SNOWFALL AND SNOWCOVER AT KNOB LAKE, CENTRAL LABRADOR-UNGAVA

by

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INTRODUCTION

OBJECTIVES

This paper is a discussion of the amount and character of snowfall and of the nature of snowcover in the vicinity of Knob Lake, P.Q. It is an attempt to draw general conclusions from observations and studies of snow made by the staff of the McGill Sub-Arctic Research Laboratory, Schefferville, P.Q., during the period 1954 - 1966.

The snowfall of central Labrador-Ungava is of considerable academic interest in connection with the inception, growth and retreat of the Laurentide Ice Sheet (e.g. Hare 1951; Barry 1960) and is of great practical importance in the development of the Churchill Falls power scheme. With regard to the latter, the unexpectedly large discharge at Churchill Falls (Hare 1966 and personal communication to WPA, 1964) might indicate errors in precipitation measurement. In view of this, the accuracy of snowfall and snowcover measurements receives particular attention in this treatment.

PHYSICAL SETTING OF THE STUDY

Knob Lake (c. 54°48'N., 60°49'W and 1645 feet above sea level) is situated close to the geographical centre of the Labrador-Ungava peninsula, 300 to 400 miles inland from Hudson Bay and the Atlantic Ocean (Adams and Findlay 1966, Fig. 1). It is located in the Labrador Trough, a region of relatively subdued ridge and valley topography with a pronounced northwest to southeast trend. The catchment area of Knob Lake itself (13.5 square miles), which appears largely in this account, is an enclave of the north-flowing (Ungava Bay) drainage within an area of generally south-flowing (Churchill River) drainage. About 23 per cent of the catchment is lake-covered and this would be a reasonable estimate for the proportion of lakes over the entire Trough.

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The Knob Lake region is on the southern border of the Forest-Tundra vegetation type. The dominant cover types are extremely open, including extensive areas of relatively recent burn. On ridge tops, Open Lichen Scrub Woodland, Lichen Heath and Lichen Scrub are normal with Open Lichen Woodland interspersed with Close Lichen Woodland and a little closed crown Boreal Forest in the valleys (see Hare, 1950a, 1959). These cover types, which are of considerable importance in determining the distribution of snow on the ground, are discussed in more detail below. The general appearance of the landscape relief and vegetation can be seen from Findlay, 1966b, Plates I, III, IV.

The climate of the area is typically subarctic, with a mean annual temperature of about 24°F., with means below zero Fahrenheit for three months of each year and slightly higher than 50°F for only two months of the year. There is an average annual accumulation of close to 5,200 freezing degree days (based on 32°F. and 1st July). The climate is cloudy (an average of less than 1,500 hours of sunshine per year) and windy, with an average of over 10 miles per hour for every month. Precipitation occurs throughout the year with an annual mean of 28.7 inches (standard deviation, s, 4.8 inches) of water of which 12.9 inches (s = 2.7 inches) is snow.

PREVIOUS WORK : DATA AVAILABLE : METHODS

A list of published results of snow research in the Knob Lake area is presented in Appendix A of Adams, 1966. Gardner (1966) provides a comprehensive review of work undertaken during the decade following the establishment of a Department of Transport aviation meteorological station (operated by McGill Laboratory) in the area in 1954. The standard DOT snow programme of gauge and depth measurements close to the station was quickly expanded to include observations of snow surface characteristics and stratigraphic studies (including measurements of density, snow temperature, hardness, and grain size and type). Particularly during IGY, efforts were made to place the station (exposed site) measurements in a regional perspective by measurement at one or more nearby sheltered sites. The IGY programme was continued during the 1959-60 winter when measurements were made at sites a considerable distance from the station, including lake locations. During the period 1960-62 there was a further expansion, including a special survey of snowcover in areas of permafrost and the establishment of a permanent, 12 point, snowcourse (see Adams and Findlay, 1966, Fig I) embracing a variety of cover types. Daily depth measurements along this course and periodic pit profiles at locations along it became standard practice at this time.

In 1963-64 a time-profile site was set out (after Haefeli, et al. 1954), using standard stratigraphic techniques, (Klein et al. 1950) at one location along the course - close to the 'sheltered site' of the IGY programme - and a detailed time-profile study was carried out (Gardner, 1964). At the time of peak snowcover, the depth of snowcover in an area around the snowcourse was mapped (on a 100 foot grid) to check the validity of the course mean snow value. During the following winter (Cowan, 1966), the snowcourse work was extended to include weekly water equivalent measurements. At the end of the winter, the snowcover of the area covered by Gardner was again mapped, but with water equivalent measurements added, and a survey was made of the snowcover of the catchment area of Knob Lake. This last took the form of a series of traverses (Adams and Findlay loc. cit.) across the basin with samples of depth and water equivalent at 500 or 1,000 foot intervals. The survey was made in conjunction with continuous run-off measurements (Findlay, 1966a, b). In 1965-66 (Rogerson, 1967), all the basic work of the previous year was repeated with further refinement of the surveys in the light of earlier experience. An additional survey of the area around the snowcourse was made in mid-winter.

As has been mentioned, lakes occupy a considerable proportion of the surface area of Labrador-Ungava: in this paper their snowcover receives special attention. Unusually detailed observations of lake-ice were made in the Knob Lake area throughout the period 1954-66 (review by Adams and Shaw, 1966). Studies of lake-ice of particular significance to lake snowcover include those of Andrews, 1962; Shaw, 1963, 1964, 1965; Adams and Shaw, 1964, 1966; Adams et al, 1966; Archer, 1966; Jones, 1967.

Thus for the entire period of meteorological records at Knob Lake, the standard DOT aviation weather and synoptic measurements of snowfall and snowcover have been enriched by a variety of snowcover studies. The data from the 1963-66 period, which are prominent in this paper, include:

Nipher Snow Gauge measurements	. . .	4 times daily, one site
Depth measurements	. . .	daily, 12 sites
Water equivalent measurements	. . .	weekly, 12 sites, 2 years
Snowcover map, vicinity of snowcourse depths	. . .	March (3), December (1 year)
Snowcover map, vicinity of snowcourse water equivalents	. . .	March (2), December (1 year)
Survey of Knob Lake catchment, depth and water equivalent	. . .	March, 2 years
Lake-ice measurements, two lakes	. . .	6 measurements weekly
Lake-ice measurements, all lakes in catchment	. . .	2 years
Discharge from Knob Lake catchment	. . .	2 years
Time profile studies	. . .	one site, approximately one per month, 3 years.

For the period in which these data were obtained, there is a continuous record of the standard meteorological elements at the DOT station and at least weekly temperature measurements and a discontinuous record of wind from sub-stations located along the snow-course, beside Knob Lake and on the lake.

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SNOWFALL AT KNOB LAKE

The value given above for the mean annual snowfall at Knob Lake, 12.9 inches of water, is the official DOT calendar year mean based on 11 years of measurements principally with a Nipher Snow Gauge. In the middle latitudes, it is often more meaningful, particularly for hydrological studies, to consider meteorological parameters in terms of a year encompassing one whole winter rather than a calendar year. This is especially true in connection with snowfall. The amount and distribution of snow at Knob Lake during an August 1st to July 31st 'snow year' are shown in Table 1. The mean annual snowfall, when calculated in this manner (now a 12 year mean) is 12.8 inches, but it is interesting to note that the standard deviation is very much smaller; 1.51 inches as compared with 2.70 inches of water.

As can be seen from the table, appreciable snow has been recorded in every month of the year at Knob Lake and snow is the dominant form of precipitation in eight months of the year. There is a primary maximum of snowfall in the early winter months, focused on November, a minimum in late January-early February, and a secondary maximum in the spring. This broad annual pattern, in part, reflects the influence of Hudson Bay which is an important source of moisture during the early winter months but which effectively freezes over in January (Tout 1964, p.123; Hare, 1950b, p.124; Burbidge, 1949). The variations in January snowfall, in particular, must be considerably affected by the actual date of freeze-up of the Bay. The extreme cold and low absolute humidities of the late December-early March period are also a factor in the mid-winter minimum of snowfall.

Apart from the convective activity over open water in Hudson Bay, convection is of slight importance in the precipitation of Knob Lake. Variations in snowfall, from month to month and between years, can largely be explained in terms of the prevailing cyclone tracks. The major proportion of snow receipts is recorded during storms associated with the passage of cyclones and their accompanying fronts (Tout, 1964, p.123).

