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THE ROLES OF SNOW, LAKE ICE AND LAKE WATER IN THE DISTRIBUTION OF MAJOR IONS IN THE ICE COVER OF A LAKE

by

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ABSTRACT

The stratigraphic variability of ion concentration in lake ice was examined and related to the processes of lake-ice formation. Ice blocks obtained from Elizabeth Lake, Labrador and Knob Lake, Quebec showed marked vertical variation in the concentration of major ions, with peaks in conductivity occurring in the white ice and an overall increase in conductivity upwards from the black-ice/white-ice interface to the top of the block. Exsolution of ions from the black ice into the water body appears to be very efficient, producing low concentrations of ions in the black ice and high concentrations in the immediate sub-ice layer of water. This sub-ice concentration of ions appears to influence the entire water column, possibly via density-induced movements. Changes in snow depth, white- and black-ice growth, and the vertical distribution of conductivity in the water column were found to be related to slushing events. A controlled slushing experiment suggested that a marked concentration of ions does occur during white-ice formation.

INTRODUCTION

Ions such as H^+, heavy metals and nutrients enter a lake from a number of major sources. These include surface runoff, groundwater, precipitation and sediments in the lake. However, during spring melt in cold regions, the ice and snow cover of the lake itself may be a significant source of ions, especially where the ratio of the area of the lake surface to that of the drainage basin is large.

When examining blocks of lake ice in connection with studies of atmosphere-lake interactions, such as nutrient loading, and oxygen and light regimes (e.g. Adams and others 1979, Wolfe 1980, Jackson and Lasenby 1982, Roulet and Adams 1984) we also observed pronounced stratigraphic and spatial variability of ion concentration within the ice cover. Although our observations are consistent with those of others (e.g. Barica and Armstrong 1971, Jones and Ouellet 1983), such variations are generally ignored by limnologists (e.g. Canfield and others 1983). They tend to use a single, vertically integrated sample from a "deep hole" site to represent the entire lake cover.

In this paper, we report our efforts to quantify the stratigraphic variability in ion concentration and we attempt to relate this variability to the processes of formation of lake ice.

METHODS

Blocks of ice were obtained from a number of lakes. Those discussed here were from Elizabeth Lake, Labrador (54°45'N, 66°54'W, 616 m a.s.l., 11.08 hm^2, 27.1 m maximum depth) and Knob Lake, Quebec (54°47'N, 66°48'W, 497 m a.s.l., 192.3 hm^2, 14.8 m maximum depth). Both of these lakes are in the Labrador Trough section of the Precambrian Shield. The ice cover of both had been studied in some detail previously (Adams 1984). The blocks were typically 30 cm x 30 cm x ice thickness. They were subsampled for water analyses using a hand saw at approximately 2 cm intervals. The subsamples were rinsed with distilled water, placed in plastic bags and melted. This procedure was checked for contamination. Since the specific conductance of the common bicarbonate-type lake water is closely proportional to the concentration of major ions, conductivity (μmhos cm^{-1}) was used as a measure of ion concentrations in the ice. The conductivity of the melted samples was determined using a YSI model 33 conductivity meter. In the case of ice from Knob Lake, a number of ion concentrations were measured directly using a Varian model AA375 atomic absorption spectrophotometer.

The evolution of the ice, including snow, cover of Knob Lake was monitored in some detail before the extraction of the block from it. Measurements of black- and white-ice thickness, snow depth, and "hydrostatic water level" were made fortnightly using standard drilling techniques. The conductivity of the water column was measured at the same time using an Electro Mark Analyzer (Markson Science Inc).

In an effort to examine further the processes of ice formation and their role in determining the distribution of

