Snow density and climate
Williams, G. P.; Gold, L. W.

Publisher’s version / Version de l'éditeur:

Transactions, Engineering Institute of Canada, 2, 2, pp. 91-94, 1958-07-01

NATIONAL RESEARCH COUNCIL
CANADA

DIVISION OF BUILDING RESEARCH

SNOW DENSITY AND CLIMATE

by

G. P. Williams and L. W. Gold

REPRINTED FROM
TRANSACTIONS, ENGINEERING INSTITUTE OF CANADA
VOL. 2, NO. 2, MAY 1958, P. 91-94

RESEARCH PAPER NO. 60
OF THE
DIVISION OF BUILDING RESEARCH

NRC 4833

OTTAWA
JULY 1958

PRICE 10 CENTS

Snow Density and Climate

ANALYZED

G. P. Williams, JR.E.I.C.* and L.W. Gold*

This report summarizes the data that have been collected on snow density since 1947 from selected observation stations across Canada. The relationships between snow density and meteorological variables, particularly wind velocity and air temperature, are discussed. From these snow density data, the insulating value of snow covers for different regions in Canada are listed.

SINCE 1947 DATA on several snow characteristics have been obtained from selected stations across Canada under the auspices of the Associate Committee on Soil and Snow Mechanics and through the co-operation of the Division of Building Research, National Research Council, the Meteorological Division, Department of Transport, and a number of private companies. The snow observations were taken in wooded areas protected from wind and in areas where the snow cover was exposed to wind action. Figure 1 shows the location of these snow survey stations.

Snow density was one of the characteristics measured with the Standard Snow Kit described in a paper by Klein, Pearce and Gold.[1] Snow densities were obtained by inserting a 250 c.c. sampler horizontally into the snow profile and weighing the snow sample so obtained. Samples were taken in the different snow layers from the ground to the snow surface at weekly and twice-monthly intervals. This report analyses these snow density observations and shows how snow density varies across Canada. In addition, the relationship between snow density, thermal conductivity of snow, heat flow from the ground and climatic factors will be discussed.

There have been several studies[2,3,4,5,6] on the thermal conductivity of snow covers. Almost all the formulae developed indicate that thermal conductivity is some function of snow density. This is understandable as loose snow contains more air spaces than dense, compacted snow. Since air is a poorer conductor of heat than ice, any increase in the quantity of the air in the snow brings about a decrease in the thermal conductivity.

Unfortunately, there have been few studies of snow density on a regional basis. Dmitrieva[7] has reported on snow density on a regional basis in the U.S.S.R. but his findings do not necessarily apply to North American conditions. Gold and Pearce[8] reported on snow characteristics across Canada in 1950 and included some observations on snow density. Gold and Williams[9] presented some information on snow density to the 13th (1956) annual meeting of the Eastern Snow Conference. These contributions do not present, in convenient form, specific information on snow density which would be of value to an engineer in such problems as snow clearing, snow loading, and heat exchange at the ground surface.

The Relationship between Snow Density and Meteorological Variables

The form of snow crystals which arrive at the ground is dependent on the history of the crystal in the air.[10,11] Since the major portion of the development of the crystal occurs in clouds well above the ground, there need be little correlation between meteorological conditions which exist at ground level and the properties of the falling snow. In mountainous regions, where the precipitating cloud is much closer to the observation level, some correlations have been detected.[10,12,13] Although meteorological conditions at the ground may not be related to the properties of the snow while it is still in the air, they are very important in determining how snow particles are deposited.[14] Of the meteorological variables that are measured, wind velocity and air temperature appear to be the dominant factors affecting the formation of the cover.[7]

Once the snow is deposited, the thermo-dynamic process involving the snow particle reverses from one of growth to one of decay, called metamorphism. Under the influence of a continuously changing environment, the physical properties of the snow modify. Temperature, gradients of temperature, pressure, gradients of pressure, all act on the snow to produce a mass movement appearing in the solid, liquid or vapour phase.[15] The resulting continuous change in the physical properties such as density is particularly noticeable in the upper layers of the cover. At a depth of 20 cm. reasonable stability is achieved.[9] Meteorological factors determine the environment in which the metamorphic process is occurring.

If correlation could be established between snow cover properties and meteorological factors, the problem of determining snow characteristics and particularly snow density would be greatly simplified. Then from the comparative abundance of meteorological data it would be possible to determine specific properties of a snow cover for areas where density measurements have not been taken.

