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Illustration of the Roles of Snow in the Evolution of the Winter Cover of a Lake

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ABSTRACT. Spatial patterns in the snow and ice cover of Elizabeth Lake, Labrador, as surveyed in late February 1979, are displayed and analysed. Relationships between distinct trends in the ice and less distinct trends in the snow are discussed within a context of processes operative during a winter. The nature of and spatial patterns in the winter cover of lakes and of their evolution have important implications for those interested in generalizing about lake ice properties and about the effects of snow and ice on the lake ecosystem.

RÉSUMÉ. L'auteur met en évidence et analyse la disposition de la neige et de la couverture de glace dans l'espace du lac Elizabeth, Labrador, telle qu'il l'a observée, à la fin de Fevrier 1979. Il discute du type de relation qu'il y avait entre les orientations nettes dans la glace et celles moins claires dans la neige, cela dans un contexte evolutif d'hiver. La nature et la distribution de la couverture hivernale des lacs, leur evolution ont des implications importantes pour ceux qui s'interessent aux propriétés génerales de la glace lacustre et aux effets de la neige et de la glace sur "l'ecosysteme" d'un lac.
Traduit par Alain de Vendigies, Aquitaine Company of Canada Ltd., Calgary.

INTRODUCTION

The development of an appreciable snowcover on a lake can be conceived as having two broad effects on the growth of ice on the lake. On the one hand, the snowcover insulates the underlying ice sheet, thus slowing its growth; on the other, it promotes ice growth by depressing the sheet below the hydrostatic water level, allowing slushing to occur and the growth of slush ice or white ice (for terminology, see Adams, 1976a) on top of the original ice sheet.

With regard to the insulating role of lake snowcover, it is important to realise that marked spatial variations in the insulating properties of the cover are common. These arise principally from effects of redistribution of snow by wind which is a very pronounced process on all but the smallest lakes. The redistribution produces greater thicknesses of snow in marginal, lee locations and at downwind locations on the lake, with shallower snow at exposed, central, and upwind locations. This pattern of thickness affects the insulative efficiency of the snowcover of various parts of the lake. Also, mechanical changes produced during wind-drifting and the differences in thickness produce a variety of sub-nival temperature regimes across the lake. These largely control the rate and nature of metamorphism of the snowpack which determine its thermal properties and thus its efficiency as an insulator (Adams and Prowse, 1978).

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The second broad effect of lake snowcover mentioned above involves its role in depressing the lake ice sheet to a point where cracking, from any cause, will result in water rising into the overlying snowpack, producing 'white ice'. This process, by reducing the thickness of the snowcover, decreases its effectiveness as an insulator and results in the rapid freezing of water which is brought into relatively close contact with the cold atmosphere. It should be borne in mind that, other things being equal, the rate of growth of a lake ice sheet slows as it becomes thicker, as a result of the decreased air/water temperature gradient. When slushing occurs, growth of the original ice sheet is halted (as there is no temperature gradient between water above and below that ice) but rapid growth of ice is promoted at the surface of the slush. In fact, where slushing occurs in the middle of a winter, when air temperatures are appreciably lower than during freeze-up, ice growth as a result of slushing can be the most rapid of the season (Adams and Shaw, 1966). The importance of snowcover in *promoting* ice growth in this way, as distinct from its retarding, insulative role, has been stressed by Jones (1969) and Shaw (1965).

It is worthy of note that those parts of a lake which have the greatest snowcover and where, in general, the snowpack provides greatest insulation, are also those which are most depressed (high snow load and thin underlying ice). Similarly, winters with high snowfall, particularly where the snow occurs early in the ice season, experience high white ice growth, but slow rates of growth in underlying black ice (Wolfe, 1979). The spatial relationship between snow accumulation and white ice growth has been demonstrated for a variety of lakes through the similarity of trends of snowcover and white ice and through the reciprocal nature of spatial patterns of white ice and 'black ice' (Adams and Brunger, 1975; Prowse, 1978). In the temporal frame of reference, it has been suggested (Williams, 1968) that equations, explaining ice growth in terms of simple measures of cold (ignoring the complications in growth which arise from snowcover), are relatively effective in a variety of ice growth environments because, in the longer term, the roles of lake snowcover in retarding and promoting ice growth are compensatory.

Work on Elizabeth Lake, Labrador, which was part of a study of areal differentiation of snowcover on land and on the lake (Adams and Barr, 1979) provided an opportunity for detailed study of relationships between spatial patterns of snowcover, white ice and black ice on a lake located in a high snowfall environment.

STUDY LOCATION AND METHODS

Elizabeth Lake, Labrador (54° 46′N, 66° 54′W, 616 m a.s.l.), is located 8 km southwest of Schefferville, Quebec, close to the Arctic/Atlantic divide of the Labrador-Ungava Peninsula. It has an area of 11.08 ha, a mean/maximum depth of 8.7 m/27.1 m and a volume of 2.45 x 10^6 m^3 (Bryan, 1966). Details of surrounding topography and vegetation are apparent from Figure 1. The lake