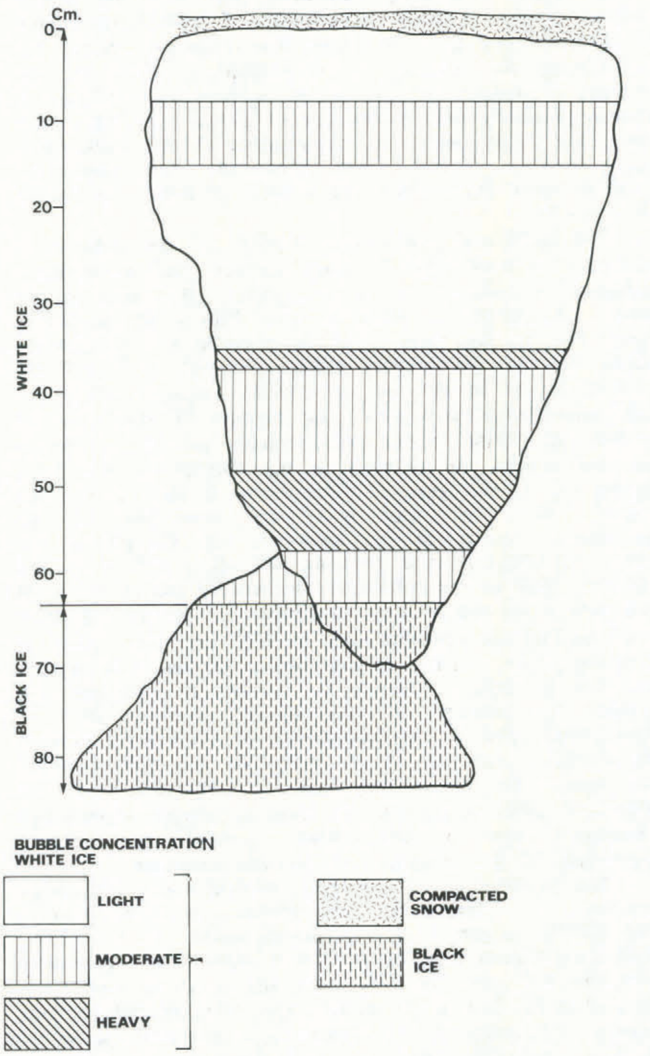

Fig.1. Structure of ice block from Elizabeth Lake, 23 February 1979, showing bubble distribution in white ice.

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ions in lake ice, a controlled slushing experiment was conducted on a pond near Trent University, Ontario (44°22'N, 78°18'W, 226 m a.s.l.). The procedures used are described below.

RESULTS AND DISCUSSION

The block from Elizabeth Lake, which was extracted on 23 February 1979, consisted of 63 cm of white ice and 22 cm of black ice (Fig.1). During this winter, as in most winters, all white ice formed in this region resulted from the rise of water through thermally-induced cracks (or through drill holes) at a time when the load of snow was sufficient to depress the surface of the ice cover below the hydrostatic water level (see Fig.2). In this case (Fig.1), white ice contained distinct layers of varying bubble

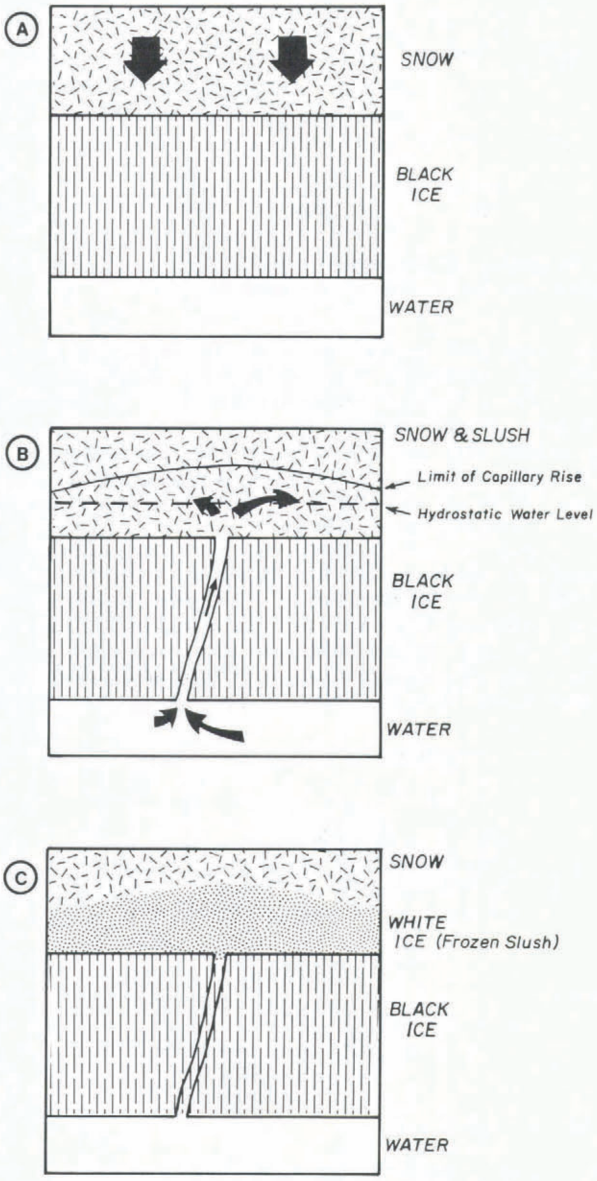

Fig. 2. Formation of white ice as envisaged in this paper. (A): ice sheet depressed by snow load, (B): water rises through a crack at a time when the surface of the ice cover is below the hydrostatic water level, (C): the resultant slush freezes from its surface downwards, concentrating ions via exsolution (see Fig.7). Some flow from the slush into the lake is possible.

density, presumably indicating different rates of freezing and/or effects of the stratigraphy of the snowpack which was slushed to produce the white ice.