For example, in 1965-66 about 40 per cent of the total receipts was recorded during the three months October - December and the greater part of this amount fell during storms which involved less than 14 days. This point is of considerable importance in the efficiency of snowfall measurements and in the distribution of snow on the grouns.

Snowiness is a particular feature of the Knob Lake climate. The number of 'snow days' (days with more than .01 inches, water equivalent, of snow) each year averages 116 with, in addition, a further hundred or so days on which a 'Trace' (less than .01 inches water) is recorded. This is a very large number of days with snowfall, especially when it is considered that the number of days with snow in June, July and August is extremely small. Days with Traces or near-Traces are characteristic of the mid-winter months when very light snow in the form of single stellar or needle crystals may be continuous for many days. To cite 1965-66 again, there were only five days on which snow was not recorded during the period December-March, which is not the period of heaviest snowfall. Owing to the low temperatures of the entire winter, snow of the single crystal variety predominates over the whole year with flakes important only in the fall and late spring and for short phases during the passage of warm fronts.

The values presented in Table 1 give a useful indication of the distribution of snowfall throughout the year, but the depth of snow on the ground as a result of the falling snow varies greatly from place to place and from year to year. Snowcover is an important feature of the Subarctic environment and one about which it is difficult to generalise. Aviation weather stations are, of necessity, situated in relatively exposed locations so that measurements of snow depth nearby will rarely be representative for a large area, especially in a cold windy climate. A mean depth value for the twelve point snowcourse at Knob Lake, a mean value for an exposed location (the meteorological station) and a mean value for a sheltered woodland location are plotted in Figure 1. This gives an indication of the magnitude of variations to be expected close to Knob Lake. From this same diagram, it can be seen that there is an effective snowcover in the area for about 265 days of each year (c.f. Potter, 1957).

This mention of snow depths was introduced to complete the account of the snow year at Knob Lake. However, any discussion of the broad features of snowfall and snowcover should be considered with the considerable limitations in accuracy of measurements of both in mind.

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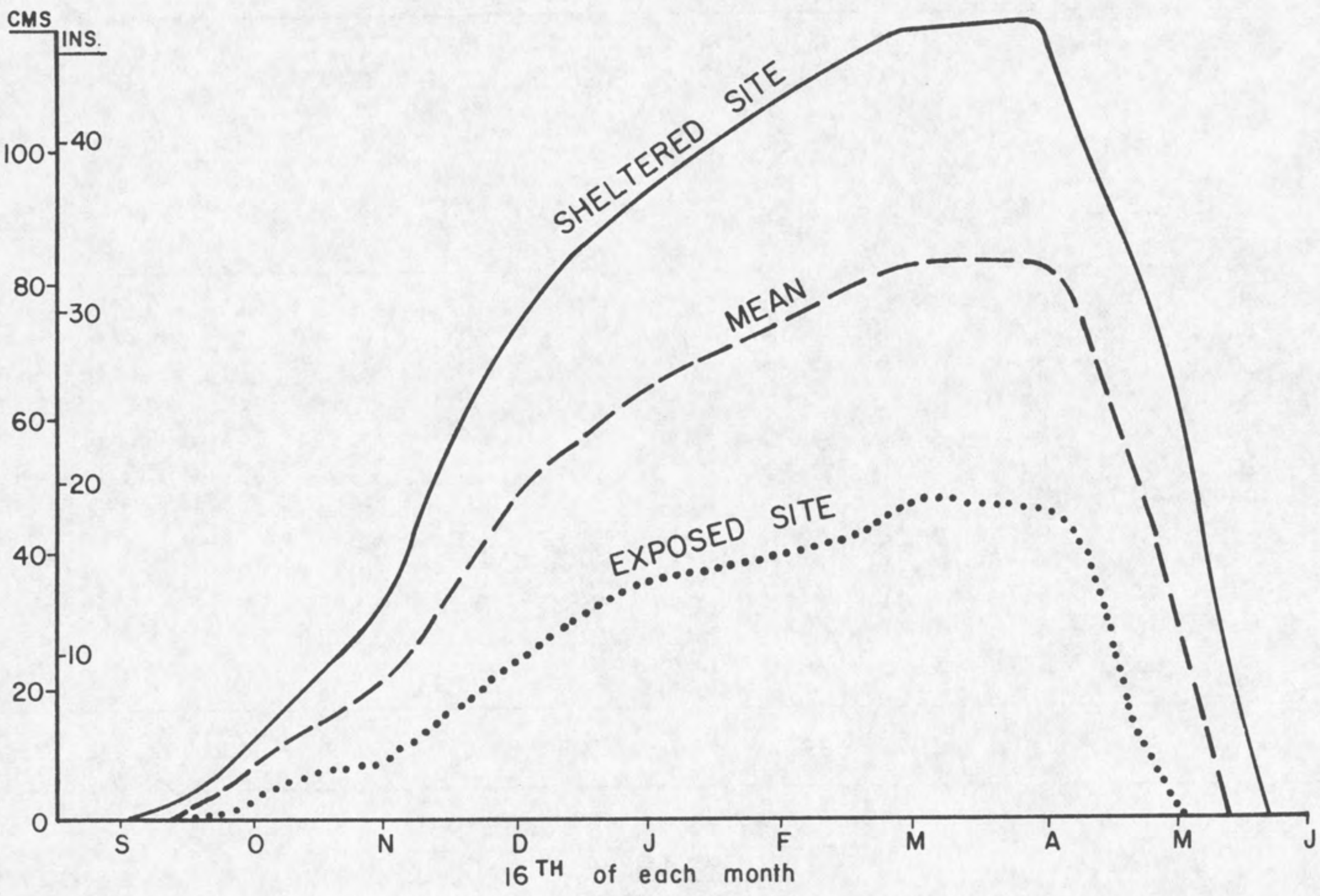
TABLE 1

Monthly and annual snowfall values
Knob Lake (ins. water)

Year	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Total
1954-55	zero	0.05	1.67	2.18	1.86	2.43	0.69	1.60	0.33	1.27	0.05	Tr	12.13
1955-56	zero	0.58	0.62	2.44	1.29	3.18	2.24	0.60	1.54	1.56	0.16	Zero	14.21
1956-57	0.06	3.96	1.43	1.42	1.40	0.36	0.88	2.59	1.14	0.69	0.39	Zero	14.32
1957-58	0.01	0.33	0.59	1.60	3.11	2.12	1.32	0.47	1.32	0.61	0.93	Tr	12.41
1958-59	zero	0.36	1.07	1.58	1.08	3.36	0.60	1.00	2.59	1.56	0.94	Zero	14.14
1959-60	zero	0.67	1.42	4.46	1.13	0.67	3.11	0.26	2.50	0.43	0.05	Zero	14.70
1960-61	zero	1.32	1.51	1.63	1.63	0.96	0.22	0.59	0.25	1.81	0.12	0.03	10.07
1961-62	Tr	1.11	1.39	2.80	2.58	2.37	0.35	0.66	0.48	0.82	Tr	Tr	12.56
1962-63	zero	0.11	0.52	1.01	1.60	1.39	1.17	1.69	1.87	0.80	0.26	zero	10.42
1963-64	Tr	0.80	1.27	2.36	0.64	1.82	0.58	2.19	0.52	1.48	Tr	0.01	11.67
1964-65	zero	0.59	1.51	2.54	1.96	1.52	2.07	0.58	0.77	0.78	0.10	zero	12.42
1965-66	1.06	0.77	2.10	3.12	1.37	0.86	1.17	1.80	0.78	1.40	0.[illegible]	0	14.43
12 yr. Mean	0.09	0.89	1.25	2.26	1.64	1.75	1.20	1.17	1.17	1.08	0.27	Tr	12.8
Range %of mn.	118	460	125	153	152	173	230	197	198	105	350	-	36
Stand. Dev.	0.30	1.03 (114)	0.51 (41)	0.89 (39)	0.40 (24)	0.93 (53)	0.83 (69)	0.74 (63)	0.73 (63)	0.04	.09	-	1.51
Snow as % of tot. Prec.	0	26	51	93	96	98	98	94	89	51	08	0	

Fig. I Seven-year mean snow depths at Knob Lake



THE MEASUREMENT OF FALLING SNOW

There are two problems connected with the measurement of falling snow by means of a Nipher Gauge, as practised by the Department of Transport in Canada. The more important of these concerns the catch of the gauge and the other concerns the procedure of measurements.