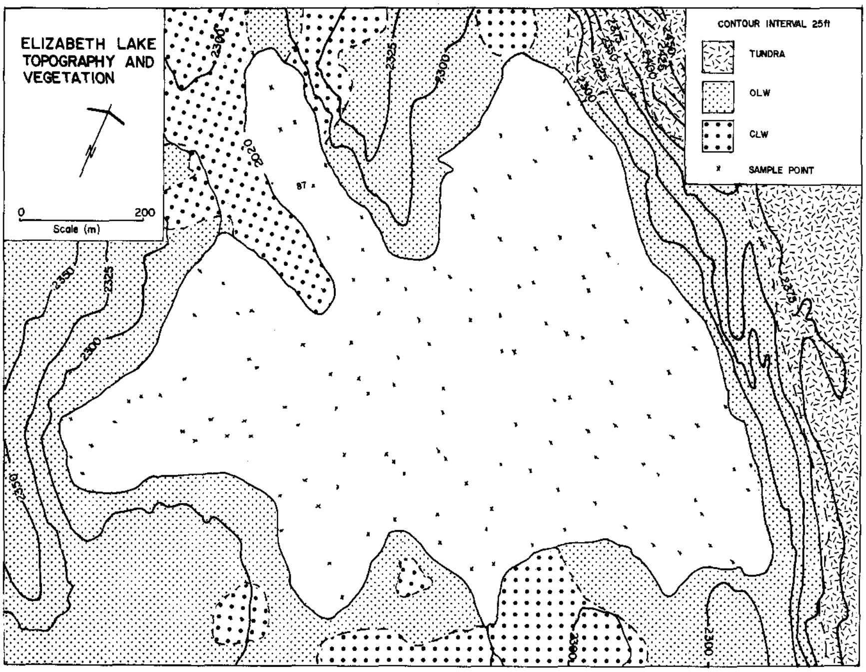

FIG. 1. Elizabeth Lake, surrounding topography and vegetation and random sample design. Note that the degree of exposure of lake margins varies with both vegetation and relief. Vegetation present included Open Lichen Woodland (OLW), Close Lichen Woodland (CLW) and Tundra.

is located in a region which receives 36 cm, water equivalent, of snow per winter, producing snow depths of 120 cm in bush locations on land. In a typical year, lakes in the area develop ice covers of 110 cm thickness. This particular study was undertaken on 21 and 23 February 1979, which is approximately eight weeks before the median date of maximum ice thickness in the area (Adams and Shaw, 1966) and was seven weeks before maximum thickness for 1978/79 was achieved. The winter concerned was colder than average by many measures and it recorded the second highest snowfall on record. The prevailing wind for the winter was WNW.

A sample size of 128 was calculated using ±2.54 cm (1 inch) of snow depth as the desirable standard error and a standard deviation for lake snowcover for a previous winter from nearby Knob Lake (Adams and Brunger, 1975). Sample sites were randomly allocated across the lake surface on a 1:48,000 map using a 1 cm^2 grid overlay and random number tables. The result of this procedure is shown in Figure 1. The sites were located in the field by turning right angles and chaining from the control lines which are shown in the figure. Errors in the field resulted in the loss of data from two sites, reducing the density of points from 11.6/ha to 11.4/ha. Also, standard deviations encountered were higher than expected. Overall statistical results of the survey are summarized in Table 1.

TABLE 1. Statistical summary of snow and ice survey of Elizabeth Lake, 23-25 February, 1979 (Note: measurements on Knob Lake, which is a standard ice survey lake located 8 km away, at this time were wi= 51, bi = 64, TI = 115, Snow = 20).

	n	n/ha	Mean	σ	Coefficient of Variation	Standard Error
SNOW						
depth (cm)	126	11.4	26.88	9.07	33.75	1.58
ICE						
wi (cm)	126	11.4	20.65	13.82	66.94	2.41
bi (cm)	126	11.4	73.66	17.82	24.18	3.11
TI (cm)	126	11.4	94.23	12.89	13.68	2.25
HWL* (cm)	126	11.4	−0.750	3.46	461.33	0.61

* Level of water in drill hole with reference to ice surface, positive values indicate water *above* the ice surface.

A complete set of snow depth measurements was obtained before drilling was undertaken. Then all sites were drilled to obtain measurements of white ice, black ice, total ice and hydrostatic water level (Fig. 2). This procedure minimized complications due to slush induced by drilling.

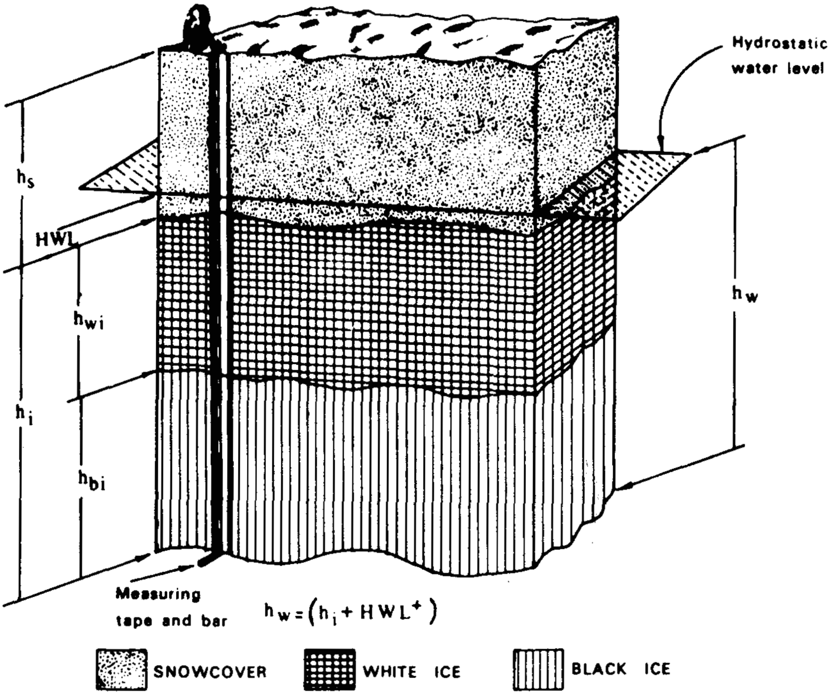

FIG. 2. The principal components of lake cover: h represents thickness and the subscripts, s, wi, bi and i denote snow, white ice, black ice and 'total ice' respectively (from Adams, 1976b).

The data were processed using the SPSS (Statistical Programs for the Social Sciences) and SYMAP (Carleton Edition 5.2.3) computer packages. The latter provides isopleth ("normal interpolation") maps and trend surface maps. First (linear), second (quadratic) and third (cubic) order trend surface maps are discussed here. The diagrams which accompany this article were drawn from computer maps which allowed differentiation by means of 12 characters.

Further details of survey design, field procedures and methods of analysis are provided in Adams and Barr (1979).

RESULTS

When examining the normal interpolation map for snow depth (Fig. 3), it is useful to bear in mind that the mean depth of snow on land in the Elizabeth Lake basin at this time was 123 cm, ranging from an average of 147 cm in areas with a fairly dense tree cover to 77 cm at tundra sites. The mean depth on the lake was 26.88 cm.

