity, radiation and cloud cover must be considered if one wishes to undertake a micro-scale study of changes in snow-cover density.

Dmitrieva (1950) presents a method of calculating the mean density of the snow cover from the following data: The time of snow cover appearance; the number of days with wind speeds over 6 m/sec between the time of appearance of the snow cover and the data of calculation; the sums of positive mean diurnal air temperatures for this period; and data on snow cover depth or amount of precipitation for cases of heavy snowfall. Dmitrieva states that an accuracy of ± 0.03 g/cm^3 was found in 91% of the calculations for regions where winter temperatures fluctuate little, and least accuracy where frequent thawing occurred. Weinberg and Gorlenko (1940) also note that the densification effect by wind on the snow cover is of significant importance. Wind fragments the snow crystals, causes the finer grains to re-sort and by packing increases the density of the snow cover.

As Williams and Gold (1958) point out, many difficulties complicate the problem of relating snow cover characteristics to climate. For example, in any one area meteorological factors vary from year to year, and the elements measured at a site may not be representative. However, they also found that wind speed and air temperature appear to be the dominant factors in the formation of the cover. Consequently, they developed a weather index using these elements to estimate average monthly densities. Although there was considerable spread in density for any particular index a correlation did exist between the variables. However, when monthly averages were calculated for sheltered stations and plotted against the weather index for the month, little correlation was found.

In the 1957 study, I developed nomographs for estimating average monthly densities. Since that study included only stations north of 62°N latitude reasonable results were obtained in the month-to-month analysis. A similar approach was tried for the 27 stations in this study, but the results were less favorable. Apparently, the climatic regime under consideration is too extensive for predicting densities from month to month. Therefore, multiple regression analysis was made in which seasonal snow-cover density was related to the average air temperature and wind speed (Table 1) observed during the same period. The resultant equation derived through the use of a computer is:

$$\rho = 0.152 - 0.0031\,T + 0.019\,W,$$

where ρ is average seasonal snow-cover density (g/cm^3),
T average seasonal air temperature (°C) and,
W average seasonal wind speed (m/sec).