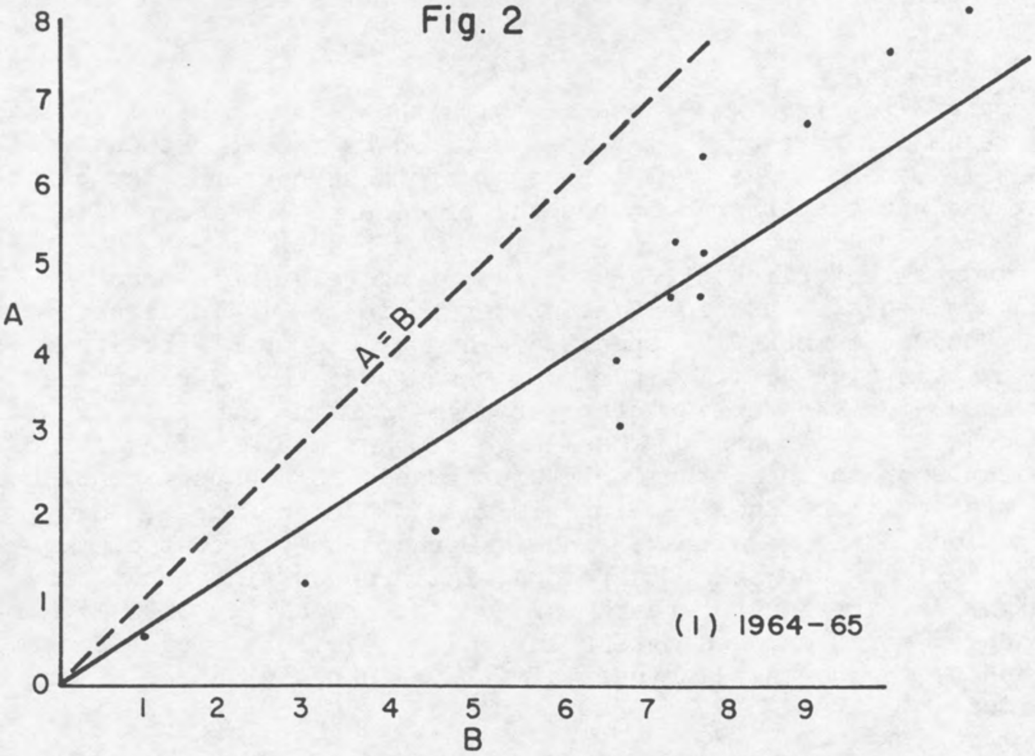
It is well established (Jackson, 1960 and references) that a Nipher Gauge tends to underestimate true snowfall. The underestimation is most pronounced when wind speeds are high. The mean wind speed at Knob Lake is over 10 miles per hour throughout the year and the monthly means for the early winter period of maximum snowfall are in excess of 12 miles per hour. These higher means are a reflection of the greater storminess of the early winter and, as has been mentioned, a large proportion of snow receipts is gained during storms, that is during periods of above average winds. Perhaps 65 per cent of the total snowfall at Knob Lake, therefore, falls under wind conditions which might be expected to greatly affect the efficiency of a Nipher Gauge located at an exposed meteorological site. This wind effect is heightened by the normal lightness of falling snow in the cold Knob Lake climate.

At official meteorological stations in Canada, the snow receipts of a Nipher Gauge are measured four times daily, at the normal synoptic hours. On each occasion, the gauge is emptied and its contents are melted to determine the water equivalent of the snowfall. If less than .01 inches of water is measured, the 'Trace' recorded does not contribute to daily, monthly or annual snowfall totals (see Jackson, 1960). Clearly such increments could have an appreciable effect on total snow receipts in, for example, a storage gauge which was emptied only once each month. The underestimation which results from this procedure chiefly affects the 35 per cent or so of snowfall at Knob Lake which does not fall during storms, but which accounts for the great majority of days with recorded snowfall.

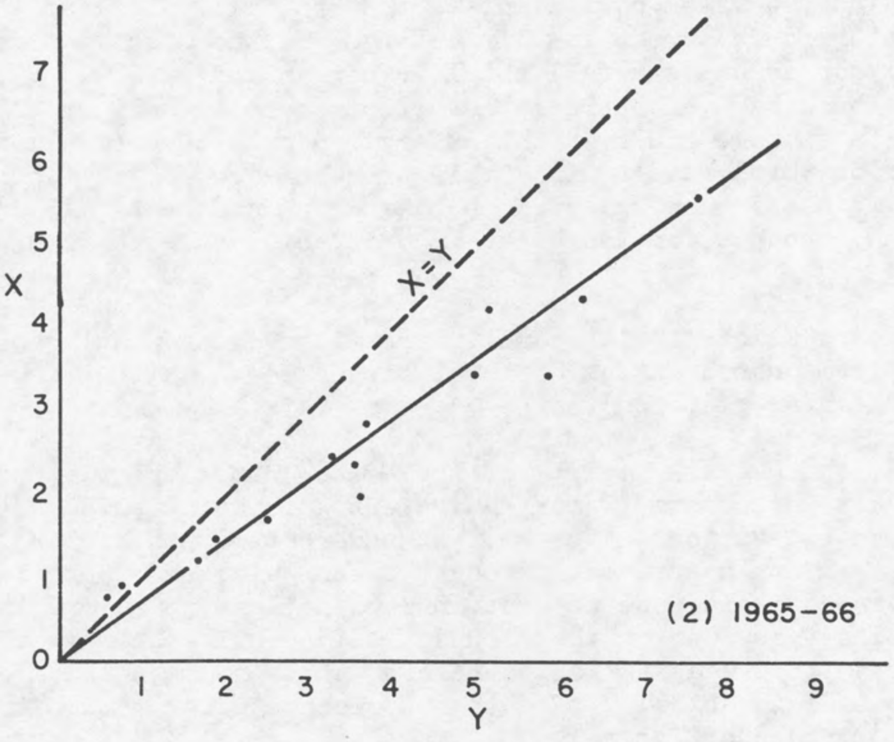
Thus it appears likely that the entire receipts of snow at Knob Lake would be undermeasured in the official Nipher Gauge, either from limitations of catch or of procedure.

In Figure 2, the weekly receipts of the Nipher Gauge are plotted against mean weekly increments (water equivalent) of the 12 point snowcourse for the two winters, 1964-66. An underestimation of the order of 25-30 per cent is apparent throughout each winter. There is no reason to believe that this underestimation does not extend beyond the period during which snow lies on the ground, to the entire snow year. The suggestion from this diagram is, therefore, that the mean annual snowfall at Knob Lake is actually more than 15 inches, water, rather than the official 12.8 inches of Table 1.

Fig. 2



Increase in snowfall W.E. measured by nipher after (A) Nov. 8, (X) Nov. 29
Increase in snowfall W.E. measured by survey after (B) Nov. 8, (Y) Nov. 29



Immediately the question of the validity of the snowcourse mean value arises, anticipating some of the discussion of a later section of this paper. Do the snowcourse measurements provide a good indication of the true snowfall of the Knob Lake area? It is sufficient to say here that intensive sampling in the vicinity of the snowcourse and over the whole Knob Lake catchment, in two winters, produced mean values which tended to confirm the snowcourse values.

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THE MEASUREMENT OF SNOW ON THE GROUND

In the Knob Lake area, where the main physiographic features are relatively simple and markedly aligned parallel to the direction of a strongly prevailing wind and where the relief is relatively low, the vegetation appeared to be the dominant surficial of snowcover. This visual impression was used as a basic assumption in mapping the snowcover during the winters 1963-66.

Vegetation maps of the area occupied by the snowcourse, which lies on the watershed of the Knob Lake catchment,and of the whole catchment, were drawn as a basis for the snow surveys (Adams and Findlay, 1966, Fig 1). The vegetation classification used was a simplified version of that of Hare (1959), whose physiognomic approach, stressing vegetation structure and its effects on the ease of penetration and intervisibility within cover types, appeared to have most meaning with regard to the re-distribution of snow by wind. The main feature of the cover types involved is their openness. The areas of true Boreal Forest are so extremely small, that, effectively, the closest cover type is Close Lichen Woodland in which trees may be 20 feet apart. The general operness is emphasized by the 23 per cent lake area.

TABLE 2

Representation of various cover types in catchment of Knob Lake, in the mapped area containing the snowcourse and along the snowcourse.