Conductivities of the subsamples of melted ice ranged from 72 μmhos cm^{-1} in the white ice to 2 μmhos cm^{-1} in the black ice (Fig.3). Three peaks appeared in the white ice, at about 15, 35 and 55 cm from the top of the block.

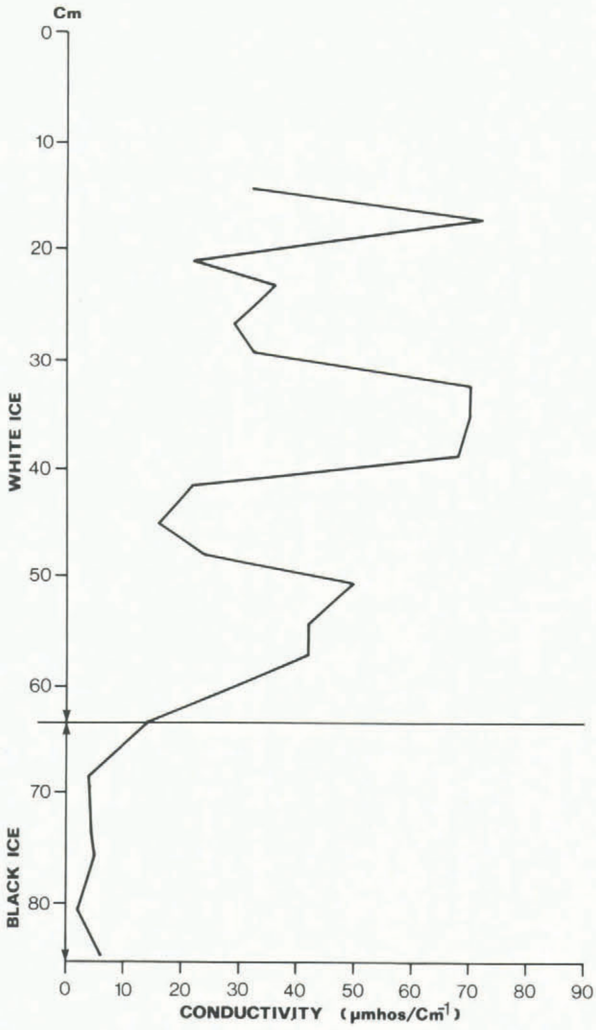

Fig. 3. Vertical distribution of conductivity in the ice block from Elizabeth Lake (cf. Fig.1).

There was a clear overall increase in conductivity upwards from the black-ice/white-ice interface to the top of the block.

The low conductivities in the black-ice component reflect exsolution of ions into the underlying, unfrozen water body as freezing proceeds at the base of the ice cover. We thought that, although there was no peak at the black-ice/white-ice interface itself, the same process might be largely responsible for the conductivity peaks in the white ice. In this case, the peaks would represent layers in which ions were concentrated, by exsolution or other means, during the formation of successive white-ice layers. The increase in conductivity towards the top of the ice block seemed to suggest involvement of increasingly ion-rich water in white-ice formation as the winter proceeded.

CONDUCTIVITY REGIME OF KNOB LAKE

As a means of further understanding this pattern, and similar patterns in other blocks, we monitored the evolution of the ice cover and of the conductivity regime of Knob Lake throughout a winter, before the extraction of an ice block. We also attempted to examine the processes of white-ice formation more closely in a controlled field situation. Figure 4 is a representation of the conductivity regime of Knob Lake for the winter of 1981-82 with an indication of the development of its ice cover. Time series of conductivities at selected water column depths are shown immediately above the ice and conductivity data. Figure 5 shows the detail of the growth with a representation of the ice block inserted in the series at the date of extraction. Daily range of temperature is shown at the top of the diagram.