Some interesting patterns are displayed in Figure 3. A large area of the lake, notably in its central portions, is occupied by depths in the 30-40 cm range. Around this area, the lake margins, especially bays, tend to stand out as areas of relatively low or relatively high depths. With the exception of two small patches, all areas of >40 cm snow are marginal with the largest area of deep snow in the eastern, that is downwind, basin. Given that the prevailing wind is somewhat north of west, it is interesting that the only two patches of >50 cm

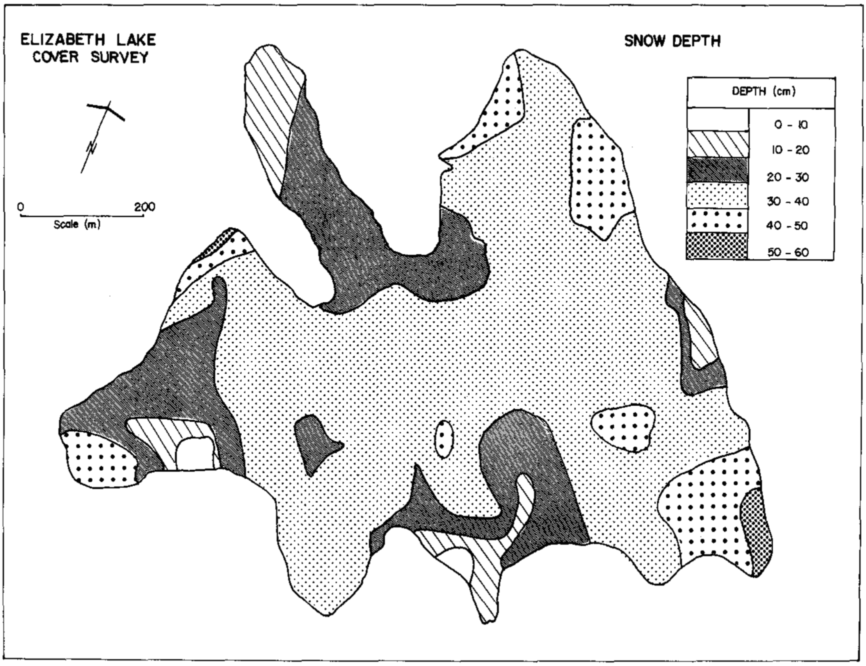

FIG. 3. Isopleth map of snow depth.

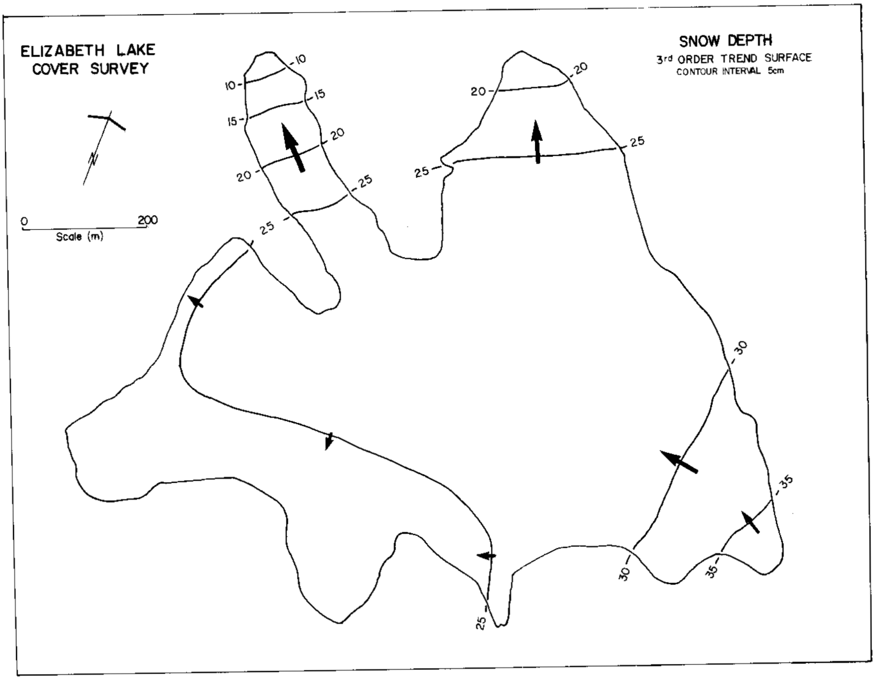

FIG. 4. **Cubic trend surface map for snow depth.**

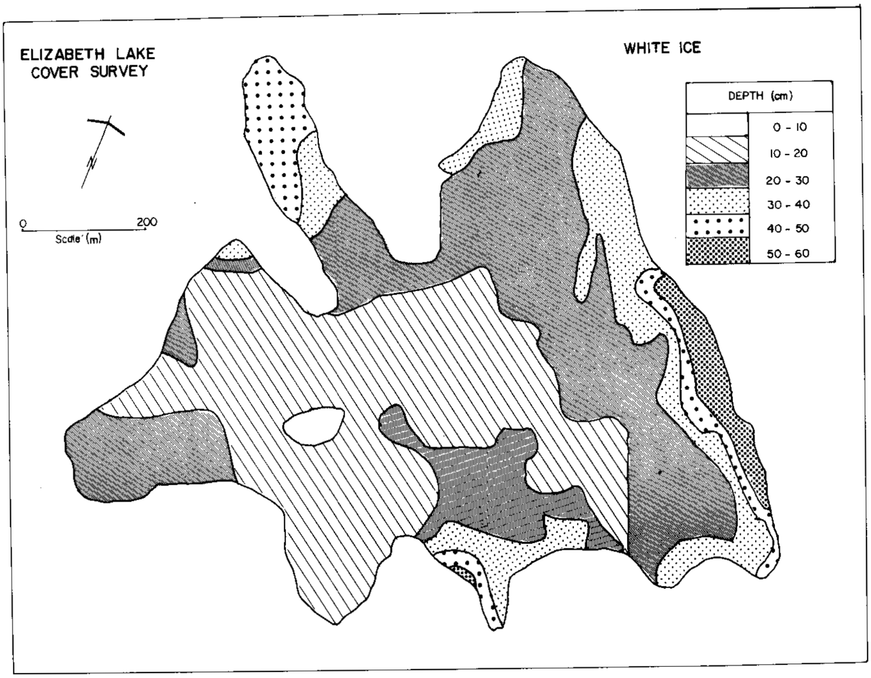

FIG. 5. **Isopleth map of white ice thickness.**

snow are located as they are — a strip at the western, upwind end of a lake and in a bay at the downwind end. The areas of low snow depth are also marginal, the only two patches of <10 cm being along the southern shoreline.