Cover Type	Description (after Hare 1959)	Catchment %	Mapped area %	Course (stakes)
Open Lichen Scrub	occasional trees, rel. abundant shrubs			2
Lichen Heath Tundra	thick lichens, abundant shrubs			0
Lichen Scrub	rocky surface, stunted trees, shrubs			0
Recent Burn	shrubs, small trees, fallen trunks			1
Muskeg	short shrub cover, few small trees			2
All classed as "Open"		47	52	5
Open Lichen Woodland	Lichen floor, spruce more than 20' apart few shrubs	15	21	4
Close Lichen Woodland	Lichen floor, spruce less than 20' apart more shrubs	15	27	3
Lake	Very exposed, smooth	23	0	0
Total		100	100	12

For the purposes of the snow survey, the very open cover types, Open Lichen Scrub, Lichen Heath, Lichen Scrub, Bog and Muskeg etc. were combined as 'Open'. The other cover types distinguished were Open Lichen Woodland, Close Lichen Woodland and Lake. The proportions of each of these in the mapped areas are indicated in Table 2. The vegetation map forms Figure 3 in Findlay, 1966b.

The 12 stakes of the snowcourse are laid in a line perpendicular to the direction of the prevailing wind and across the grain of the country, over three quarters of a mile of the floor of the valley in which Knob Lake is situated. The first stake is located inside the meteorological enclosure at the Laboratory and the other stakes are separated from it by the airstrip. The stakes encompass a variety of vegetational situations (Table 2). For convenience the artificially cleared location of the first stake has been classed as "recent burn".

The detailed snowcover of the immediate vicinity of the snowcourse include only the stakes lying beyond the airstrip. The depth and water equivalent pattern was fairly consistent from year to year although the magnitude of differences between the shallow, packed, Muskeg snowcover, the deep drifts of leading edges of woodland and the deep, relatively less

TABLE 3

Summary of results from map of snowcourse vicinity

1964-65

	DEPTHS (INS)						WATER CONTENT (INS. WATER)				
Cover Type	n	Mean	Max.	Min.	Stand Dev.	SE of Mean	n	Mean	Max.	Min.	Stand Dev.	SE of Mean
"Open"	71	39.7	77.0	17.0	18.4	2.19	39	10.8	26.0	3.4	6.2	0.98
Open Lichen Woodland	40	56.9	91.0	36.0	13.9	2.20	19	12.2	22.2	6.3	4.5	1.04
Close Lichen Woodland	57	66.4	101.0	47.0	11.6	1.54	30	17.4	28.4	6.8	5.9	1.09
Lake	-	-	-	-	-	-	-	-	-	-	-	-

Weighting for the area of each cover type, the mean depth is 50.5 inches and the mean water content, 12.9 inches

1965-66

	DEPTHS (INS)						WATER CONTENT (INS WATER)					
Cover Type	n	Mean	Max.	Min.	Stand Dev.	SE of Mean	n	Mean	Max.	Min.	Stand Dev.	SE of Mean
"Open"	80	40.0	60.0	26.0	8.8	0.99	49	11.1	19.3	5.7	3.3	0.48
Open Lichen Woodland	35	50.6	74.0	37.0	7.6	1.29	18	14.6	19.9	10.7	2.69	0.62
Close Lichen Woodland	43	56.1	67.0	44.0	6.1	0.93	17	16.7	23.3	11.1	3.94	0.96
Lake	-	-	-	-	-	-	-	-	-	-	-	-

Weighting for the area of each cover type, the mean depth is 46.6 inches and the mean water content 13.3 inches.

TABLE 4

Summary of results from catchment survey

1964-65

	DEPTHS (INS)						WATER CONTENT (INS. WATER)					
Cover Type	n	Mean	Max.	Min.	Stand Dev.	SE of Mean	n	Mean	Max.	Min.	Stand Dev.	SE of Mean
"Open"	138	43.5	89.0	0.0	14.8	1.26	43	12.3	36.0	3.5	5.4	0.83
Open Lichen Woodland	57	56.8	101.0	33.0	13.7	1.81	25	15.2	39.9	7.5	2.2	0.45
Close Lichen Woodland	44	54.1	79.0	36.0	8.5	1.29	15	11.4	15.3	8.8	1.2	0.32
Lake (unadj)	65	19.7	69.0	8.0	9.6	1.19	10	6.3	17.3	2.5	3.9	1.25

Weighting for the area of each cover type, the mean depth is 41.4 inches and the mean water content 11.2 inches.

Adjustment for white ice: adding 12.0 ins. to lake snow depth (making 31.7 ins.) and 3.7 ins. water to lake water content (making 10.0 ins.) the catchment mean values become:

Depth: 44.1 inches   Water Content: 12.1 inches

1965-66

	DEPTHS (INS)						WATER CONTENT (INS. WATER)					
Cover Type	n	Mean	Max.	Min.	Stand Dev.	SE of Mean	n	Mean	Max.	Min.	Stand Dev.	SE of Mean
"Open"	72	41.4	52.0	2.0	13.3	1.81	44	13.0	23.8	3.4	4.8	0.72
Open Lichen Woodland	30	50.8	68.0	35.0	7.6	1.40	14	15.5	19.8	13.1	3.2	0.85
Close Lichen Woodland	40	50.05	65.0	40.0	5.6	0.89	22	15.0	20.9	5.1	3.4	0.85
Lake (unadj)	57	17.1	34.0	5.0	-	-	57	6.2	10.0	2.0	1.9	-

Weighting for the area of each cover type, the mean depth is 38.5 inches and the mean water content 12.1 inches.

Adjustment for white ice: adding 15.9 ins. to lake snow depth (making 33.0 ins.) and 4.26 ins. to lake water content (making 10.45 ins.) the catchment mean values become:

Depth: 42.2 inches   Water Content: 12.1 inches dense snow of sheltered sites varied considerably. The greatest contrast between these situations appears in the 1965 (end of 1964-65 winter) maps (Adams and Findlay, 1966, Fig. 2), which demonstrate the effectiveness of the redistribution of snow by wind in a winter with above average winds and below average temperatures. Extremes of depth and water equivalent were much less in the mild, relatively calm, winter of 1965-66 (Rogerson, 1967), so much so that, despite appreciably higher snow receipts, some sheltered areas had a thinner snowcover than the previous year (Table 4).

The range of depth and water equivalent which make up the mean value for the snowcover of each cover type in the snowcourse vicinity, overlap considerably (Table 3) but testing, using standard error of the mean and and Student's 't' indicates that they are in all cases distinct. The differences are significant at the 5% level of probability except for Close and Open Lichen Woodland 1966, which were only significantly different at the 10% level. This last is a reflection of the more limited redistribution of snow during the warm, calm 1965-66 winter.

Weighting for the area occupied by each cover type, the mean values of depth (inches) and water equivalent (inches, water) were 50.5 and 12.87 in 1965 and 46.6 and 13.34 in 1966 (Table 3). These compare with 51.4 and 12.9 (1965) and 43.0 and 12.1 (1966) for mean values from the 12 points of the permanent snowcourse. Thus the means from the over 80 samples of the mapped area and the means from the 12 points of the snowcourse are very similar.

The arbitrary selection of vegetation classes as a basis for snow mapping appears, therefore, to be confirmed, in this case, by statistical testing. The similarity of the means from the mapped area and from the snowcourse adds weight to the assumption that the latter provides a meaningful indication of the true snowfall of the Knob Lake area.

However, the vegetation cover of the course area cannot be considered representative of the whole of the Knob Lake catchment. In particular, lake and ridge top situations are entirely absent. To what extent then, can the snowcourse itself, be considered representative for the catchment?

At the end of the 1964-65 and 1965-66 winters, within a week of the mapping in the snowcourse vicinity, a series of sampling traverses was made across the catchment area of Knob Lake, again perpendicular to the prevailing wind and to the grain of the relief. In 1966, the sampling interval (500 feet and 1,000 feet respectively for depth and water equivalent) was shortened on the lakes which were considerably under-represented in the 1965 survey owing to their limited cross-valley extent. The results of these surveys are summarized in Table 4. In both years, the vegetation-based groups of measurements were distinct for water equivalent and depth except for Open Lichen Woodland and Close Lichen Woodland which were only distinct for water equivalent in 1965. This lack of a clear distinction between the snowcovers of these two cover types in the basin as a whole may be due to a difference, from the point of view of distribution of snow, between Close Lichen Woodland in broad stands and Close Lichen Woodland in relatively isolated clumps. In the snowcourse area, this cover type comprises 45% of the total area and takes the form of a relatively extensive stand; this is typical of the Close Lichen Woodland of the northern part of the Knob Lake catchment (Findlay, 1966, Plate IV). Close Lichen Woodland forms 30% of the catchment as a whole but the "Close" proportion of the southern half of the basin is made up of relatively isolated, small, stands (Findlay, op. cit., Plate III). Each individual stand is relatively open to the wind so that its snowcover is more akin to that of Open Lichen Woodland than to that of large stands of Close Lichen Woodland. This point is perhaps strengthened by an examination of Tables 3 and 4. Depths are greater in the Close Woodland of the mapped snowcourse area than for the same cover type in the basin as a whole and densities are lower. This is a reflection of the more compact snowcover of the small "Close" stands in part of the catchment.

