

ILLUSTRATIONS OF EFFECTS OF ICE IN THE DISTRIBUTION OF MAJOR IONS  
IN LAKES

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ABSTRACT

As the surface layers of a lake freeze, ions are exsolved and concentrated in the, decreasing, unfrozen water body. This process affects the entire water column but is most marked in the immediate sub-ice layer. Sub-ice ion concentrations are reduced when ions are lost from the water body during slushing events which produce ion-rich 'white ice' on top of the original ice sheet. The entire ice sheet, by its physical presence, by its partial control of stratification in the unfrozen water column and, on melting, through the release of ions and water contained in it, greatly influences the lake's spring ion regime. Illustrations of such effects are given from a variety of situations involving different proportions of white ice and black ice. The lakes concerned are Knob Lake, northern Quebec, and Plastic Lake, southern Ontario.

When water freezes, dissolved solids, particulates and gases are exsolved producing ice which is relatively pure. In the case of a lake ice sheet, thickening downwards into a lake, exsolved substances become concentrated in the cold, and therefore light, layer of water immediately beneath the ice. Exsolution is most efficient when the rate of freezing is slow.

As a result, the freezing of the surface layers of a lake produces an ice sheet which is relatively pure overlying a layer of water into which exsolved ions have been concentrated.

Should cracking occur when such an ice sheet is depressed below the prevailing lake level, by the weight of snow lying upon it, water can pass through the cracks into the snow to produce slush (Fig. 1). On freezing, which it does from its surface downwards, this slush becomes a new layer of ice superimposed on the original ice sheet. This ice is formed of a mixture of snow meltwater and ion-rich water from immediately below the original ice sheet. Although some ions might pass back into the lake through cracks which induced slushing, most exsolution products remain in the ice cover, some in the snowcover. Such slushing-freezing events can occur several times in a winter.

In this case then, the ice-forming process results in a removal of ions from the unfrozen water column and their concentration in the lake's winter cover.

Where this type of slushing occurs, the winter cover of a lake has three main components (defined in Figure 1). There is the relatively pure 'black' ice, the relatively ion-rich 'white' ice and a snowpack, more or less reduced by slushing. The snowpack contains atmospherically-derived ions with some contamination from lake-derived ions (Allan and Adams 1985) resulting from the capillary effect shown in Figure 1.

The unfrozen lake body is variously affected by the mode of formation and nature of these cover layers. It gains ions from black ice growth and loses ions during slushing phases (Adams and Lasenby 1985). During spring, it tends to be relatively diluted by black ice melt but more or less gains ions from the melt of white ice and snow, especially the former. In some situations, for example most winters in the high arctic where snowfall is low, the black ice effect dominates. In others, white ice or snow may dominate.

Figures 2-4 show various winter cover situations. In each, the evolution of the ice sheet is shown in detail with a portrayal of the conductivity regime of the lake. Conductivity (specific conductance) is a measure of the concentration of major ions in water. High conductivities mean high concentrations. As individual lake conductivities vary greatly, according to local circumstances, differences in magnitude of conductivity between the two lakes used here should be ignored.

In Figure 2, there is an increase in conductivity as the winter proceeds with a strong tendency for the immediate sub-ice layer to have highest values. However, there are periodic reductions in conductivity which are particularly noticeable in the sub-ice layer. These reductions are picked out by the conductivity plots (for various lake depths) at the top of the diagram. The increase in conductivity is related to black ice growth and