It is important, when interpreting these diagrams, to bear in mind the nature of the measurements involved and

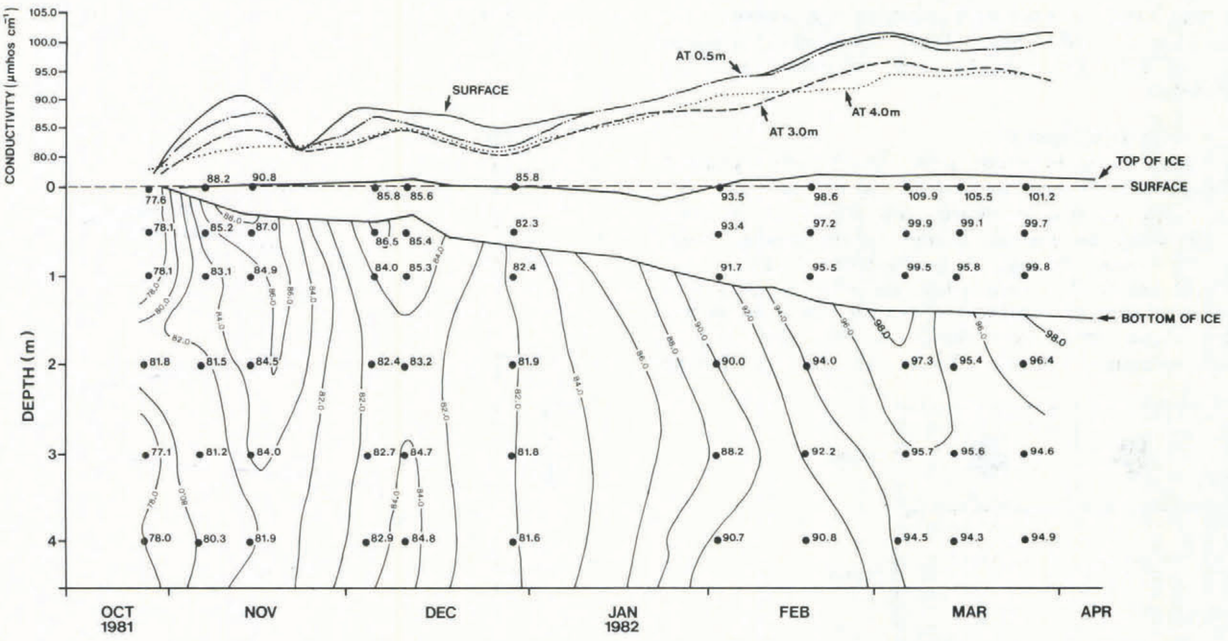

Fig. 4. The conductivity regime of Knob Lake with an indication of ice growth, winter 1981-82. Note the plots of values from selected strata inserted above the ice portion of the diagram.

the nature of the process of white-ice formation in this sub-Arctic location which is very cold and has a high snowfall. All ice measurements were made through a drill hole 10 cm in diameter in the vicinity of a marked measuring site. Appreciable local variation in ice thickness can be expected on lakes such as this (e.g. Adams and Roulet 1980). The conductivity measurements were made downwards from the top of the water column so that an increasing number are within the drill hole as the winter proceeded.

When a hole is drilled in floating ice, water rises up it from beneath. The volume of water involved is at least the area of the drill hole multiplied by the length of the water column in it but, where the ice surface is depressed below the hydrostatic water level, it may be larger as the water rises above and spreads out over the surface of the ice, within the snowpack. The conductivity values within the drill holes in Figure 4 cannot be thought of as representing a stratum of water across the lake, as can those lower in the conductivity profiles. We envisage the water in the drill holes, and that which spreads out over the ice during a slushing event, as being drawn from a more or less thin layer immediately below the ice.

It can be seen (Fig.4) that, with the exception of "hesitations" in November and December, there is a general increase in the conductivity of the water column as the winter proceeded. This increase, which has been documented by others (e.g. Barica 1977), is most pronounced in the surface and near-surface layers and least pronounced in the bottom layers. There is also an increase in the range of