Weighting for the area occupied by each cover type, mean values for depths and water equivalents were calculated for the catchment (Table 4). The value thus obtained is a good indication of the amount of snow lying on the land and on the lakes at the end of the winters concerned. However, owing to the special character of the lakes' snowcover, the mean values cannot be considered as representing the total receipts of the catchment for the two winters without further adjustment.

Lakes' snowcover - a special case

The values presented for 'unadjusted' snow depths and water equivalents on the lakes in Table 4 are remarkably low. To some extent this might be expected, as the lakes can be considered as the extreme case of an 'open' situation. They have an unusually smooth surface, are the largest open areas in the region and are particularly exposed to the prevailing northwest wind owing to their great southeast-northwest extent. It would appear possible, therefore, that deflation of snow from the lakes into downwind land areas could account for low values of end-of-winter snowcover on a lake. However, this is by no means the whole picture and as lakes form almost a quarter of the surface area in the Knob Lake catchment, their snowcover merits further attention.

Unless freeze-up happens to coincide exactly with the date from which snow begins to accumulate on the land, a difference can be expected between a winter's snow accumulation on the land and on the lakes. In the Knob Lake area for the two years in question, this point can be ignored.

Under certain circumstances, the first layer of ice formed on a lake can include a considerable amount of snow. This happened to be the case in the Knob Lake area in 1965 but it is not normal. However, it is normal for considerable amounts of snow to be incorporated into the lakes' ice cover each winter as a result of slushing and the resultant formation of white ice or snow ice. Slushing occurs as a result of cracking at a time when the ice sheet is depressed below the hydrostatic water level by its load of snow (see, for example, Shaw 1963, 1965). At Knob Lake, this process is particularly important during the early winter months, when snowfall is high and the ice cover is relatively thin. Thus, at the end of a winter, the snow present on a lake does not represent the entire receipts of the lake less an amount deflated, but only the amount of snow which has fallen since the last slushing phase (plus any snow not involved in the slushing) less an amount deflated.

When a lake ice cover is slushed, for example, to a depth of 10 inches, slightly more than 10 inches of its snowcover is inundated since there is a certain amount of capillary rise into the snow and some overlying snow collapses into the slush. However, it is convenient to assume that 10 inches of white ice forms, including a 10 inch thick layer of the original snowcover. Thus an indication of the total depth of snow falling, for example, on Knob Lake for the 1964-65 winter can be obtained by combining the thickness of white ice and the depth of snowcover present at the end of the winter (e.g. Adams and Findlay, 1966, Figs 6 and 7).

It is not so easy to estimate the water content of the snow involved but a mean density of 0.3 gm/cc would be a reasonable value for all snow in slush phases during a winter in this area.* The estimate is, in fact, probably high but the slight overestimate is somewhat offset by the underestimate of the depth of the snow involved. Thus in the example given, 10 inches of slush includes 10 inches of snow at 0.3 gm/cc. The resulting 10 inches of ice (assuming a density of 0.9 gm/cc) has a water content of 9 inches of which 3 inches was originally snow. The actual thickness of white ice, at the end of the winter in the Knob Lake area varied from 10 to 26 inches during the period 1954-66.

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* The density of lake snowcover can be calculated from snow depths, ice thickness and the height of water in drill holes. (Shaw, 1964; Adams, Shaw and Archer, 1966.) Adams and Findlay (1966) present a detailed calculation of this type and consider the variation of white ice thickness from lake to lake.

The effect of adjusting the lake snowcover values for snow present as white ice at the end of the 1964-65 and 1965-66 winters is shown at the foot of Tables 4a and b. The new lake mean values are still very distinct from those of the other cover types and they are still the lowest values in the area but this now represents the true effects of deflation and packing in an exceptionally 'open cover type'. The adjustment of the lake values represents a gain in snow receipts for the whole catchment area of 0.9 inches, water, in 1964-65 and 1.0 inches, water in 1965-66.

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KNOB LAKE SNOWFALL

We have, therefore, five values for total snow receipts at Knob Lake for the period between initiation and peak of snowcover in 1964-65 and 1965-66. There are juxtaposed in Table 5. It would appear that the undermeasurement of the Nipher Gauge, indicated by the snowcourse measurements is confirmed by the more extensive surveys. In some ways, it is surprising that the snowcourse should provide a value so similar to that of the overall catchment survey. It seems that the lack of lake and ridge top situations in the vicinity of the snowcourse is offset by the over-representation of Muskeg (30% of the snowcourse mapped area as compared with 2% in the catchment) and the inclusion of the very open meteorological station site.

TABLE 5

Winter snow receipts at Knob Lake by various means (water equivalent)

	1964-65			1965-66		
	ins.	%	n	ins.	%	n
Nipher	9.36	(100)	-	9.42	(100)	-
Snowcourse	12.1	(130)	12	12.1	(129)	12
Map (snowcourse area)	12.9	(138)	88	13.3	(141)	84
Catchment Survey (unadj.)	11.2	(121)	93	12.1	(129)	137
Catchment Survey (adj.)	12.1	(130)	93+	13.1	(139)	137+

Note: these values are for the period between the date on which a permanent snowcover became established and the date of the snow surveys (mid-March). Naturally, the dates of these events varied.

Thus the snowcourse apparently provides a useful indication of snow receipts for the entire area and it would appear that the official snowgauge value at Knob Lake is low by 23-28% of the true snowfall. The annual snowfall value appears to be closer to 16 than 12.9 inches of water.* An undermeasurement of precipitation over a large part of the Labrador-Ungava Peninsula would explain the excess of discharge from the Churchill River system over measured receipts (less probable evaporation losses), mentioned at the beginning of this paper. It is possible that the undermeasurement of snowfall, demonstrated here for Knob Lake, affects precipitation values for the whole peninsula.

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KNOB LAKE AREA SNOWCOVER

Although further refinement of the relationship is necessary, the basic control of the snowcover by cover type (through its effect on wind) in the Knob Lake area has been demonstrated here. There is a mosaic of snowcover, shallow and packed in the open areas, deeper and less dense in the sheltered areas, which is a reflection of the distribution of vegetation types and of lakes. Most of the areal data presented here were obtained at the time of peak snowcover but there is no reason to believe that the effect of most cover types is very different at other times, except very early in the winter. For Example, a snowcover map of the snowcourse vicinity in December 1965 showed the same general pattern as the map of the same area at the end of that winter (Fig. 3).

Redistribution of snow by wind is effective to differing degrees in the different cover types. It is normal, for example, for the snow falling before and during the passage of frontal systems to be redistributed rapidly by the high (NW) winds in the cold area behind the wave. The different effects of this redistribution in different cover situations can be seen in Figures 4 and 5. Particularly notable are the sharp temporary peaks of snowcover at open sites, wind effects are much less at sheltered sites.