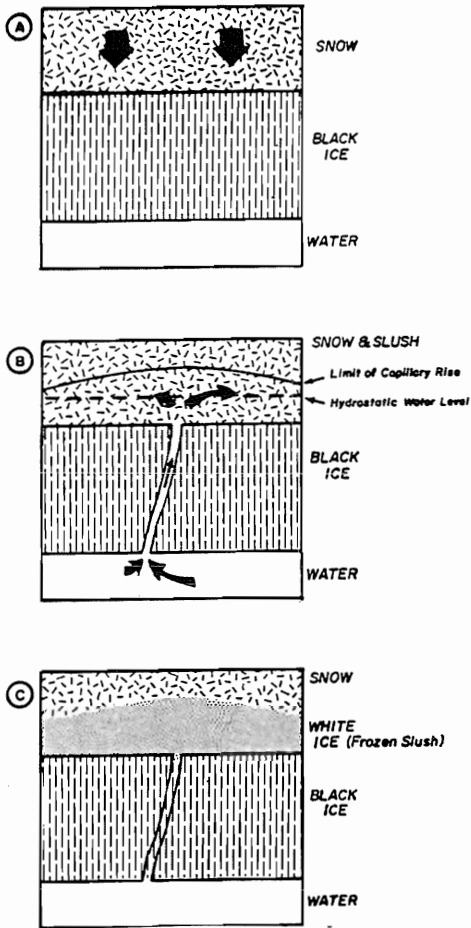
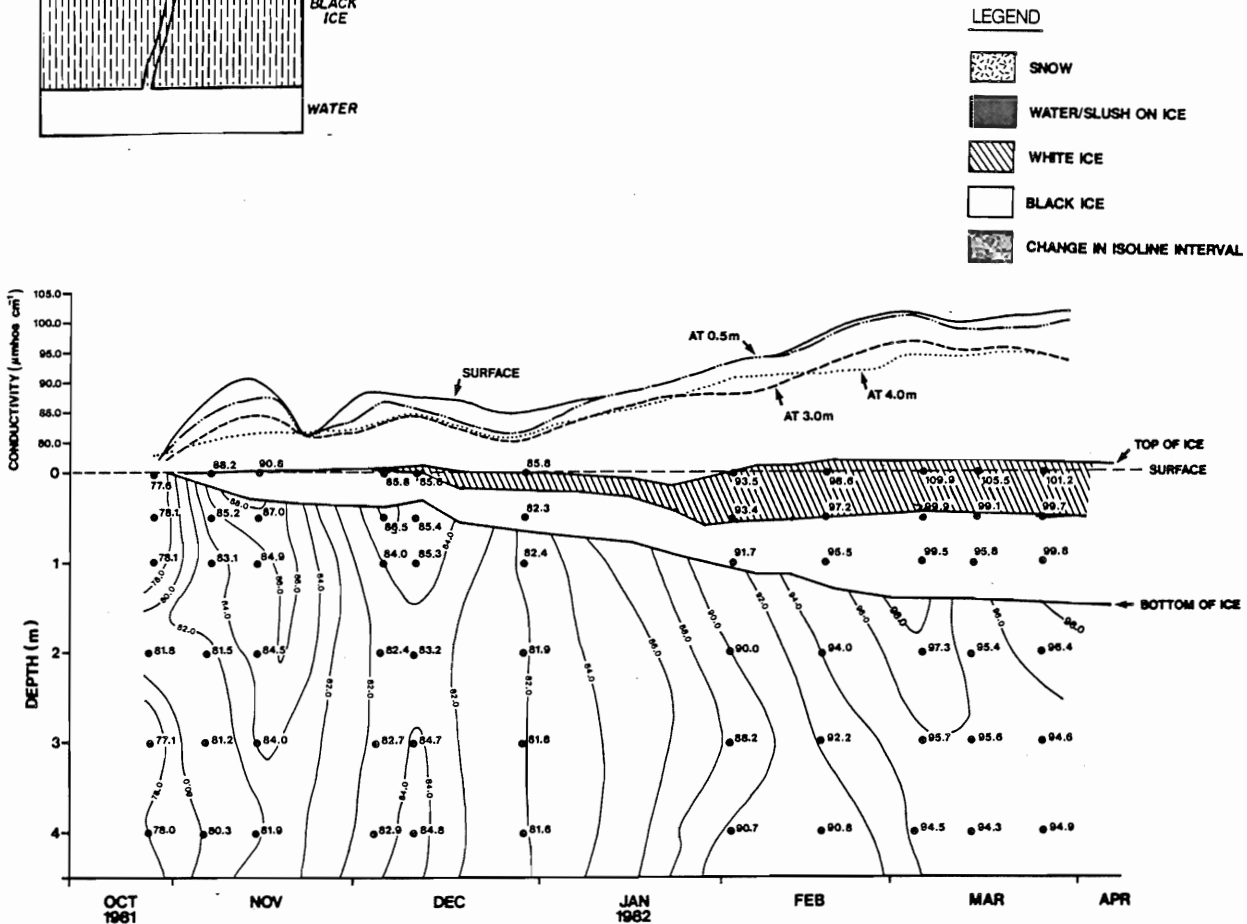


Figure 1. Formation of white ice by slushing from below (see Shaw 1965) Black ice (frozen lake water) has low ion concentrations of ions derived from ion-rich sub-ice water and from the snow. Because of the capillary effect shown, snow remaining after a white ice event will contain traces of lake-derived ions. During melt, each of the layers will have a different impact on the lake, in terms of ion inputs. It should be noted that white ice produced from snowmelt, rain or land runoff on ice, rather than from lake water as envisaged here, will have different ion concentrations than those envisaged here (see, for example, Kingsbury et al. 1984).