The third order trend surface (Fig. 4) slopes out of the eastern bay, across the lake and into the margins and bays of the west, south and north. Thus the deeper patches of snowcover in the west and southwest (Fig. 3) disappear leaving an upwind-downwind pattern of snow depths and a suggestion that all margins except the eastern, downwind ones are sites of relatively shallow snowcover. However, these trends are slight with the exception of the northwest arm.

The distribution of white ice (Fig. 5) represents snowcover which has been incorporated into the ice sheet as a result of the slushing process. Mean thickness at the time of the survey was 20.65 cm, in the same order of magnitude as mean snow depth. In this case, there is a very marked concentration of higher values in the eastern half of the lake and in the northwest arm. It is not difficult to visualize the effect of a WNW wind here, concentrating snow, which now appears as white ice, at the downwind end of the lake and at lee locations such as the northwest arm. The detail of this distribution is affected by the vegetation and topography of the lake margins (Fig. 1); for example, the northwest arm is greatly affected by the stand of Close Lichen Woodland which is upwind of it.

An interesting example of detailed reciprocal relationships between snow depth (Fig. 3) and white ice thickness is the replacement here of the area of

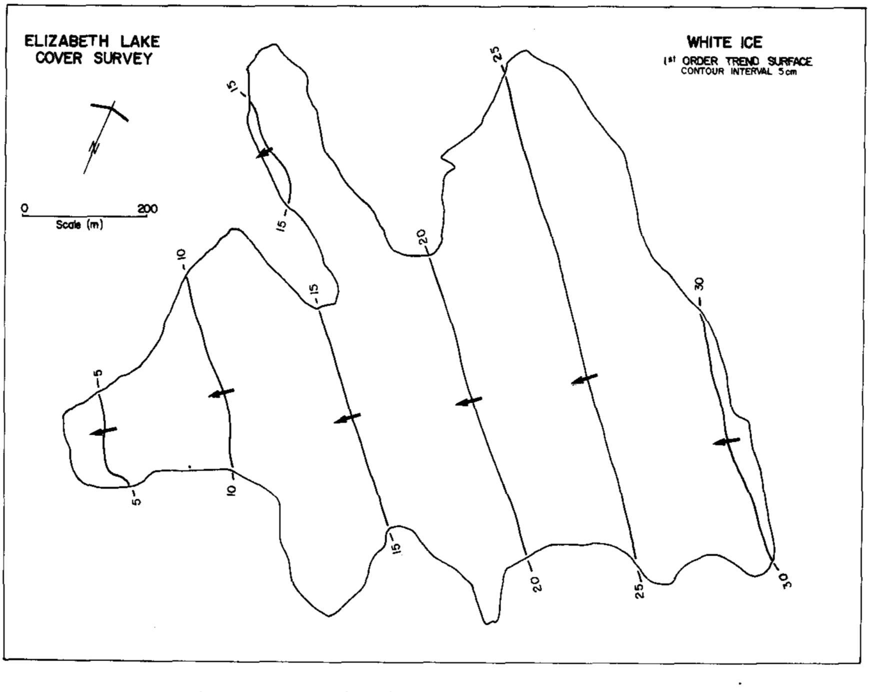

FIG. 6. Linear trend surface map for white ice thickness.

TABLE 2. Correlation coefficients (r), coefficients of determination (r^2), variation explained and not explained by the fitted surface and total variation for first, second and third order trend surfaces.

COVER COMPONENT	FIRST ORDER SURFACE					SECOND ORDER SURFACE					THIRD ORDER SURFACE				
	r	r^2	Variation Explained	Variation Not Explained	Total Variation	r	r^2	Variation Explained	Variation Not Explained	Total Variation	r	r^2	Variation Explained	Variation Not Explained	Total Variation
Snow	.26	.07	0.68×10^{3}	0.92×10^{4}	0.98×10^{4}	.31	.10	0.92×10^{3}	0.89×10^{4}	0.99×10^{4}	.35	.12	0.12×10^{4}	0.86×10^{4}	0.99×10^{4}
White Ice	.46	.22	0.48×10^{4}	0.17×10^{5}	0.22×10^{5}	.67	.45	0.99×10^{4}	0.12×10^{5}	0.22×10^{5}	.78	.61	0.14×10^{5}	0.84×10^{4}	0.22×10^{5}
Black Ice	.21	.04	0.16×10^{4}	0.35×10^{5}	0.36×10^{5}	.74	.55	0.20×10^{5}	0.16×10^{5}	0.36×10^{5}	.79	.62	0.23×10^{5}	0.14×10^{5}	0.36×10^{5}
Total Ice	.12	.01	0.29×10^{3}	0.18×10^{5}	0.19×10^{5}	.14	.02	0.38×10^{3}	0.18×10^{5}	0.19×10^{5}	.23	.06	0.11×10^{4}	0.18×10^{5}	0.19×10^{5}

very shallow (<10 cm) snow on the south side of the lake by an area of very thick white ice. This suggests a recent slushing event and in fact this location is adjacent to an outlet stream so that ice is kept thin by moving water, thus promoting frequent slushing.

All three trend surface maps for white ice are included to illustrate the effect of fitting increasingly complex surfaces to the distributions obtained. There was an appreciable increase in the level of explanation achieved by the surfaces, up to the third order, in the case of all cover components (Table 2).

The first order, linear, surface (Fig. 6), shows a ENE ⟶ WSW slope which appears to be considerably influenced by the long strip of thick white ice along the eastern shore of the lake which was apparent in Figure 5. This pattern changes dramatically in the second order surface (which has a single point of inflection) which exhibits a bowl-like topography, with lowest values near the centre of the lake (Fig. 7). The upwind-downwind effect is still present in the steep gradients of the eastern half of the lake but this new pattern suggests, in contrast to the pattern of current snowcover (Fig. 3), that accumulation around the lake margins, especially in bays and inlets, is a persistent feature of snow distribution during the winter. The centre of the lake must be persistently kept relatively free from snow. The third order surface (two points of inflection, Fig. 8), emphasizes the 'bowl' pattern, and shifts the area of low values further towards the centre of the lake. However, the bay in the southwestern corner of the lake now becomes an exception, exhibiting decreasing white ice thickness towards the shore.