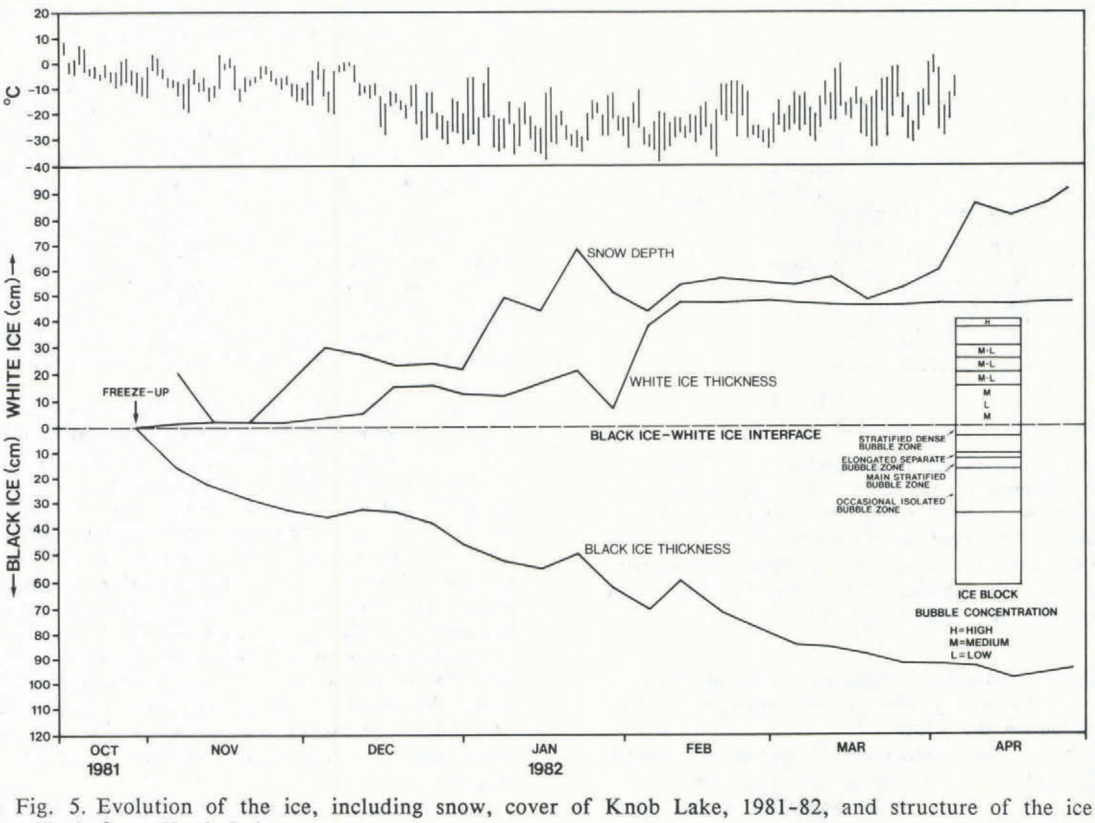

Fig. 5. Evolution of the ice, including snow, cover of Knob Lake, 1981-82, and structure of the ice block from Knob Lake.

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conductivity values in the water column. This is probably a reflection of the increasing chemical stratification as a result of exsolution. In the early ice season (until mid-November), there was a rapid increase in conductivities of the near-surface layer with only a small increase deeper in the water column. This was followed by the most marked reduction in conductivities of the winter, a reduction which was least noticeable at the bottom of the lake. After December, values increased again to reach the highest levels of the winter at all depths. The highest values in the water column were consistently in the near-surface layer. There was slight evidence of the double maximum (top and bottom) reported for Char Lake by Schindler and others (1974). The only exception to this general increase in values was a slight hesitation in January and February.

EVOLUTION OF ICE AND SNOW COVER OF KNOB LAKE

The development of the conductivity regime can be considered in conjunction with the evolution of the ice, including snow cover. When water freezes, ions are more or less efficiently exsolved (Pounder 1965). Generally, as the rate of freezing becomes faster, so the exsolution becomes less efficient. The exsolution of ions from a thickening black-ice cover into the underlying unfrozen water body has been well-documented (e.g. Welch and others 1976).

There was a rapid growth of black ice during the period following freeze-up (until mid-November) and then growth slowed somewhat until mid-December when there was a hesitation (Fig.5). By the end of December, the growth of black ice had returned to its previous rate to be further interrupted by two pronounced hesitations, one in late January and the other in early February. Then, after a short period of accelerated growth, the black-ice cover thickened slowly but steadily until the date on which the ice block was extracted. The rapid initial growth of black ice to a thickness of approximately 40 cm shows up in the heavy bubble layer in the ice block shown as an insertion into Figure 5. These bubbles indicate relatively inefficient exsolution of ions. This is reflected in the plots of conductivity and ion concentration in Figure 6 by small peaks in ion concentration at the 10 cm level. However, black-ice concentrations or conductivities in Figure 6 are consistently lower than the values for white ice.