Figure 2. (below) Knob Lake, Quebec (55°N, 67°W, 11 ha), a winter of high snowfall and thick white ice. Note conductivities for various depths plotted at top of diagram (see Adams and Lasenby, 1985).



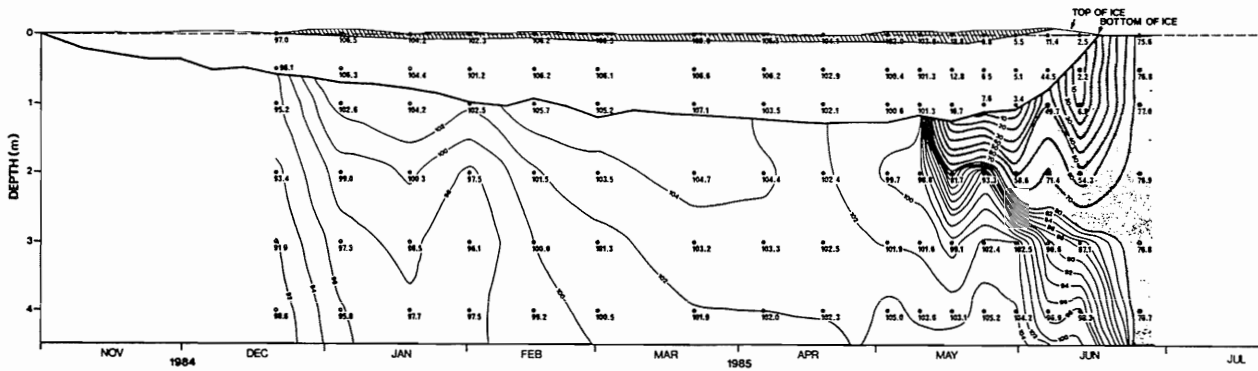
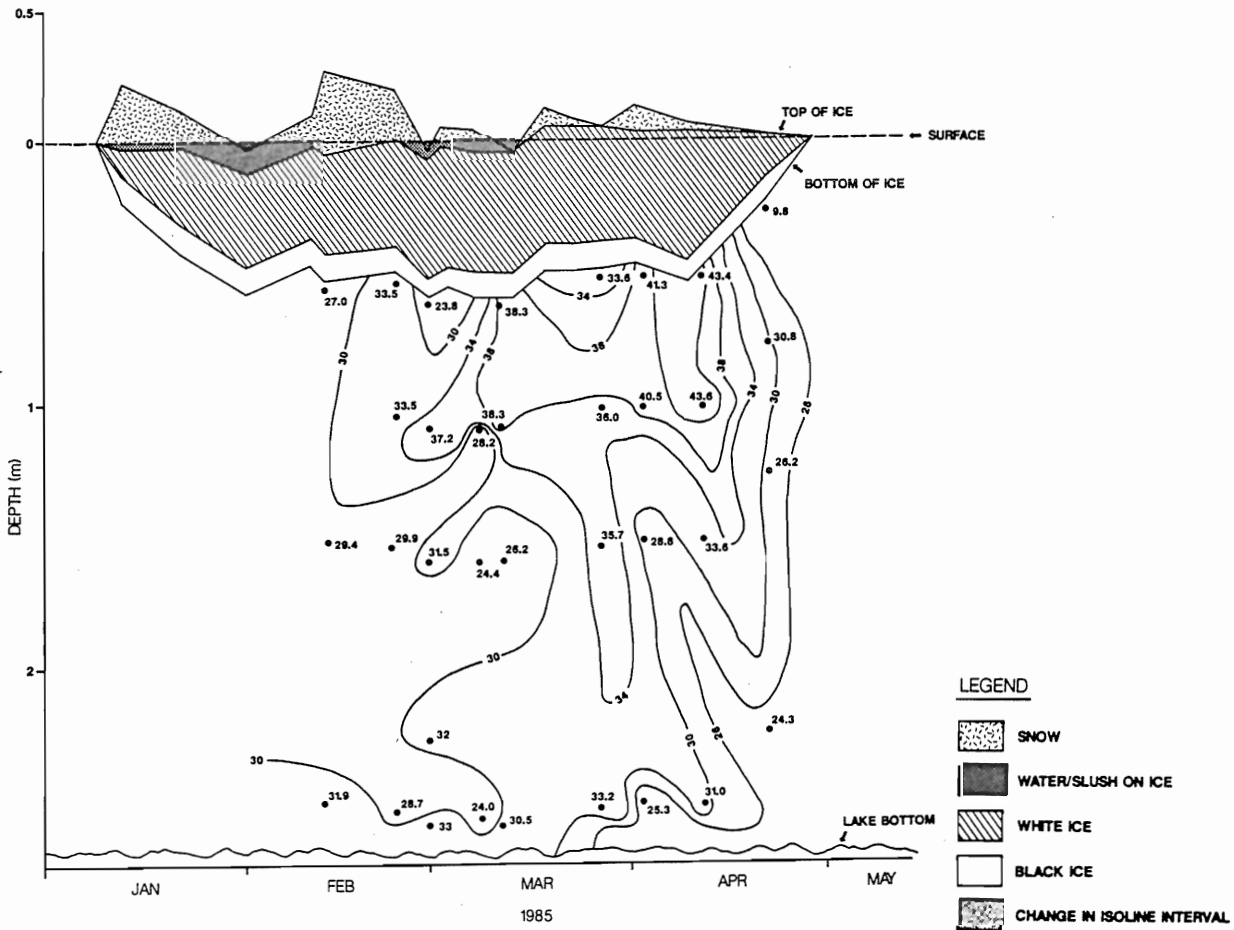