Many difficulties complicate the problem of relating snow cover characteristics to climate. In any one area meteorological factors vary from year to year. Further variability is introduced by the influence of topography, vegetation, and other factors intimately involved in the formation of the cover. This variability makes it difficult to assign average values to the properties measured. For example, wind velocity, temperature, humidity, etc. measured at a site may not be representative of the average wind velocity, temperature, humidity, etc. which exist at the time of measurement over the observation area.

*Research Officer, Division of Building Research, National Research Council of Canada, Ottawa.
Paper received 14 August 1957.

A further difficulty is whether the weather data, usually recorded as averages, are truly representative of the weather which influenced the snow cover. For example, in a single month one major storm with high winds might be the dominant factor affecting the snow cover characteristics for that month. The average wind velocity recorded for the month might not be representative of the wind velocities which occurred during the storm. Another example would be the effect of a single day of freezing rain or thaw which would have an influence on the snow cover not reflected in the monthly average temperature values.

The Relationship between Snow Density and a Weather Index

To overcome some of the difficulties associated with site and climatic variations, only data collected during months of continuous cold at stations with exposed sites were used to determine the first relationships to be presented. Since wind velocity and temperature appear to be the dominant factors in the formation of the cover, these elements only were used to calculate an index of the climate.

The air temperature and wind velocity data were combined into a weather index. Attempts to relate air temperature or wind velocity separately to snow density failed to show significant results. The monthly air temperatures were divided into six classes: +25°F. to +15°F.; +15°F. to +5°F.; +5°F. to −5°F.; −5°F. to −15°F.; −15°F. to −25°F.; −25°F. to −35°F. which covered the range of monthly air temperatures encountered. The monthly average wind velocity was divided into six classes: 0—5, 5—10, 10—15, 15—20, 20—25, 25—30 m.p.h., which covered the range of wind velocities encountered. The weather index was made by adding the class numbers of wind velocity and temperature. For example, if the average monthly air temperature was 0°F. it would fall in class 3 (+5°F. to −5°F.). If the average monthly wind velocity was 8 m.p.h. it would fall in class 2 (5—10 m.p.h.). The weather index for this month was the sum of the two classes which in this case equals five.

Every month was assigned a weather index, which could be compared to an average monthly density. Figure 2 plots the average monthly density of the layer lying between 4 in. and 12 in. from the snow surface, against the monthly weather index for exposed stations. It is seen that though there is a considerable spread in density values for any particular index a correlation does exist between these two variables.

When the monthly averages were calculated for sheltered stations and plotted against the weather index for the month, little correlation was found. This is because most of the sheltered stations are located in a part of Canada subject to weather fluctuations that produce melting and rain. This factor plays a major role in determining the characteristics of snow cover.

Both air temperature and wind velocity appear to influence snow density. For example, density values at Old Glory Mountain, British Columbia, and Resolute, N.W.T., are comparable. Yet in a typical year the average winter temperature at Old Glory Mountain can be 25°F. to 30°F. higher than the average winter temperature at Resolute. However, the average wind velocity at Old Glory Mountain is almost double that recorded at Resolute. When the two factors of wind velocity and air temperature are combined into an index, the two stations have comparable weather indices.

It is not clear how temperature enters into the relationship. Bossolasco[12] has shown that the density of the snow decreases with decreasing temperature from 0°C. to −15°C. and then reverses this trend for temperatures below −15°C. It may be that the temperature is not the real variable involved, but merely an indicator of other processes. For example, the low temperatures that occur at Resolute or on the Prairies may be associated with the many snowfalls contributing less than one inch per snowfall to the snow cover. A snow cover built up in such small steps would have greater opportunity to be thoroughly worked over by the wind. Stations with higher average temperatures are likely to have snowfalls which contribute a considerable amount to the cover.

Snow Density Variation across Canada

In order to present more specific information on snow density, all the density values from depths 0 to 36 in. from all stations were analysed statistically. Table I shows calculated values of mean density, standard deviation, and the number of density observations at each snow survey station. With the wide variation in atmospheric conditions across Canada it is not surprising to find a wide variation in snow density values from station to station.