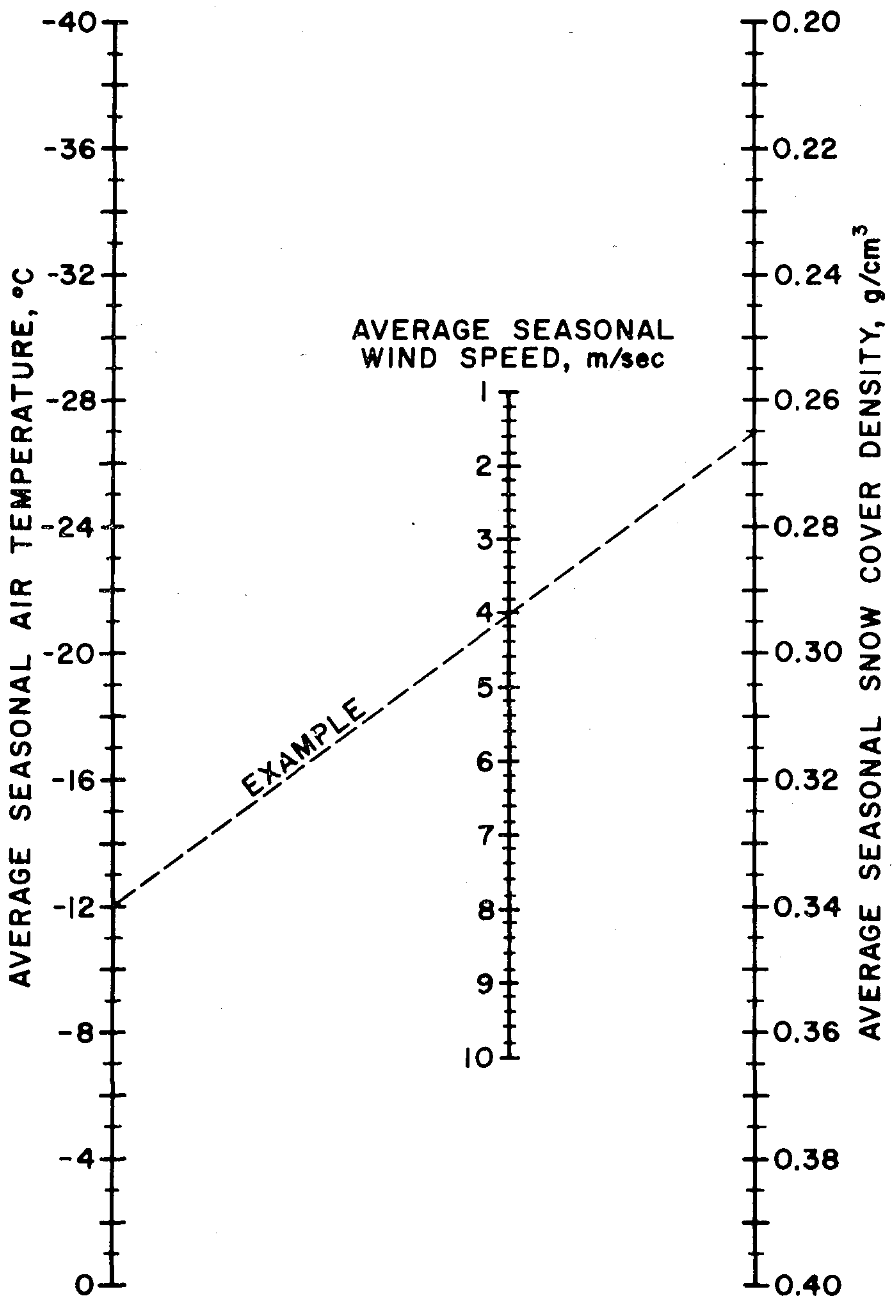

Fig. 4. Nomograph to estimate average seasonal snow-cover density. The term "seasonal" refers to November through March inclusive, unless the average air temperature for the month is above freezing. Example: Assume the average seasonal air temperature and wind speed for a location are −12°C and 4.0 m/sec. In Fig. 4, extend a straight line through these two points and read 0.265 g/cm^3 on the snow density scale

The correlation coefficient and the standard error of estimate are 0.84 and 0.025 g/cm^3, respectively.

By coincidence, the numerical constant (0.152) appearing in the equation is almost identical to that given by Dmitrieva (1950) for the average density of fresh snow (0.15 g/cm^3). This value, obtained from two independent studies, implies that when the Arctic, Subarctic and Temperate Zones are considered the average density of freshly fallen snow is higher than the generally accepted water equivalent value of 10%. Figure 4 is the nomograph developed from the above equation.

V. Test and Application of the Nomograph

To test the nomograph, the densities for 10 locations not included in the study were estimated. These stations (Table 2) were used because they cover a wide climatic range and their average observed densities were reported by Gold and Williams (1957). Their report, dated 1957, stated that the snow survey was initiated in 1946. Consequently, average air temperature and wind speeds for the winter seasons between 1946 and 1957 (Table 2) were used as the independent variables (Department of Transport, 1946–57).

Table 2. Observed average density, seasonal air temperature and wind speed for stations in Gold and William's (1957) report used to test nomograph

Station	Observed average snow density (g/cm^3)	Average seasonal temperature (°C) (1946–57)	Average seasonal wind speed (m/sec) (1946–57)
Edmonton, Alberta	0.224	−10.8	3.7
Maniwaki, Quebec	0.233	− 8.2	3.2*
Forestville, Quebec	0.237	− 9.4*	4.4*
Aklavik, NWT	0.242	−24.7	2.5
Moosonee, Ontario	0.242	−13.4	3.5
Whitehorse, Yukon	0.254	−13.9	4.0
Ottawa, Ontario	0.275	− 7.7	4.7
Winnipeg, Manitoba	0.279	−12.6	5.7
Churchill, Manitoba	0.325	−21.6	6.8
Old Glory, British Columbia	0.369	− 9.6	8.2

* Values obtained from nearby stations.