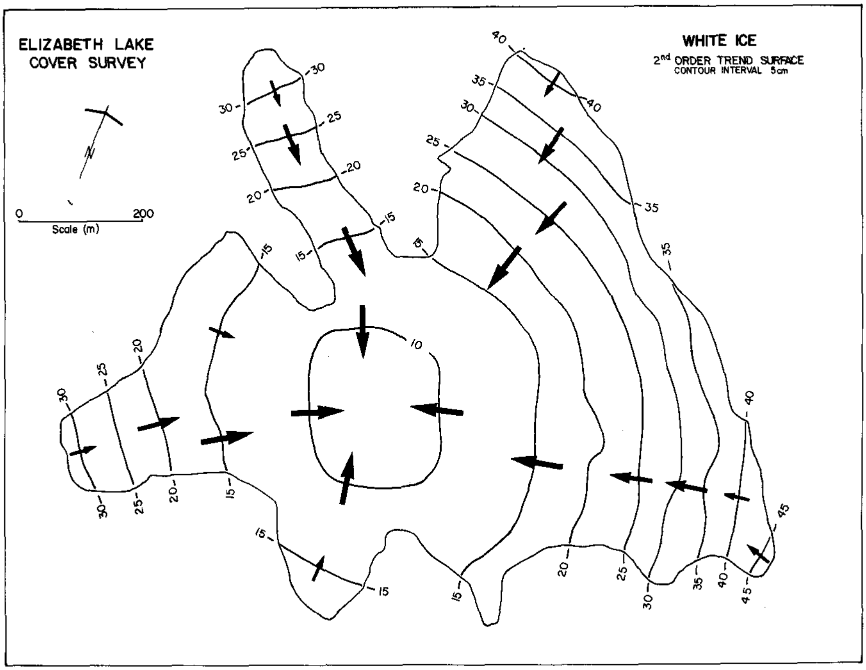

FIG. 7. **Quadratic trend surface map for white ice thickness.**

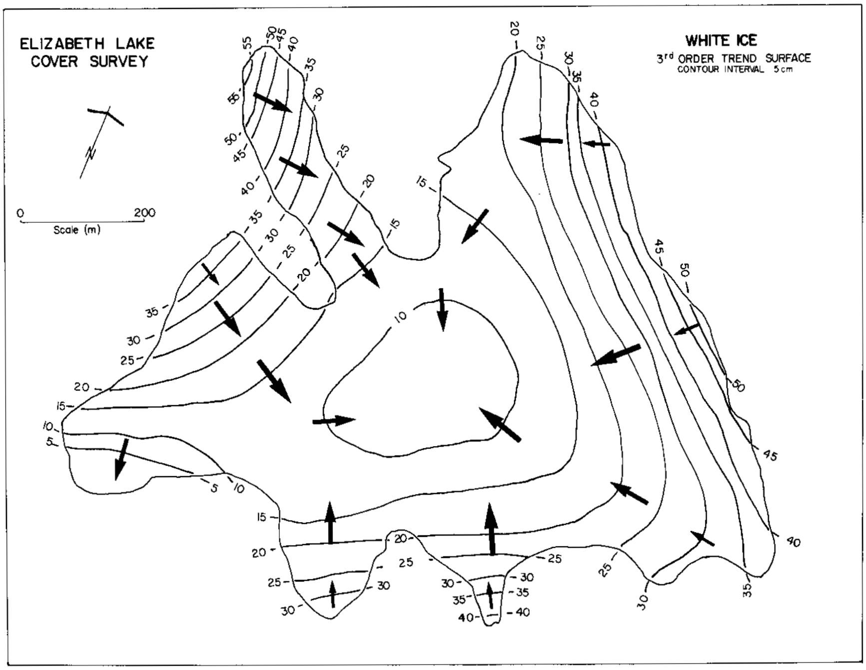

FIG. 8. Cubic trend surface map for white ice thickness.

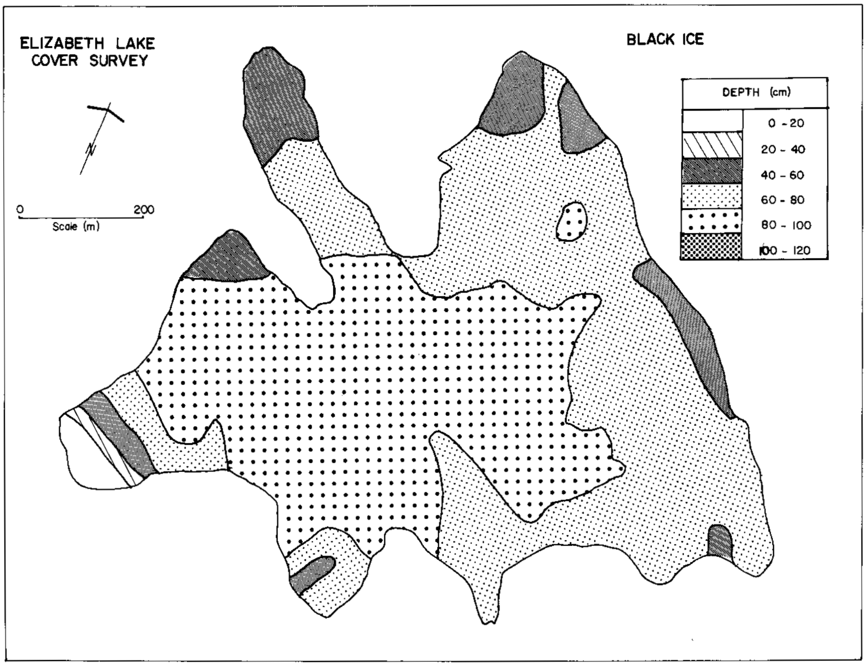

FIG. 9. Isopleth map for black ice thickness.