Figure 3. Knob Lake, Quebec, a winter of low snowfall and thin white ice. Conductivities generally higher than Figure 2, a steady rise in values during ice growth. Note pronounced diluting effect as ice sheet melts (see Doran, 1986).

Figure 4. Plastic Lake, Ontario (45°N, 78°W, 32 ha), a short, relatively warm, winter with periodic melting and rain. Note relatively slight rise in conductivities as winter proceeds with slight peak immediately under the ice. Periodic reductions result from snowmelt and rain penetrating the ice cover (see Allan 1986).



associated exsolution. The periodic reductions can be related to losses during slushing phases. It is notable that changes do occur throughout the water column, not only just beneath the ice. This reflects the fact that ion concentrations are affected by things other than ice growth (e.g. water-sediment exchanges) and that there is circulation of water (and ions) in the relatively stratified water column beneath the ice (Schindler et al 1974, Welch and Bergmann 1985).

Figure 3 shows the same lake in a winter of unusually low snowfall and white ice growth. For this winter, the lake was more akin to lakes in the high arctic than to lakes in the snowy subarctic. In this case, conductivities were generally higher than in Figure 2, with a steady increase in values as black ice thickened. Again, the immediate sub-ice layer has peak values but in this case there are no periodic reductions. This diagram shows the melt phase in some detail (see Doran 1986). Although, of course, meltwater from land snow plays an important role, the dramatic dilution of the water column as the thick, "pure", black ice sheet melted is clearly apparent.

Figure 4 shows a lake in a cold temperate region where snow and white ice dominate in the winter cover. This cover developed in a short winter in which there were occasional snow melts and rainfall. For much of its life, the cover had slush on it. It should be noted that an ice sheet with slush above and water below has a 0°C temperature gradient so that it ceases to grow. At such times, the sheet may even become thinner.

In this diagram, there is a modest increase in conductivity as the ice sheet develops, with a slight peak immediately beneath the ice. There are periodic reductions of conductivity which are associated not so much with slushing but with the penetration of rain and/or snow meltwater into the lake. These inputs may have been through cracks or other apertures in the ice but more likely they reflect penetration via a relatively permeable icesheet, isothermal at 0°C (Brownman 1974, see also Jones and Ouellet, 1983).

One purpose for presenting these illustrations of the evolution of lake conductivity regimes under diverse snow and ice covers is to draw attention to the importance of detailed winter cover observations in limnology. Full appreciation of winter limnological processes is not possible from perfunctory and simplistic observation of the cover which is such a dominant control of them.

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