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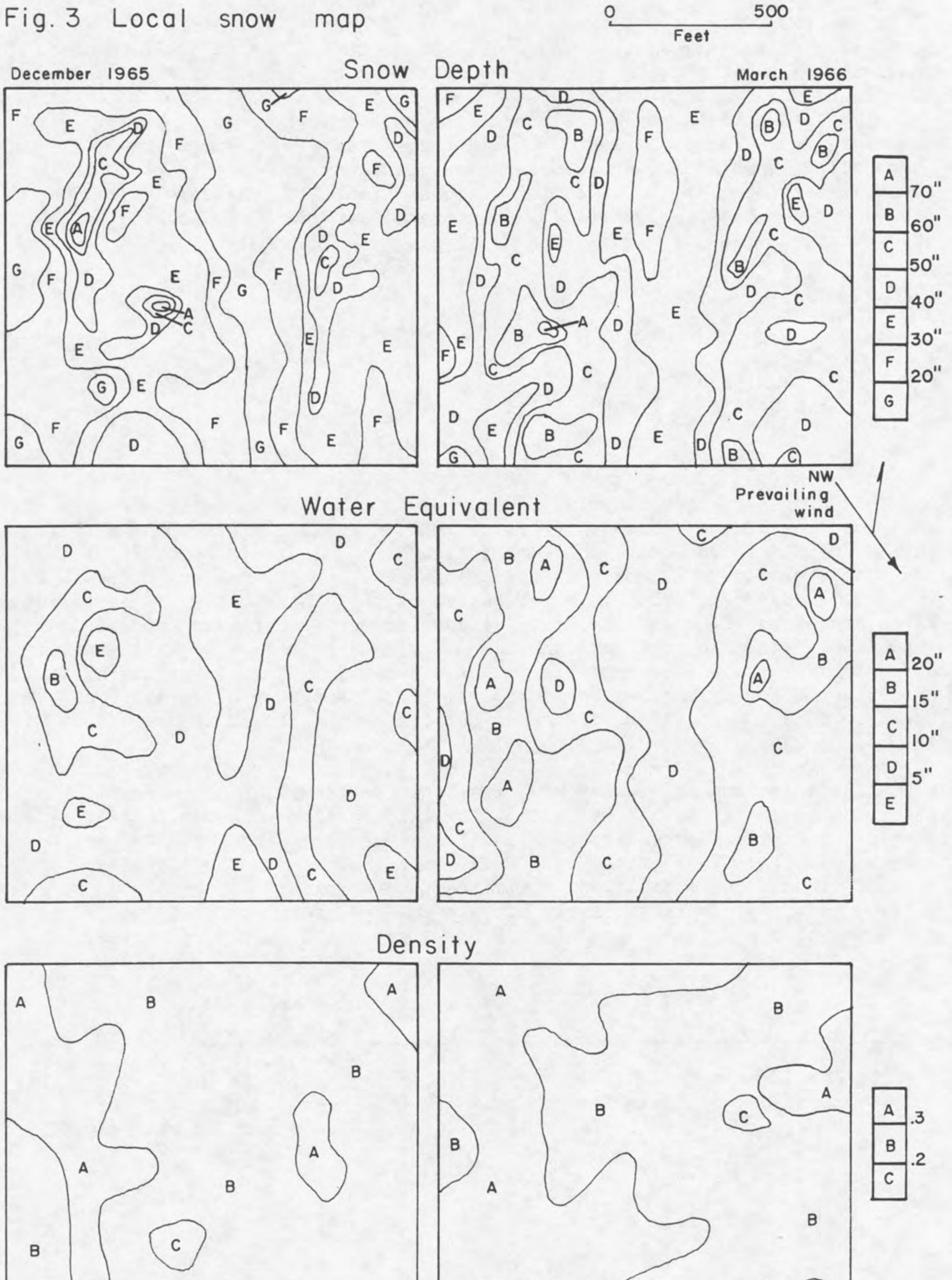
* It should be noted that Findlay (1966b.p 34), allowing for evaporation and other losses considers the undermeasurement to be considerably greater. The value suggested here should be considered as a minimum.

Fig. 3 Local snow map



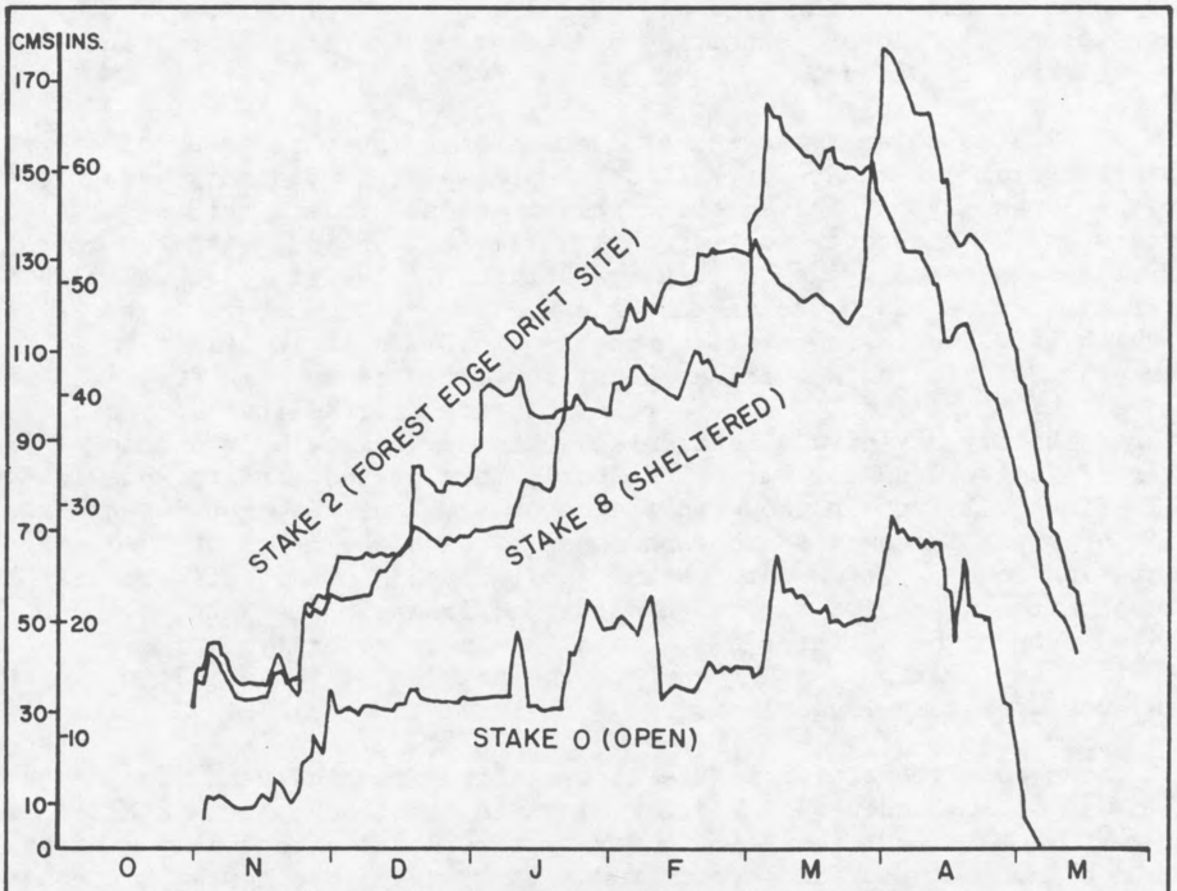


Fig. 4 Snow depths at selected sites 1963-64

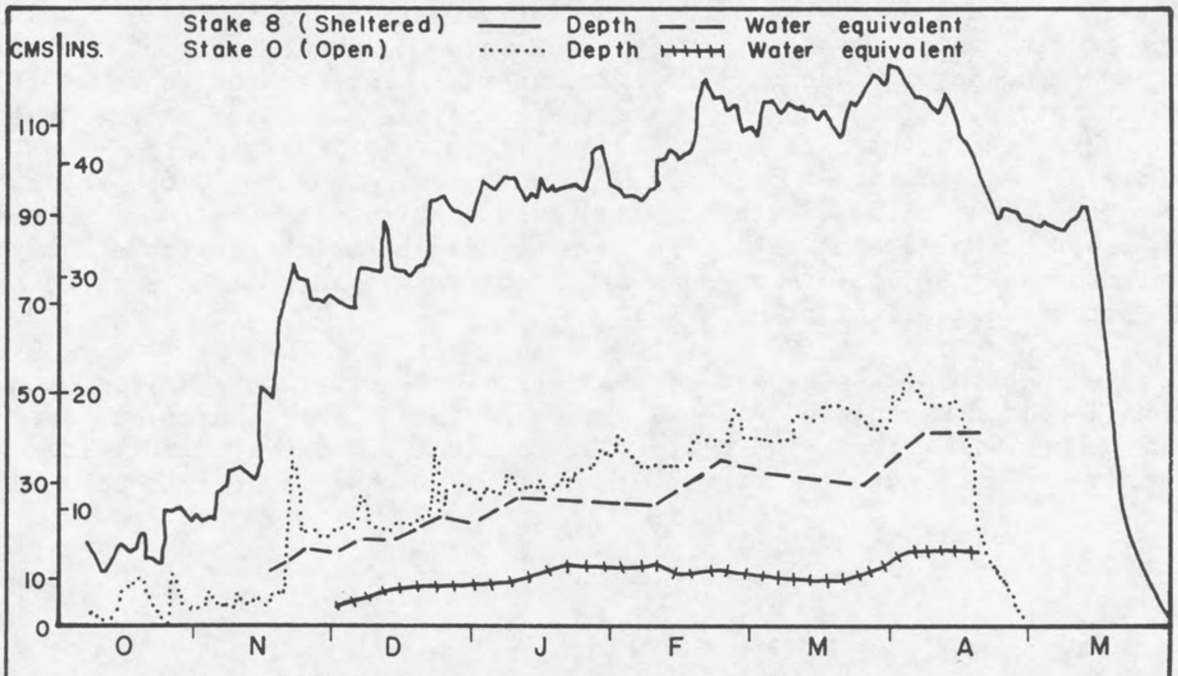


Fig. 5 Snow depths and water equivalents at selected sites 1965-66

Thus there are smaller depths, higher densities and greatest fluctuations of depth at open sites, and greatest depths, with moderate densities and greatest increments of snow during wind at the leading edges of cover. There are large depths with lowest densities and least redistribution by wind, at the sheltered locations.