The mean densities at Old Glory, Resolute and Churchill are 0.369, 0.356 and 0.325 respectively. As snow density is apparently increased by cold temperatures and wind, it is not surprising to find the highest density values at Resolute and Churchill, in northern Canada, and at Old Glory Mountain (7,000 ft. level) in southern B.C. Melting temperatures during the winter season can also increase snow

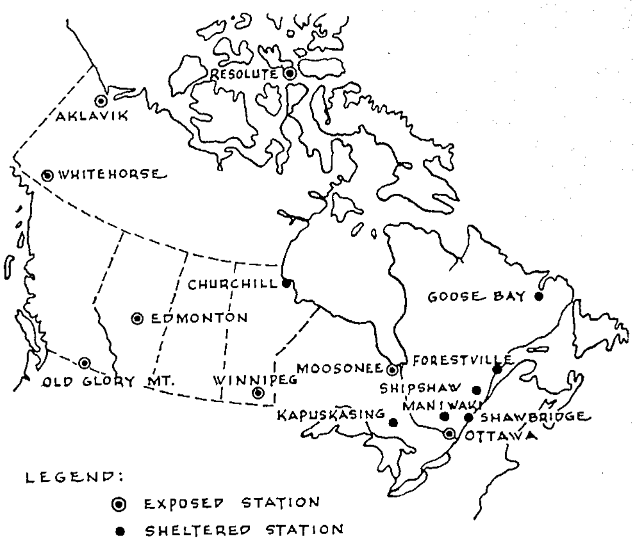

Fig. 1. Map showing the locations of snow survey observation stations.

Table I. Calculated Mean Density and Standard Deviation for Snow Survey Stations shown on Fig. 1

	Number of Observations	Mean Density (gm/cm.^{3})	Standard Deviation (gm/cm.^{3})
Exposed Stations			
Winnipeg	69	0.279	0.050
Aklavik	93	0.242	0.053
Resolute	261	0.356	0.052
Old Glory	92	0.369	0.070
Ottawa	48	0.275	0.076
Moosonee	102	0.242	0.063
Whitehorse	65	0.254	0.056
Edmonton	42	0.224	0.045
Sheltered Stations			
Fort Churchill	92	0.325	0.108
Goose Bay	110	0.243	0.068
Maniwaki	82	0.233	0.073
Forestville	82	0.237	0.077

density as evidenced by the comparatively high mean of 0.275 at Ottawa. The mean values at the rest of the stations ranged from a high of 0.279 at Winnipeg to a low of 0.224 at Edmonton.

The standard deviation is generally higher at sheltered stations than at exposed stations. The standard deviation is not only a measure of snow density variation but it is probably also a measure of the variability of winter climate. For example, the stations in eastern Canada—Goose Bay, Maniwaki, Forestville, and Ottawa—show a higher standard deviation than in northern and western Canada. Winnipeg, Edmonton, Resolute, Aklavik, and Whitehorse have almost equal standard deviations.

Insulating Value of the Snow Cover

Most investigators have found that the thermal conductivity, K, of snow varies directly as the square of the density. Using Abel's' formula ($K = 0.0068\rho^2$ where ρ is the snow density) the mean density data, and the mean density plus or minus the standard deviation, values for the mean thermal conductivity, and the limits between which the thermal conductivity would lie 70 per cent of the time, were calculated for locations across Canada. These figures are tabulated in Table II.

During the 1955-56 winter, observations made at Ottawa

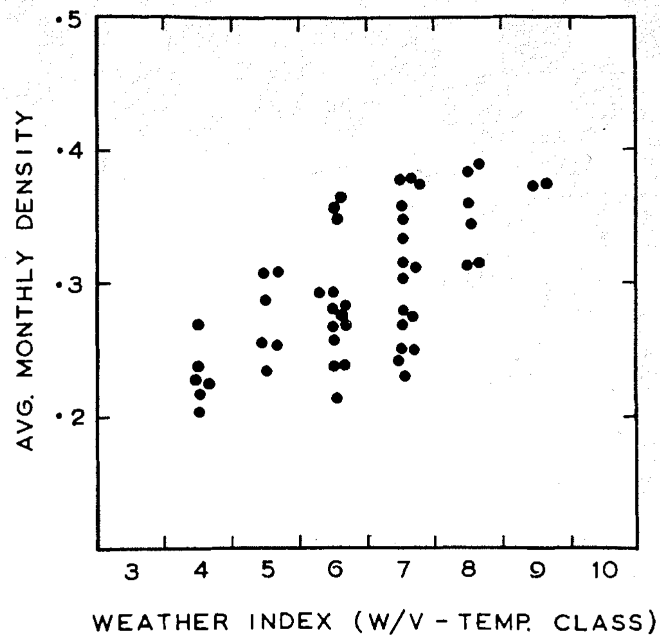

Fig. 2. Weather index related to monthly density values at exposed stations across Canada.