Figure 5 shows the observed and estimated densities for these stations. There is good agreement between the values (correlation coefficient=0.91) and the standard error of estimate obtained from a least squares computation was 0.016 g/cm^3.

The results of density computation from this nomograph gave sufficient confidence to warrant its application to a number of stations throughout North America. The necessary climatological data for ten years (1952–63) of record for 61 stations (Table 3) were compiled and average seasonal density values were estimated from the nomograph. These values, plus those observed in this and the Gold and William's (1957) study, were

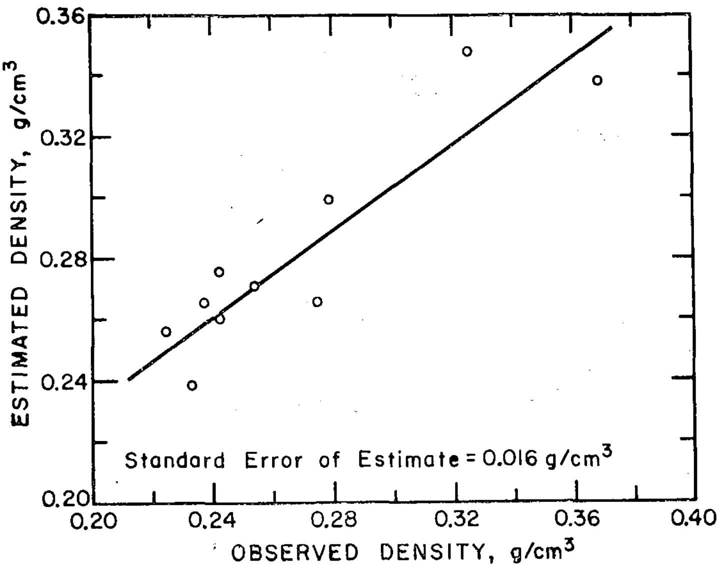

Fig. 5. Estimated versus observed densities for ten test stations (from Gold and Williams, 1957)

Table 3. Stations for which average snow-cover densities were estimated from nomograph

Station		
Aishihik, Yukon	Fort William, Ontario	Portland, Maine
Arctic Bay, NWT	Glasgow, Montana	Prince George, British Columbia
Baker Lake, NWT	Grand Prairie, Alberta	Rapid City, South Dakota
Barrow, Alaska	Green Bay, Wisconsin	Regina, Saskatchewan
Bethel, Alaska	Hall Beach, NWT	Sheridan, Wyoming
Bismarck, North Dakota	Harrington Harbour, Quebec	Sioux City, Iowa
Brochet, Manitoba	Havre, Montana	Smithers, British Columbia
Buffalo, New York	Hay River, NWT	Snag, Yukon
Cache Lake, Quebec	Holman Island, NWT	Spence Bay, NWT
Cambridge Bay, NWT	Indian House Lake, Quebec	Spokane, Washington
Chesterfield, NWT	Kotzebue, Alaska	Summerside, Prince Edward Island
Clyde, NWT	Mayo Landing, Yukon	Teslin, Yukon
Coppermine, NWT	McMurray, Alberta	The Pas, Manitoba
Coral Harbour, NWT	Medicine Hat, Alberta	Thule, Greenland
Duluth, Minnesota	Nitchequon, Quebec	Trout Lake, Ontario
Ennadai Lake, NWT	Nome, Alaska	Watson Lake, Yukon
Fort Chimo, Quebec	Norman Wells, NWT	Williston, North Dakota
Fort Nelson, British Columbia	North Bay, Ontario	Yellowknife, NWT
Fort Reliance, NWT	Northway Junction, Alaska	
Fort Simpson, NWT	Nottingham Island, NWT	
Fort Wayne, Indiana	Pagwa, Ontario	
	Port Harrison, Quebec	

used to draw an average seasonal snow-cover density map for North America (Fig. 6). Using the density ranges of the four categories described previously the continent was divided into zones. The zones were separated at density values of 0.24, 0.27 and 0.31 g/cm³.