Within the cover types selected as a basis for this study of snowcover, deviation from the mean, for both depth and water equivalent, was greatest for the 'Open' type in seven out of eight cases. This might be expected, as this is the snowcover most directly affected by wind, with considerable variations in packing due to local variations in relief, etc. Also this cover type embraces a considerable range of vegetation types (Table 2) some of which, if studied in detail, probably exhibit quite distinct characteristics of snowcover, at least for parts of the winter. For example, an area which is 'open' from the point of view of trafficability or intervisibility may have a considerable low scrub growth or a thick ground cover of fallen trunks. During the early part of the winter, this low cover will effectively retain snow and the cover type only becomes 'open' from the point of view of snow when the snowcover exceeds the depth of the lower vegetation cover. It is interesting that, in this study, differences between sites as varied as open ridge tops, frozen Muskeg etc. could be treated over a whole winter as parts of a single cover type. This has important implications with regard to the mapping of the complete winter snowcover over very large areas.

The cover type exhibiting least variation from the mean (for depth only) was Close Lichen Woodland. Again this might have been expected as snow within this most sheltered cover type is least affected by wind and it should be possible to find broad stands of it which neither gain nor lose snow as a result of wind effects. The problem of small relatively isolated stands of Close Lichen Woodland has been mentioned and is an aspect of the cover-snow relationship which requires further attention. The fact that there is generally a greater variation of water equivalents about the Close Woodland mean does not detract from the above statement about depths. With a relatively close tree cover, there is insufficient wind to ensure that snow packs evenly into all sheltered locations; for example into areas immediately beneath trees or under a scrub cover. Thus the Close Woodland snowcover has a uniform depth but an uneven density distribution. Sometimes this creates problems in the use of a snow sampler as the instrument may penetrate cavities, devoid of snow or which contain very light snow and will not pick up efficiently.

The most consistent water equivalent values were obtained from Open Lichen Woodland where wind effects are moderate and where gains and losses of snow, resulting from wind redistribution, can be conceived as being compensatory. The greater variation in depth of this cover type is a reflection of a 'leading edge' effect. Large drifts accumulate at the junction with the Open cover type. This point emphasizes the importance of cover type boundaries in snowcover mapping; one possible refinement of the survey procedure described here would be the establishment of marginal cover types for separate treatment. For example, the mean value for our Open snowcover includes part of a drift at its junction with Open Lichen Woodland - another part of the same drift appears in the mean value for the Open Lichen Woodland. The fact that the leading edge drifts did not produce greater variations of water equivalent around the mean for Open Woodland is due to the fact that the snow on its side of the drift is less dense than the well packed snow on the Open side.

The lakes' snowcover is a very special "cover" effect and has already been discussed. It is notable that the process of white ice formation has the effect of promoting the deflation of snow not involved in the slushing phases. As a result of white ice formation, the snowcover is kept thin and it is difficult for a stable snowcover to develop. In some years parts of the ice cover of Knob Lake are snow-free even at the peak of the snowcover season.

In this treatment of snowcover, we have stressed the main controls of snow on the ground in the Knob Lake area, cover type and wind. We have mentioned in passing the modifying effect of warm and cold winters. There are other important secondary factors, such as the occurrence of liquid precipitation in mid-winter, which can have a considerable effect on snow distribution. The map of an end-of-winter snowcover should always be considered with the nature of the particular winter in mind. In the following section the development of the snowcover is briefly discussed from time-profile studies at one site (Figure 6).

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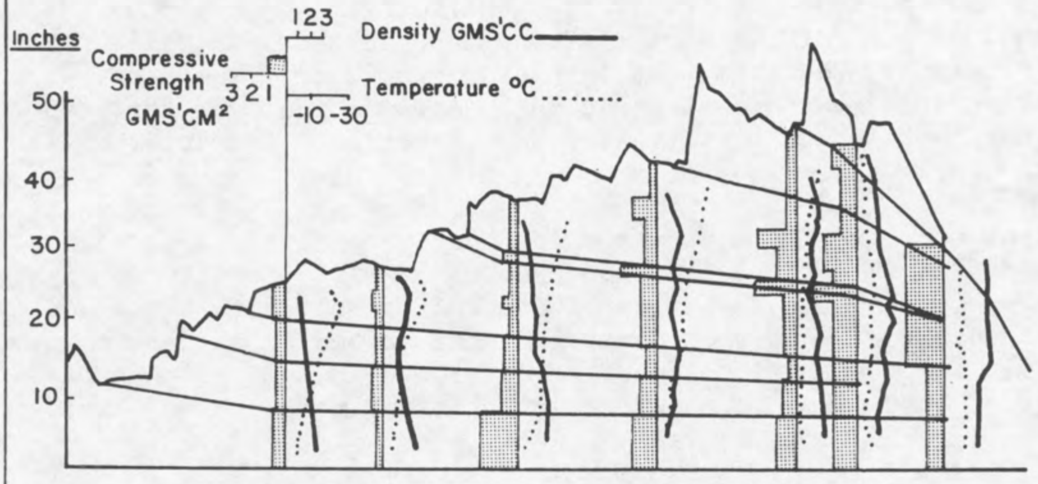
THE DEVELOPMENT OF THE SNOWCOVER AT A SHELTERED SITE NEAR KNOB LAKE

Considering first the depth measurements shown in Figure 6, plotted from daily readings at a stake close to the time-profile plot, it is clear that wind effects are apparent even at this deliberately selected sheltered site. Abrupt changes in surface level are least in 1965-66 which had the lowest winds and highest mean temperatures (Table 6). The lower air temperatures of the first two years are reflected also in the steeper