Table II. Insulating Value of Snow Covers Across Canada

Calculated Values for Coefficient of Thermal Conductivity of Snow

	K* mean		K* max.		K* min.	
	Cal.	B.t.u.	Cal.	B.t.u.	Cal.	B.t.u.
	cm.² °C./cm. sec.	ft.² °F./in. sec.	cm.² °C./cm. sec.	ft.² °F./in. sec.	cm.² °C./cm. sec.	ft.² °F./in. sec.
Exposed Stations						
Winnipeg	0.00053	0.00043	0.00074	0.00059	0.00036	0.00029
Aklavik	0.00039	0.00031	0.00059	0.00048	0.00024	0.00020
Resolute	0.00086	0.00069	0.0013	0.0011	0.00063	0.00051
Old Glory	0.00093	0.00075	0.0013	0.0011	0.00061	0.00049
Ottawa	0.00052	0.00042	0.00084	0.00068	0.00027	0.00022
Moosonee	0.00039	0.00031	0.00063	0.00051	0.00022	0.00018
Whitehorse	0.00044	0.00034	0.00065	0.00053	0.00027	0.00021
Edmonton	0.00034	0.00028	0.00049	0.00040	0.00022	0.00017
Sheltered Stations						
Fort Churchill	0.00072	0.00058	0.0013	0.0010	0.00032	0.00026
Goose Bay	0.00040	0.00032	0.00066	0.00053	0.00021	0.00017
Maniwaki	0.00037	0.00030	0.00064	0.00052	0.00017	0.00014
Forestville	0.00038	0.00031	0.00067	0.00054	0.00017	0.00014

* $K = .0068\rho^2$ cal./cm.²/°C. sec.

gave the following values for K:

Snow Density ρ gm./cm.³	K cal./cm². °C./cm. sec.
0.20	3.24×10^{-4}
0.25	4.38×10^{-4}

These values, calculated from a number of observations taken over two-week periods in February when the ground surface temperature was constant, agree within 20 per cent with the figures calculated using Abel's' formula.

Observations on snow density and snow depth show that higher densities (except for mountainous regions) are usually associated with shallow snow covers and extreme wind and temperature conditions (i.e., prairies, arctic barrens). The combination of these factors are favourable for maximum heat exchange from the ground to the air. Therefore, the ground frost problem is many times more severe in these areas than in the tree-belt region where the snow can accumulate to reasonable depths and wind action is greatly reduced. In forest regions snow becomes a very effective insulator: it is not unusual for the ground to remain unfrozen or ice cover on lakes and rivers to be poorly developed when the snowfall is appreciable and the snow cover develops early in the season. In practice, reasonable values of the thermal conductivity of snow in cal./cm. °C. sec. would be a minimum of 1.7×10^{-4} and a maximum of 6.5×10^{-4}, except for exposed locations such as on the Prairies, in the Arctic or on high mountains where values would range from a minimum of 6.0×10^{-4} and a maximum of 13.0×10^{-4}.

Conclusion

The structure of the snow crystals which arrive at the ground and the thermodynamic processes which take place within a snow cover are largely determined by meteorological factors. However, the problem of correlating meteorological factors with snow density and other snow properties is complex and unlikely to be exactly determinant. The data shown in Figure 2 and Table I can be used to make a rough estimate of the range of snow densities likely to be encountered under Canadian conditions.

Other properties of the snow cover, such as hardness and thermal conductivity, are directly related to the density and thus indirectly to meteorological factors. The hardness observations made in the snow survey have been analysed and correlated to the density.[16] Utilizing the results of other workers, limits have been suggested for the thermal conductivity values of normal snow covers. Continued observations should improve these correlations between snow properties and climate.

The thermal regime of the ground is determined by the heat exchange processes which occur at the surface and is thus intimately related to the over-all climate. A study of meteorological factors and how they influence the ground surface, including the snow cover, thus becomes of greater significance as Canadian development proceeds northward.