The formation of a few centimetres of white ice in mid-November removed the initial snow cover of the lake (Fig.5) but the first major slushing event of the winter occurred in mid-December when white ice increased abruptly to 15 cm. The next surge of white-ice growth was in late January-early February when the thickness grew to 50 cm. Thereafter there was never again sufficient snow to depress the combined black- and white-ice cover below the hydrostatic water level to induce further white-ice formation. The three phases of white-ice growth did not appear as distinct layers in the white-ice portion of the ice block although there were some distinct bubble layers in it (Fig.5). It is possible that a change is detectable at the 15 cm level (i.e. base of the last phase of growth).

Figure 5 also provides an excellent illustration of interrelationships between the three components of lake cover shown: snow, white ice and black ice. In the white-ice event of December, for example, there is a decrease in snow depth following slushing and a cessation of black-ice growth during the slushing phase. This last reflects the absence of a temperature gradient between the unfrozen water body and the slush. When the layer of white ice has formed, there is a modest acceleration of black-ice growth beneath a poorly insulated, albeit thicker, ice cover.

EVOLUTION OF THE WINTER COVER AND LAKE CONDUCTIVITY

Although the field procedures described above were such that related events concerning ice formation and water-column conductivity may not appear to coincide exactly in Figures 4 and 5, it is possible to discern some of the links between the processes of ice formation and the lake-conductivity regime. The dispersal of the first conductivity peak beneath the ice (mid-November) appears to be related to the first white-ice phase, and that of the second peak (early December) to the second white-ice phase. This reduction in ion concentration could be a result of the removal of the ion-rich layer from immediately below the ice and its redistribution over the surface of the ice. The effect of the last white-ice phase (late January) is less apparent. There was perhaps a slowing of the rapid increase in ion concentration which was affecting the entire water column by this time (see plots at top of Figure 4). The marked increase in conductivity of the entire water column, to the highest winter values, especially the upper layer, was a feature of the last phase of ice growth when black-ice growth proceeded slowly but steadily, uninterrupted by white-ice formation. This was the stage of most efficient exsolution into the water body.

The fact that the increase in conductivity was not confined to the immediate sub-ice layer, suggests that density-induced circulation was occurring (cf. Schindler and others 1974). Since there is no reason to believe that the sediments should become a more effective source of major ions at this time, the increasing conductivity at all depths might be explained in terms of "the sinking of solute-rich water originating from freeze-out" (Schindler and others

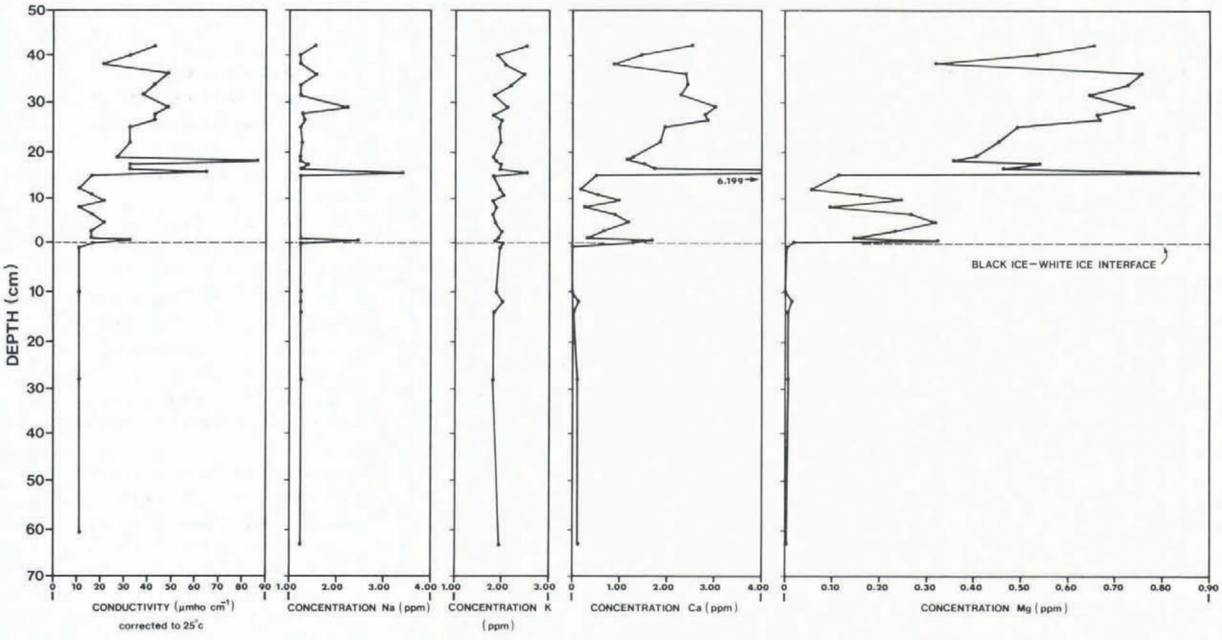

Fig. 6. Conductivity and ion profiles in the ice block from Knob Lake.