Gold and Williams (1957) divided Canada into five main snowfall regions. In addition

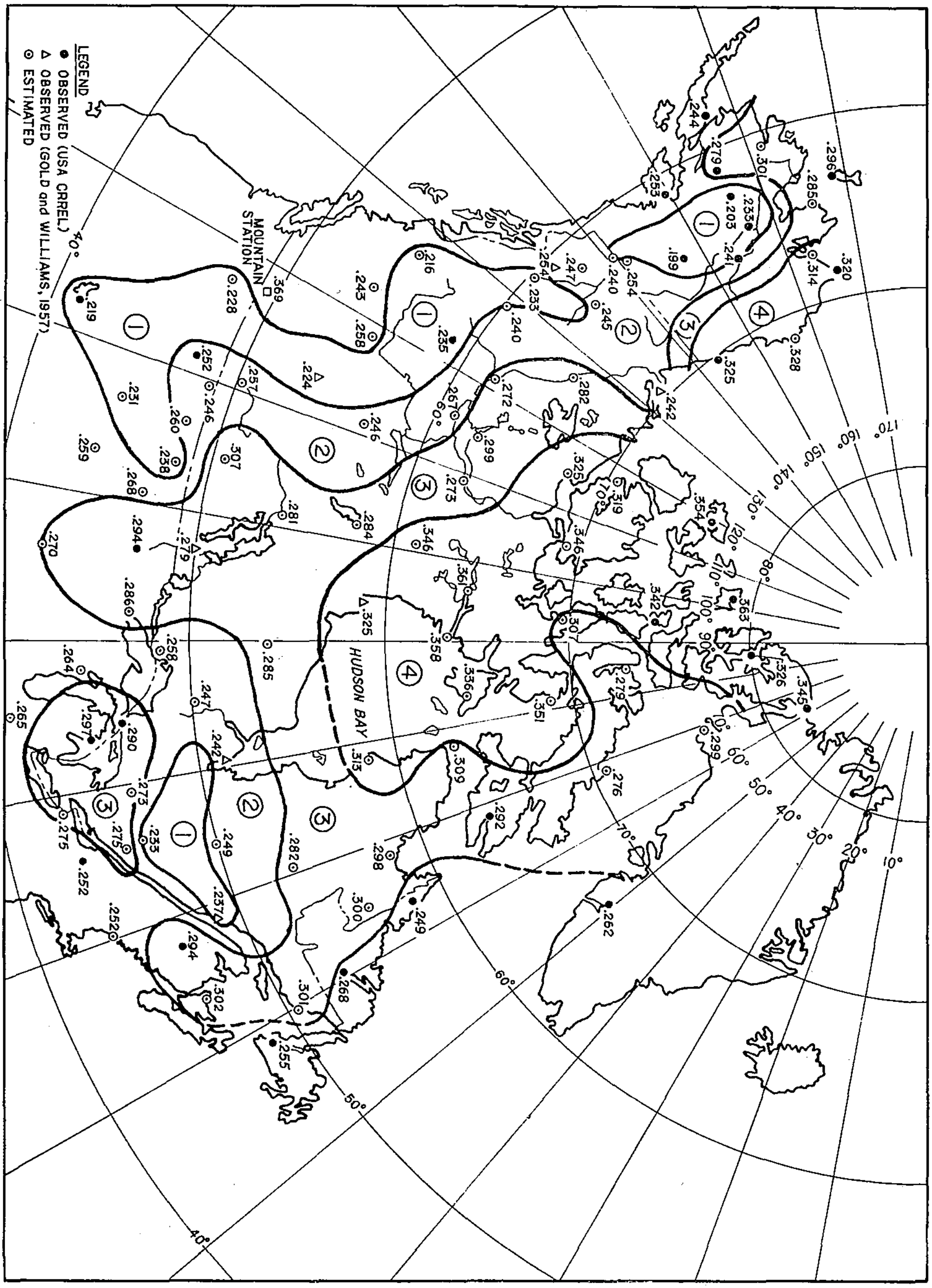

Fig. 6. Average seasonal snow-cover densities. Categories 1–4 are separated at densities of 0.24, 0.27 and 0.31 g/cm³

to the physical characteristics of the snow cover these regions were determined by the amount of snowfall, temperature, time of first snowfall, and the length of time the snow stays on the ground.