Fig. 6 Time profiles 1963 – 66

(1) 1963 – 64



(2) 1964 – 65

(3) 1965 – 66

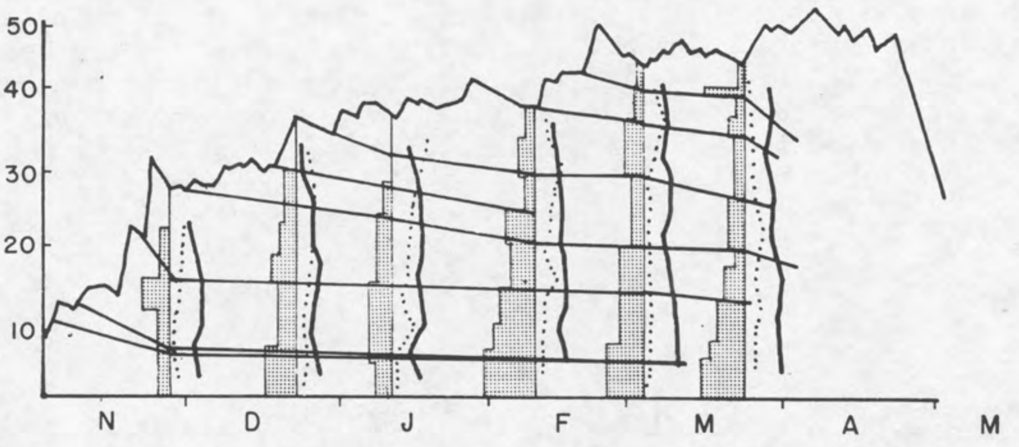


TABLE 6

Climatological and snowcover data for the winters 1963-66 at Knob Lake

	CLIMATE				SNOWCOVER							
	Mean Temp °F.	Extr Min. Temp °F	Mean Wind Speed m.p.h	Total sun hrs.	Date of Meas-urement	Snow Depth ins.	Mean Density gm/cm^3	Mean Temp °F	Min. Temp °F	Level of min ins. from surface	Max Temp °F.	Level of Max ins. from surface
1963												
Oct.	31	15	14	71	x	x	x	x	x	x	x	x
Nov.	21	-05	11	25	x	x	x	x	x	x	x	x
Dec.	-05	-31	14	40	15	26	.25	09	-09	26	27	0
1964												
Jan.	-09	-37	11	109	04	30	.25	07	-09	30	27	0
Jan,	x	x	x	x	29	42	.25	12	-04	42	27	0
Feb.	-06	-31	12	118	26	48	.25	10	-09	48	27	0
Mar.	-02	-49	13	163	27	50	.26	16	05	50	28	0
Apr.	18	-25	12	178	15	49	.29	25	21	31	27	49
May	33	15	12	135	02	34	.39	27	25	23	28	34
Mean/ Total	10	-19	12	839								
1964												
Oct.	27	08	10	34	x	x	x	x	x	x	x	x
Nov.	13	-22	09	47	18	17	.17	23	19	17	25	0
Dec.	-03	-37	09	61	04	39	.23	27	25	39	27	0
1965												
Jan.	-13	-33	11	93	19	40	.23	07	-13	40	28	0
Feb.	-07	-40	09	124	27	57	.27	19	10	57	28	0
Mar.	03	-20	10	165	x	x	x	x	x	x	x	x
Apr.	16	-09	08	208	06	52	.36	19	16	46	30	0
May	33	11	10	170	07	46	.35	30	28	46	32	0+32
Mean/ Total	09	-18	10	902								
1965												
Oct.	25	04	11	40	x	x	x	x	x	x	x	x
Nov.	13	-06	11	51	26	28	.21	23	18	28	28	0
Dec.	-05	-33	08	86	22	38	.23	25	19	38	28	0
1966												
Jan.	03	-46	09	39	10	38	.27	16	-08	38	28	0
Feb.	01	-36	08	80	08	39	.27	21	10	34	30	0
Mar.	13	-24	07	166	01	46	.28	25	19	36	28	0
Mar.	x	x	x	x	23	44	.26	28	25	30	34	0+39
Apr.	25	-03	10	174	04	56	.30	32	30	30	36	56
May	31	04	09	130	x	x	x	x	x	x	x	x
Mean/ Total	13	-18	09	766								

temperature gradients of their snow profiles.' In response to these gradients, and the associated vapour pressure gradients, constructive metamorphism was most pronounced in the years 1963-65 (Gardner, 1964; Cowan, 1966), and was least in 1965-66. In the first year, depth hoar (beaker crystals and plates) was present in December and by March it dominated the lowest layers and was in evidence as high as the 35-40 inch level. By contrast, in 1965-66, depth hoar was confined to the layer within ten inches of the base of the profiles throughout the year (Rogerson, 1967). As a result of the limited constructive metamorphism in this last year, densities of the lower layers remained persistently high. The reduction of density in these layers in the first two years is probably more typical of this location.

After rapid initial compaction, partly due to wind, the reduction in layer thickness is slow as a result of the particularly low temperatures and radiation of the typical Knob Lake winters. Compaction of layers (and redistribution of snow in certain layers) is considerably affected when ice layers form early in the winter and persist until the melt season. These are most marked in the first set of profiles but it is probable that such ice layers are a fairly common feature in this area, as short periods (a few days) of above-freezing temperatures, with liquid precipitation,are not unusual in the otherwise extremely cold winters (Tout, 1964, p.50 - 52). For these layers to form and persist, however, it is necessary for the temperatures to return to the normal low levels immediately following the spell of warmer weather. In 1966 a warm spell in January persisted for a few weeks and was not followed by the exceptionally cold weather which is usual in late January and early February. In this year no ice layers of note formed.

It is extremely difficult to generalize about the composition, structure and physical characteristics of the snowcover of a region in, for example, the manner of Gold and Williams (1957). The profiles presented here are for a sheltered site at a location with a thick lichen ground cover, and even another sheltered site in the same vicinity might exhibit different characteristics. It is probable, for example that depth hoar is better developed here than it would be over a vegetation-free surface. The snowcover at Open sites would be entirely different again, in character as well as in depth. And again, the temperatures presented here are those measured at the time of the pit studies (early afternoon), so that diurnal changes are not included.

The data presented in Figure 6 and Table 6 do allow some generalization in the light of earlier profile studies in the area. As might be expected in an area which receives snow throughout the winter but with a maximum in the early winter months, mean snow density increases steadily during the winter. As the climate is generally cold, however, densities are never very high (0.3 gm/cc) before the onset of the melt. The snowcover is at its coldest in mid-January with a mean of about 7°F. and a minimum in the vicinity of -10°F., with air temperatures of about -10°F. (mean) and about -35°F. (min) in 1964 and 1965. In January 1966, the lowest mean snow temperature was 16°F. with a minimum of -8°F. while air temperatures were close to 0°F. (mean) and -46°F. (min.).

* * * * * * * * * *

CONCLUDING REMARKS AND FUTURE WORK

1. The official snowfall at Knob Lake is an underestimate of the true receipts by more than three inches, water, on average. It is probable that this type of error occurs at many places in Labrador-Ungava as the sites of aviation weather stations are not normally conducive to good, hydrological, precipitation measurement. To some extent, the undermeasurement could be offset simply by locating a standard gauge at, for example, a Close Lichen Woodland site. This gauge would be emptied infrequently.

2. It would appear that the snowcourse at Knob Lake provides a useful indication of true snowfall in the area.

3. The approach to snowfall and snowcover measurement used here could be extended to encompass much larger areas, such as the Churchill River catchment, with little difficulty. Small scale maps of the physiography and cover types of the Peninsula are already available (Hare, 1959 and references) to provide a useful working basis for such an undertaking. It would be necessary to establish snowfall regions (tentative at first), large areas of uniform snow receipts, within each of which small study areas would be selected for annual snowcover measurements. These study areas would be chosen so that, within them either cover type or physiography (probably the latter) could be considered as constant with regard to the distribution of snow on the ground.

Snowcourses would be established in each study area (stakes located subjectively at first) and their validity tested against results from end-of-winter snow surveys of the types described above. The objective of the first years' work would be the adjustment of the snowcourses to eliminate discrepancies between results from them and from the surveys.

After such tests, it would be possible, in normal climatological years, to place some confidence on the value provided by the snowcourse for its general area and the snowcourse values together would provide a meaningful catchment snowfall. Doubtless modification of the original snowfall regions would be required as results accumulated and ideally it would prove possible to eliminate some of the original snowcourses. A small party, travelling by air, could cover an adequate network of such study areas in March every year.

If the snowcourse areas selected were sub-drainage basins with relatively simple, stable, outlets, additional studies (sometimes extended over the whole winter) could be undertaken periodically in conjunction with detailed discharge measurements. This work would include stratigraphic studies (especially temperature work) and micrometeorology. As a preliminary to such work, it would be simple to install thermistors, above and below ground, at the snowcourse sites which could be read on a routine basis by the annual survey parties. From the hydrological point of view, continuous records of snow receipts and losses, using the snow pillow technique would be a valuable addition to such intensive programmes.

4. The relationship between cover type and snowcover still requires considerable refinement. The effects of cover type on the distribution of snow, the stratigraphic development of snow and on the melting of the snow all command attention. Virtually no detailed winter micrometeorological studies have been done in Labrador-Ungava. As a single example of the type of work which would be worthwhile, further study of the wind-cover type-snow relationship would be most valuable. A programme of this type could be extended to the summer season to provide information on the roughness height of the various cover types.

5. In the whole of central and southeastern Labrador-Ungava, at least, snowcover mapping without a consideration of white ice would result in a considerable error in the calculation of a winter's snow receipts. In surveying white ice, it is necessary to encompass the range of variations which occur on a single lake and the differences in thickness between lakes.

6. The time profile technique is an excellent method of recording snowcover data. It draws the observer's attention to the development of the snowcover and provides a clear visual record of each winter. The scope of the technique has by no means been exhausted in the Knob Lake work so far. Time profiles, including temperature work, at a variety of sites would be an obvious part of an overall programme such as that described in 3, above. They would provide important basic information on the ripening of the snowpack and runn-off from it.

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