Acknowledgements

The authors wish to acknowledge the work of the observers who over a period of years measured snow density at the different stations across Canada, often under adverse weather conditions. This report would not have been possible without their co-operation and effort.

Special mention must be made of the continued interest and co-operation of Mr. Andrew Thomson, Controller of the Meteorological Division of the Department of Transport and many members of his staff. This paper is a contribution from the Division of Building Research, National Research Council, and is published with the approval of the Director.

References

1. KLEIN, G. J., PEARCE, D. C., and GOLD, L. W., Method of Measuring the Significant Characteristics of a Snow Cover, National Research Council, Associate Committee on Soil and Snow Mechanics, T.M. 18, November 1950, p. 60.
2. ABEL'S, G. Sutochyni khod temperatury v snegn i Zavisimost' mexhdu te plopro vodnost'iu snega i ego plotnost'iu (Daily Variation of Temperature in Snow and the Relation between the Thermal Conductivity of Snow and its Density) Meteorologischesku ustnik, T.M. 3) 1893.
3. JANSSON, M., The Thermal Conductivity of Snow (Text in German). *Öfversigt K. Vetensk. Akad. Förhandl.*, vol 58, no. 3, pp. 207–22, 1901.
4. DEVAUX, J., L'Economie Radio-Thermique des Champs de Neige et des Glaciers. *Ann. de Physi.*, vol. 20, no. 5, 1933.
5. KONDRATYEVA, A. S., Thermal Conductivity of the Snow Cover and Physical Processes Caused by the Temperature Gradient. Published in Physical and Mechanical Properties of Snow and their utilization in Airfield and Road Construction. Moscow, Leningrad, Akademiia Nauk U.S.S.R., 1945. SIPRE Translation No. 22, March 1954, 13 p.
6. YOSIDA, ZYUNGO and Colleagues, Physical Studies on Deposited Snow, 1. Thermal Properties. Inst. of Low Temperature Science, No. 7. Hokkaido University, Sapporo, Japan, 1955, pp. 19–74.
7. DMITRIEVA, N. G., Calculation of Snow Cover Density Using Meteorological Data (Raschet plotnaste snezhnogo pokra po meteorologischehim dannyiim, Meteorologiia i Gidrologiia, No. 2) SIPRE Translation No. 24, 1954, 4 p.
8. PEARCE, D. C. and GOLD, L. W., The Canadian Snow Survey 1947–1950, Tome 1. Assoc. Int. d'Hydrol. Scient. I.U.G.G., Brussels 1951. National Research Council, Associate Committee on Soil and Snow Mechanics, T.M. 21, Ottawa 1951.
9. GOLD, L. W. and WILLIAMS, G. P., Some Results of the Canadian Snow Survey. Presented to the Eastern Snow Conference, Hanover, New Hampshire, February 9–10, 1956.
10. D'OOGE, C. L., Snowfall and Temperature on a California Mountain. *Nature*, vol. 175, no. 4454, 1955, p. 465–466.
11. GOLD, L. W. and POWER, B. A., Dependence of the Forms of Natural Snow Crystals on Meteorological Conditions. *J. Meteor.*, vol. 11, no. 1, pp. 35–42 (1954).
12. BOSSOLASCO, M., The Formation of Precipitation (Text in Italian—English Summary). *Geofisica Pura e Applicata.*, vol. 28, pp. 208–222, 1954.
13. GOLD, L. W. and WILLIAMS, G. P., Dependence of Snowfall on Temperature. *Nature*, vol. 177, no. 4520, pp. 1137–38, June 16, 1956, National Research Council, Division of Building Research, NRC 3990.
14. RICHTER, G. D., Snow Cover, its Formation and Properties. Academy Science U.S.S.R. Popular Science Series, Publishing House of the Academy Science U.S.S.R., Moscow, Leningrad, 1945.
15. DE QUERVAIN, M., Schnee als Kristallines Aggregat. *Experientia*, vol. 1, no. 7, 1945. SIPRE Translation 21, 1954.
16. GOLD, L. W., The Strength of Snow in Compression. *Journal of Glaciology*, vol. 2, no. 20, October 1956, pp. 719–25. National Research Council, Division of Building Research, NRC 3930.

A list of all publications of the Division of Building Research is available and may be obtained from the Publications Section, Division of Building Research, National Research Council, Ottawa, Canada.