Except for eastern Canada, their arctic region coincides closely with Category 4 where the highest densities are recorded. Except for some eastern portions and the area around the Great Lakes, Category 3 corresponds roughly with their Northern Forest region. The region they classify as the freeze-thaw area, which included mostly the Atlantic Provinces, southern Ontario and southern Quebec, approximately coincides with the Category 1, 2 and 3 areas used in this study. As they point out, rain, heavy snowfalls, ice lenses within the snow cover, sleet and above-freezing temperatures are common in this area during the winter. Similarly, the other two regions (1-Prairie zone, and 2-Western Mountain and Coastal zone) covered portions of Canada where areas assigned to Categories 1, 2 and 3 are used in this study.

VI. Discussion

The system developed in this study provides an estimate of the average snow density for a general area over a number of years. It does not attempt to predict the density of a snow cover from point to point nor from week to week, nor year to year. Estimated values for 61 locations and observed values for 37 other locations were used to divide North America into geographical areas which fall into one of four predefined ranges of density. Except for those areas with snow densities above 0.31 g/cm^3 it is shown that the density of the snow pack increases slightly from month to month during winter.

The snow cover and its characteristics are extremely variable in areas such as a coastal-mountainous region (Alciatore, 1916; Tsomaia, 1956; McKay, 1964). The snow packs in these regions range from the permanent snowfields at higher elevations to an occasional, brief, snow cover in the warm coastal plains and valleys. Large changes in density that occur in a short distance are exemplified by the mountain station, Old Glory, British Columbia (Fig. 6). The value for this station places it in Category 4 whereas a station nearby is in Category 1, indicating that the area bridges four categories. The scale of the map and insufficient data preclude the delineation of the intermediate categories. Consequently, caution should be used when interpreting Fig. 6 in mountainous areas. In some portions of such regions, where the winter air temperatures and wind speeds over a wide area are reasonable uniform, the results presented in this study are applicable. For example, the stations in Category 1 in western United States and Canada and the interior of Alaska are mostly sheltered stations in valleys or on the lee sides of mountains where light winds and low densities are consistently observed.

Acknowledgments

The data used in this report were made available through the combined efforts of personnel associated with the Air Weather Service, U. S. Air Force; the Weather Bureau, U. S. Department of Commerce and the Meteorological Branch, Canadian Department of Transport. The author wishes to thank Dr. Robert Gerdel and Professor Fred Sanger, USA CRREL, for their technical review of the paper. Mr. Roy Bates, USA CRREL, assisted with the computation and tabulation of the data.

References

1) ALCIATORE, H. F. 1916 Snow densities in the Sierra Nevada. *Monthly Weather Review*, **44**, 523–527.

2) BADER, H., HAEFELI, R., BUCHER, E., NEHER, J., ECKEL, O. and THAMS, Chr. 1939 Snow and its metamorphism. Beitrage zur Geologie der Schweiz, Geotechnische Serie, Hydrologie, Lieferung 3, Bern; 1954, *SIPRE Trans.*, **14**, 1–313.

3) BILELLO, M. A. 1957 A survey of Arctic snow-cover properties as related to climatic conditions. *SIPRE Res. Rept.*, **39**, 1–9.

4) DE QUERVAIN, M. 1945 Snow as a crystalline aggregate. Experientia, **1**; 1954 *SIPRE Trans.*, **21**, 1–7.

5) Department of Transport, Canada 1946–1957 and 1952–1963 Monthly record. Meteorological observations in Canada. Meteorological Branch, Department of Transport.