The mean thickness of black ice was 73.60 cm, almost four times as thick as the white ice. In the broad view, the normal interpolation map (Fig. 9) is a mirror image of the corresponding white ice map. The eastern half of the lake and the northwest arm are largely <80 cm as are areas in bays in other parts of the lake. The open western part of the lake is dominated by a zone of >80 cm. With the exception of two locations (the upwind, western, shore and the promontory of the south), the margins of the lake are characterized by <80 cm black ice, with considerable stretches of <60 cm.

The 'mirror image' aspect of relationships between the spatial distributions of white ice and black ice is clearly evident when the respective third order maps are compared (Figs. 8 and 10). The topography of the black ice surface is that of a conical hill, centred somewhat to the west (upwind) of centre of the lake, with a marked gradient outward in all directions. In this case, the inlets and bays are notable for low ice thicknesses. The bay in the southwestern corner is not an exception here as it was in the case of white ice — black ice decreases in thickness towards all margins.

The distribution of total ice thicknesses (black ice + white ice) is shown in Figure 11. Mean thickness was 94.23 cm. It is apparent from the map that values in the 80-100 cm class, which contains the mean, dominate areally with above and below average values, especially the former, at both central and marginal locations. The equivalent third order trend surface (Fig. 12) is extremely bland. No distinct trend is apparent.

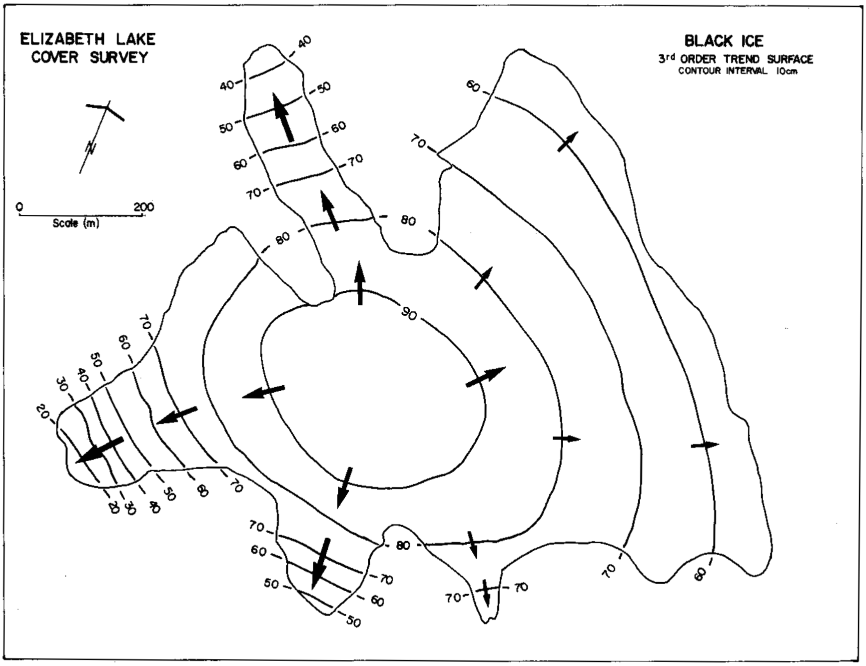

FIG. 10. Cubic trend surface map for black ice thickness.

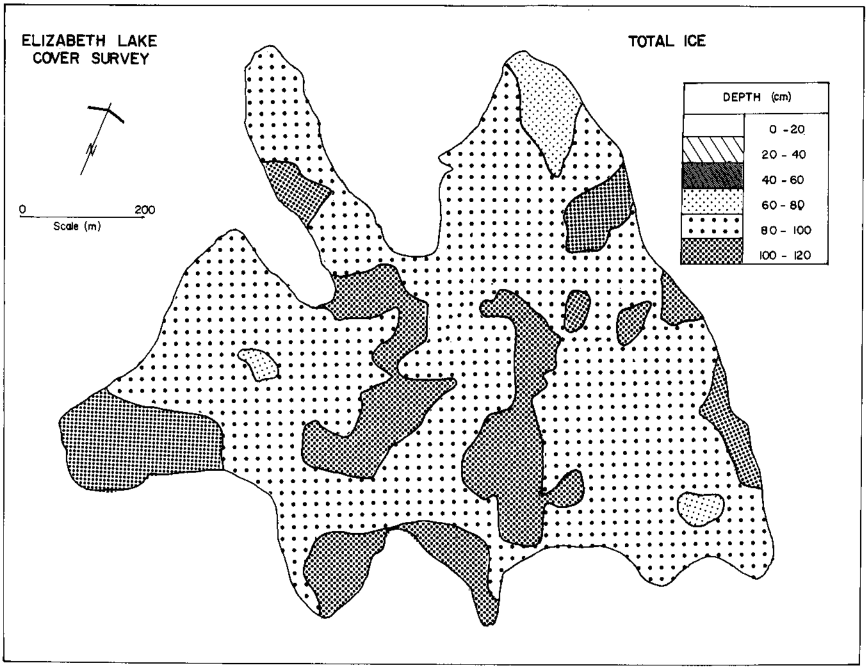

FIG. 11. Isoplethfor total ice (black ice + white ice) thickness.