1974) rather than in terms of a turnover of the water column.

The conductivity profile of the ice block from Knob Lake, extracted on 5 April 1982 (Fig.6), showed some of the features seen in the block from Elizabeth Lake (Fig.3). Conductivity was uniformly low in the black ice (slightly higher than in the case of Elizabeth Lake) and showed an irregular profile in the white ice, with marked peaks and a tendency towards increased conductivity with distance from the black-ice/white-ice interface. It appeared that there was an increase in conductivity (i.e. a concentration of ions) towards the base of the major white-ice layer suggesting a concentration of ions in the lowest slush layer, possibly as a result of exsolution as the slush froze from its upper surface downward

Measurement of individual ions in the subsamples from the block from Knob Lake tended to confirm the concentration pattern inferred by conductivity measurements (Fig.6), as might be expected. However, there is a clear suggestion that some ions are affected differently by the process of freezing exsolution than others. The pattern of K concentration, for example, is much more uniform than the other two shown.

SLUSHING EXPERIMENT

The pond experiment, mentioned above, was carried out in an effort to follow the slushing-freezing processes of white-ice formation. The surface of a pond (covered by 35 cm snow, 17 cm white ice and 22 cm black ice) was slushed to a depth of 15 cm by drilling a hole in it. Pond surface water had a conductivity of 533 μmhos cm^{-1} while the snow had a conductivity of 37 μmhos cm^{-1} before slushing. The initial conductivity of the slush was ~400 μmhos cm^{-1}. After 4 d, 10 cm of ice had formed and the conductivity of the remaining slush had increased to 856 μmhos cm^{-1} (Fig.7). Unfortunately, warm weather and rain intervened before the slush layer had all become ice. The experiment did however suggest that marked concentration of ions occurs during white-ice formation.

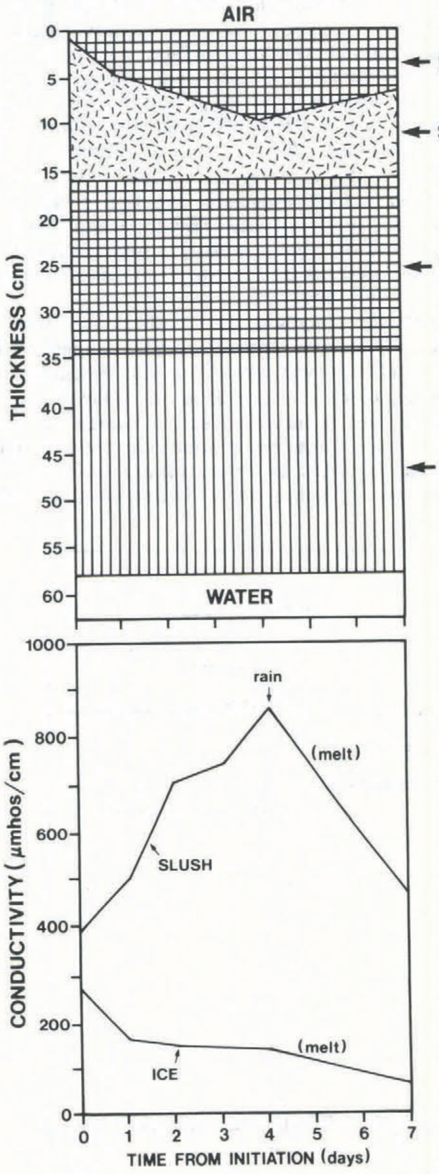

Fig. 7. Results of pond experiment designed to examine the process of exsolution during white-ice formation.

CONCLUDING REMARKS

1. This work has demonstrated that there is a marked vertical variation in the concentration of major ions in ice covers which form on lakes in regions where snow is sufficient to produce white ice. In the case of underlying black ice, exsolution of ions from the ice into the water body appears to be very efficient. This produces low concentrations of ions in the black ice and high concentrations in the immediate sub-ice layer of water. This sub-ice concentration of ions appears to influence the entire water column, presumably via density-induced movements which overcome the weak thermal stratification which is typical of ice-covered lakes.