6) DMITRIEVA, N. G. 1950 Calculation of snow-cover density using meteorological data. *Meteorölogiia i Gidrologiia*, **2**; 1954, *SIPRE Trans.*, **24**, 1–4.

7) FORMOZOV, A. N. 1946 Snow cover as an integral factor of the environment and its importance. Moscow Society of Naturalists, Moscow, USSR; *Translation* by Boreal Institute, Univ. of Alberta, Canada, Occasional paper, No. 1, 176 pp.

8) GOLD, L. W. 1958 Changes in a shallow show cover subject to a temperate climate. J. *Glaciol.*, **3**, 23, 218–222.

9) GOLD, L. W. and WILLIAMS, G. P. 1957 Some results of the snow survey Canada. *Res. paper*, No. **38**, Division of Building Research, National Research Council, Canada, 15 pp.

10) KINGERY, W. D. 1960 On the metamorphism of snow. *Ice Res. Lab. Rept.*, No. **61-1**, Massachusetts Institute of Technology, Cambridge, Mass., 9 pp.

11) KLEIN, G. J. 1950 Canadian survey of physical characteristics of snow-covers. *Tech. Memorandum*, No. **15**. National Research Council of Canada; Reprinted from Glaciers and Climate 1949 *Geografiska Annaler*, H. **1-2**, 106–124.

12) KONDRAT'EVA, A. S. 1945 Thermal conductivity of the snow cover and physical processes caused by the temperature gradient. Acad. Sci. USSR, Moscow; 1954 *SIPRE Trans.*, **22**, 1–13.

13) MCKAY, G. A. 1964 Relationships between snow survey and climatological measurements. *In* Surface Waters. General Assembly of Berkeley, IUGG, Publ. No. **637**, 214–227.

14) MODE, E. B. 1948 The Elements of Statistics, Prentice Hall, Inc., New York, 378 pp.

15) RIKHTER, G. D. 1945 Snow cover, its formation and properties. Acad. Sci. USSR, Moscow; 1954 *SIPRE Trans.*, **6**, 1–66.

16) SHEPELEVSKY, A. A. 1938 The distribution and gradual change of density in snow cover. *Trans. Arctic Inst. Sci. Res.*, **110**; *Translation* by Headquarters, U. S. Army Air Forces, Weather Division, Pasadena, California, 24 pp.

17) THORNTHWAITE, C. W. 1950 Estimating soil tractionability by climatic analysis. Office of the Quartermaster General, U. S. Army Environmental Protection Rept. No. **167**, 66 pp.

18) TSOMAIA, V. Sh. 1956 Methods of calculating snow density in a mountainous area. *Trudy Tbibisskogo N.-I. Gidrometeor. Instituta*, **1**, 69–77.

19) U. S. Air Force 1952–63 Mean monthly wind speeds and mean monthly temperatures for selected stations. Air Weather Service, Data Control. Div.

20) U. S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) 1954 Instructions for making and recording snow observations. *Instruction Manual*, **1**, 10 pp. (revised 1962).

21) U. S. Weather Bureau 1952–63 Climatological data. National Summaries and Alaska Summaries, U. S. Department of Commerce.

22) WEINBERG, B. P. and GORLENKO, S. M. 1940 Snow cover and its dynamics. *In* Ice, Moscow, 410–440; *Translation* by Office of Technical Services 1963 *Trans.* 63–20479, 23 pp.

23) WENGLER, F. 1914 The specific density of snow. Inaugural-Dissertation, Friedrich-Wilhelms Univ., Berlin, 86 pp.

24) WILLIAMS, G. P. and GOLD, L. W. 1958 Snow density and climate. *Res. Paper*, No. **60**, Division of Building Research, National Research Council, Canada, 4 pp.

25) WORK, R. A. 1948 Snow layer density changes. *Trans. Amer. Geophys Union*, **29**, 4, 525–546.

26) YOSIDA, Z. and colleagues 1955 Physical studies on deposited snow, I. Thermal properties. *Contr. Inst. Low Temp. Sci.*, **7**, 19–74.