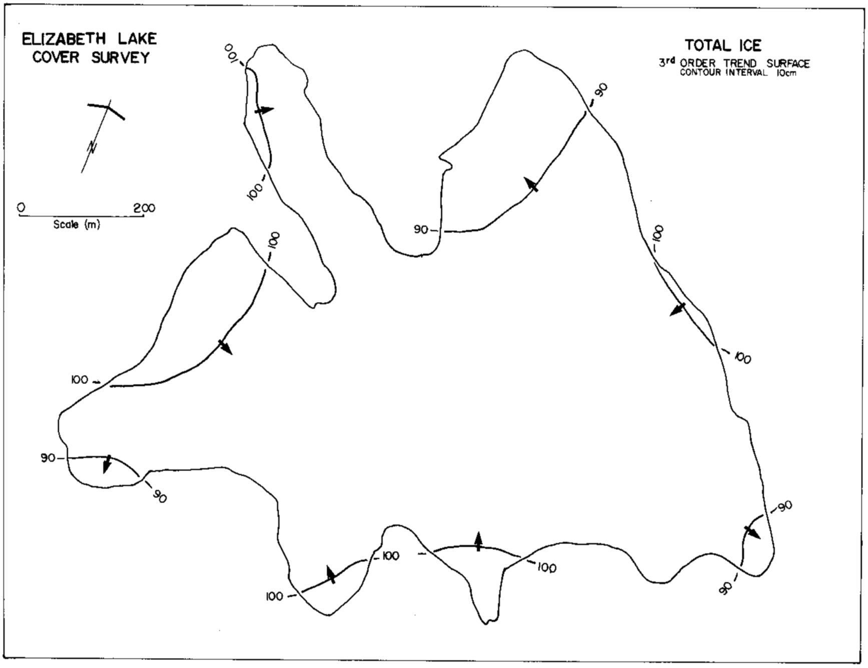

FIG. 12. Cubic trend surface map for total ice thickness.

DISCUSSION

Where snowcover plays an important role in the growth of lake ice, the evolution of the ice sheet, and indeed of the entire lake cover (snow and ice) can be conceived as being of a cyclic nature. There is a cyclic variation of growth processes and an associated cyclic variation in spatial pattern of cover components.

With regard to the processes, a stage in which black ice growth dominates under an increasing snowcover is succeeded by one of rapid white ice growth following slushing. During the slushing-white ice phase there will be no growth of black ice, possibly even a thinning of it as a result of erosion at its base. When all the slush is frozen, black ice growth begins again beneath the new layer of white ice and a snowcover which is again generally increasing. As the ice sheet thickens, larger quantities of snow are required to depress it to allow another slushing phase to begin.

This sequence might occur several times, producing layers of white ice. It can be envisaged as a series of lakewide events or as the result of events at different points on the lake, controlled by quite local circumstances. Lakewide spatial patterns, such as those discussed here, can be conceived as arising from either situation.

The cyclic pattern in the evolution of spatial patterns in the cover components of a lake can be described as follows. Snow falling on the lake accumulates or is redistributed so that some locations (notably downwind and marginal sites) develop a greater cover than others (notably central locations somewhat upwind of centre). The floating ice sheet is depressed most in areas where snow accumulation is greatest and this is emphasized over time by the fact that ice growth is generally slowest in those areas. Thus an upwind→downwind, centre→margin, pattern of black ice (thicker→thinner) is developed in response to a similar, but reverse (thinner→thicker) snowcover pattern.

When slushing occurs, the deep snow-thin black ice areas are most affected so that white ice growth is most pronounced in them. Thus an upwind→downwind, centre→margin, pattern of white ice (thinner→thicker) develops. It should be noted that spatial differences of black ice will become more pronounced during the slushing-white ice phase as its growth stops and thinning may occur in slushed areas whereas growth continues elsewhere.*

During and immediately following a white ice phase, the lake snowcover will exhibit much less marked spatial variability but distinct trends will develop again as redistribution of snow across the lake surface continues.

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* A common cause of the cracking which produces slushing is thermal stress. It appears likely that the lakewide spatial patterns in snowcover may be important even in quite local slushing events as the least insulated parts of the lake (i.e., those least liable to flooding) are subject to greatest thermal stress. Cracking patterns suggest that cracks may run from such areas to areas which are depressed by a thick snowcover. Such areas might not otherwise slush — small lakes or ponds which accumulate large quantities of snow, but which are little affected by wind, sometimes do not develop much white ice.

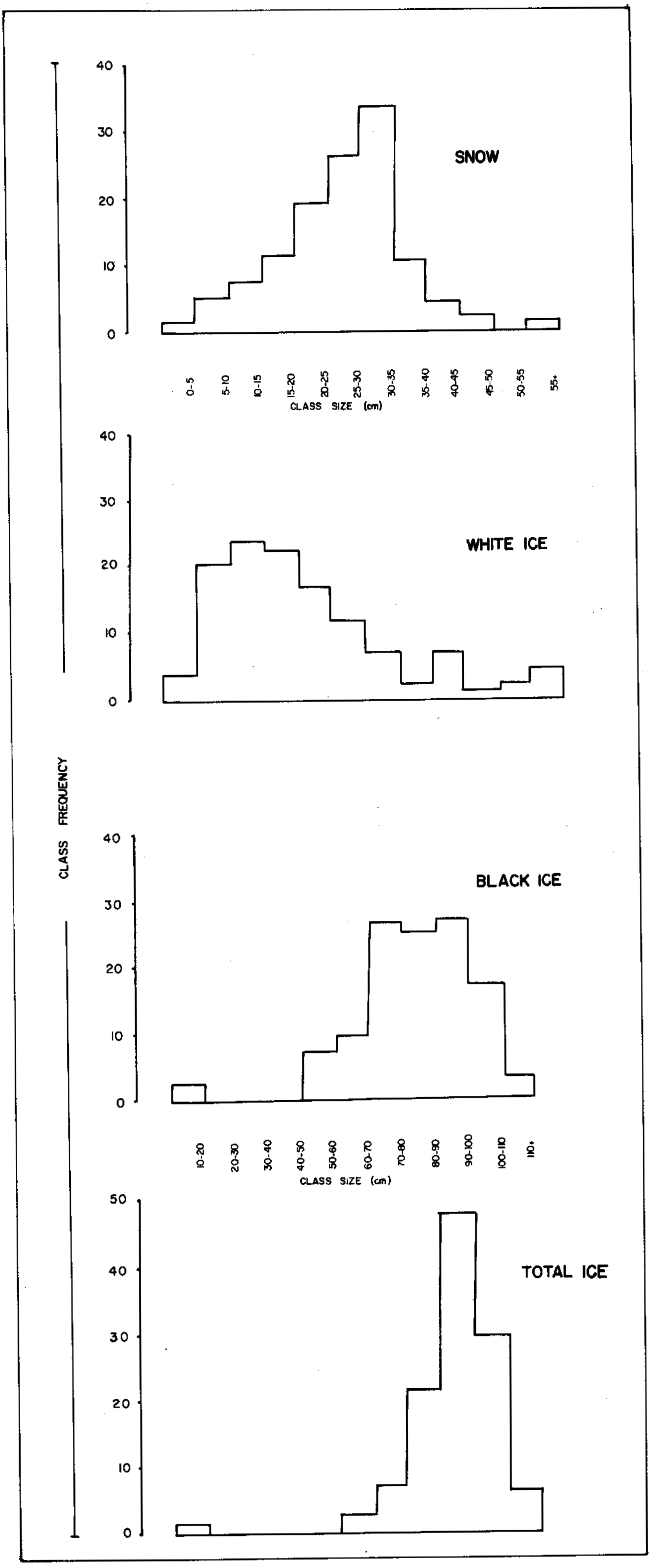

FIG. 13. Frequency distributions for major cover components discussed.