In white ice there is evidence of a concentration of ions in the lower parts of a slush layer by exsolution, as freezing proceeds. It is possible that this process is aided by gravity and/or by exsolution effects associated with metamorphism and percolation of meltwater through the pack before slushing, as described by Colbeck (1981) for land snowpacks. This concentrating process produces sharp peaks in conductivity profiles of the ice blocks. In general, exsolution is less efficient in the slush environment (background conductivities are high relative to those in black ice). It also appears that, in the slush environment in particular, there is a differential exsolution of ions so that some ions may be better indicators of ice-forming processes than others (see Fig.6).

The relationship between increase in conductivity in white ice and distance from the black ice/white ice interface appears to result from the fact that increasingly ion-rich water is involved in slushing phases as the winter proceeds. Loss of ions during slushing is an important feature of the conductivity regime of the lake.

2. The stratification of ions in lake ice covers provides an interesting record of interactions between the water body, the ice and snow cover, and the atmosphere. It has important implications with respect to "the differential release of constituents of lake-surface snow, slush, white ice and black ice during melting" (Gunn and Keller 1985) into the water body during spring melt. In our lakes, snow remaining on the lake after the initial runoff period and black ice have a diluting effect during the melt. White ice, on the other hand, contains high concentrations of ions, with extremely high concentrations in some strata. The white-ice ions often include the larger part of the winter's atmospheric inputs (wet and dry fallout) plus ions derived from the lake itself via the freeze-out from the black-ice layer. Because the snow is relatively low in conductivity these latter re-cycled ions are the major spring input from the winter cover of the lake.

Thus, the evolution of the ice, including snow, cover of the lake, and the sequence and timing of spring melt, becomes very important in determining the detail of inputs of major ions into the lake. Where a thick, multilayered white-ice cover is present, a slow melt, proceeding from the surface downward, can be conceived as producing high-concentration injections of ions into the lake as peak ion strata melt. A rapid melt, which quickly involves both the white- and black-ice components, would have quite a different effect.

3. The processes described here are part of direct and substantial interactions between "the water body" and "the atmosphere" at a time of year when "the lake" is viewed as being cut off from "the atmosphere". Lake water is brought into direct contact with the atmosphere and is temporarily lost to the unfrozen body. Ions are taken from the water body and it is probable that some atmospherically-derived ions reach the water body (via drainage during the slushing process) at intervals during the winter. This is an aspect of

the mass and chemical balance of lakes which is quite well understood in the literature on winter oxygen deficits in lakes (e.g. Welch and others 1976) where black-ice exsolution is recognized as a gain and slushing is recognized as a loss of oxygen.

4. This paper focuses on the situation in which white ice is formed on the surface of a black-ice cover as a result of the slushing of a snowpack from below (Fig.7). White ice is also formed by other means which do not involve water drawn from the under-ice water body. These include slush produced by snowmelt, by rain on snow and by the flooding of a lake-ice cover by land surface runoff or by groundwater flow. The implications of these situations, in terms of the winter-long evolution of the lake cover and of the conductivity regime of the lake, and in terms of the impact of spring melt, will be quite different. Studies of spring loading of lakes should include careful monitoring of the evolution of ice (including snow) cover. The implications of spring melt of the winter cover of lakes dominated by black ice, as in, for example, the high Arctic (e.g. Schindler and others 1974) or the prairies (e.g. Barica 1977), are quite different from those for lakes where white ice is a normal component of the ice cover.

5. White ice is clearly an important and complex component of the winter cover of lakes in snowy regions. It has considerable biological implications, in addition to those discussed here. It is known to be highly variable spatially: for example, late-winter values on Elizabeth Lake in 1978-79 ranged from 0 to 65 cm (Adams and Roulet 1980). All calculations of atmospheric loading of lakes must take such variability into account rather than relying on a single block. Such calculations should also be made with an awareness of the possible importance of "re-cycled" ions as distinct from atmospherically-derived ions.

6. Although drilling is the standard means of measuring ice growth and of obtaining water samples from a lake, it should be realized that, in snowy situations, it will tend to induce slushing and white-ice growth. Thus a regular drilling programme can have the effect of significantly altering all of the processes and phenomena discussed here.

ACKNOWLEDGEMENTS

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