Thus, for snowcover, phases in which wind-induced distribution patterns become more marked are interrupted by slushing events which mitigate or remove the wind patterns (Adams and Prowse, 1978).

In terms of the overall ice sheet beneath this snowcover, the phases of white ice growth, to a greater or lesser extent, offset the snowcover-related pattern of ice growth which arises from the role of snowcover as an insulator. In terms of the whole ice sheet ("total ice", here), the end of a white ice growth phase is a stage in which spatial variability is relatively low.

The compensatory nature of white ice growth and black ice growth, reflecting the growth promoting and retarding roles of snowcover suggested by Figures 8, 10, and 12, is graphically displayed in the frequency distributions of the Elizabeth Lake data (Fig. 13). On this lake, at the time of the survey and in the winter concerned, black ice was by far the major component of the sheet so that it dominates in the total ice frequencies.

Trends were most pronounced in black ice and white ice, especially the former; there was least trend in total ice. These observations are in accord with stages of ice growth described above. There was a discernible spatial pattern in the snowcover but it was much less marked than that of either white ice or black ice. This suggests that sufficient time had occurred since the last major slushing phase for some wind-redistribution to take place. In fact comparison with observations made on 18 January along a profile located in the northwestern arm (Fig. 14) indicates that at least one slushing-white ice growth phase had occurred in the preceding five weeks. It is possible that more than one phase occurred during the early part of the winter.

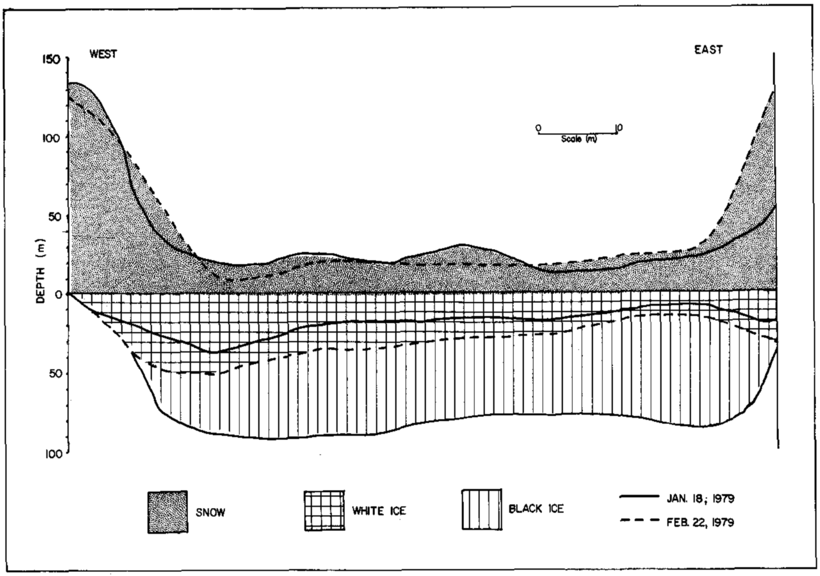

FIG. 14. Cross sections of the northwest arm in the vicinity of stake 87 (Fig. 1) on the dates indicated. Note the lack of distinct trends in the snowcover in contrast to the patterns of white ice and black ice.

CONCLUDING REMARKS

The set of measurements obtained for Elizabeth Lake provide an unusually good illustration of a lake cover most parts of which have *completed* at least two, possibly several, white ice forming phases. Such a cover, characteristically, shows a marked spatial trend in the black ice component, a trend which is most closely related to patterns in the white ice component (representing persistent snow distributions) rather than to the current overlying snowcover. In this case, snowcover did exhibit a fairly marked trend suggesting that sufficient time had elapsed since the last slushing phase for redistribution of snow to occur. The overall pattern of total ice thickness showed little correspondence to patterns in the overlying snowcover at the time of the survey or to historic patterns of snowcover as represented by white ice.

The cyclic nature of ice growth on lakes such as this considerably affects the nature of 'peak' ice on a lake. During the late winter, growth of ice at the ice sheet/water interface will be relatively slow for most parts of the lake even during periods of very low air temperature. However, should slushing take place, a great increase in thickness can occur rapidly. Thus differences in maximum thickness between years might well be accounted for by patterns of snow loading and the potential for slushing at certain periods rather than by degrees of cold. Also, for short periods during each winter, particularly in slush-prone areas of lakes, predictions of ice thickness using measures of cold such as degree days, making allowance only for the insulating role of snowcover, are likely to considerably underestimate total ice thicknesses. The *stage* of ice growth at the time of a survey becomes very important.

Spatial patterns identified here and the evolutionary processes associated with them have important implications for those interested in making generalizations about or predictions of conditions in the ice and snowcover of a lake or in the water body beneath that cover. The interaction between lake and atmosphere which produces the cover is usefully viewed as a highly dynamic, rather irregular cycle of events which may be markedly out of phase between various locations on the lake. Marked spatial trends do however develop, particularly in the ice *(sensu stricto)* components of the cover, which provide some potential for lake-wide discussion and explanation of the cover phenomena and their implications. However, when making use of such trends, care should be taken *not* to forget the temporal and spatial variability of processes which produced them. An example of this is the fact that a given thickness of highly layered white ice, resulting from several slushing phases, has very different implications in terms of ice properties and chemical composition than a similar thickness resulting from a single slushing event. The very different behavior of light passing through layered and non-layered ice (Maguire, 1975) is a good illustration of this point.

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