Some Illustrations of Roles of Lake Ice In Limnology

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INTRODUCTION

For a number of reasons, Colour Lake, Axel Heiberg Island (see, Table 1) provides an excellent basis for clear illustrations of roles of ice cover in limnology. One of these is that water in the lake is very distinct chemically from most of the water produced by the lake catchment (Adams and Allan, 1987; English *et al.*, 1991). For example, it has a higher conductance (ca. 700 μS cm^{-1}) and a lower pH (3.8) relative to snow meltwater inputs (ca. 60 μS cm^{-1} and pH 6.5). This difference allows tracking of water within the lake system. Also, for a high arctic lake, Colour Lake has an unusually detailed ice-cover record as well as a record of water column conditions.

The purpose of this paper is to present graphic illustrations of ice-water interactions as an aid to understanding processes in high arctic lakes. The illustrations are also relevant for high latitude lakes in Antarctica where the suite of ice cover situations includes numerous perennially ice covered lakes (e.g., Wharton *et al.*, 1991).

A. ICE COVER AND SPRING MELT

The ice covers of lakes in the high arctic can be more than 2m thick in the spring. As a result, even where the ice is not aground, the ice covers are in contact with a considerable proportion of the lake sides which are in permafrost. When melt begins, doming in the centre of the lake and thermal erosion around the margins (Heron, 1985) combined with the firm seal between ice cover and lake sides causes a marginal moat to develop. Initially, this moat is entirely on the ice surface.

Table 1. Morphometric Values For Colour Lake

Geographical Location	79° 25'N 90° 45'W
Height above Sea Level	176 m
Maximum Effective Length	650 m
Maximum Effective Width	220 m
Surface Area	102,070 m^2
Mean Width	157 m
Shoreline Length	1500 m
Volume	1,034,570 m^3
Maximum Depth	24.0 m
Mean Depth	10.1 m
Drainage Basin Area (incl. lake)	0.80 km^2
Drainage Basin Area (excl. lake)	0.79 km^2

Figure 1a shows such a moat for Colour Lake. It is this moat, rather than the unfrozen water body beneath the ice, which is the initial recipient of meltwater inputs. Figure 1b (from Allan, 1986) provides velocity values and measures of the chemistry of water in one year's moat. Moat development is one of the reasons for the distinctiveness of high arctic lakes like Colour Lake from water in their catchments. During the early melt, the unfrozen lake is simply not interacting with its catchment, at least in terms of the water which passes through the surface ice moat.

As melt continues, the ice moat widens and deepens and becomes connected to the water column under the ice. Interaction between catchment meltwater and unfrozen lake water body then begins. Initially however, the presence of the ice, between the lake and the turbulent atmosphere, greatly inhibits widespread circulation in the lake. Thus, the cold, low-density meltwater remains separate from the main body of the lake displacing lake water near the sides (Fig. 2a). In a sense, at this stage, the moat has become a shore lead. Then, the incoming meltwater spreads out towards the centre of the lake, under the ice but still above the original water column (Fig. 2b). Ultimately, this produces the situation shown schematically in Fig. 3 (Schindler *et al.*, 1974). At this stage, land meltwater passes under the ice but over the underlying water column to the outlet almost as though it was still on top of the ice (e.g. Buttle and Fraser, 1992). As the ice covers of high arctic lakes persist well into the summer, and in some

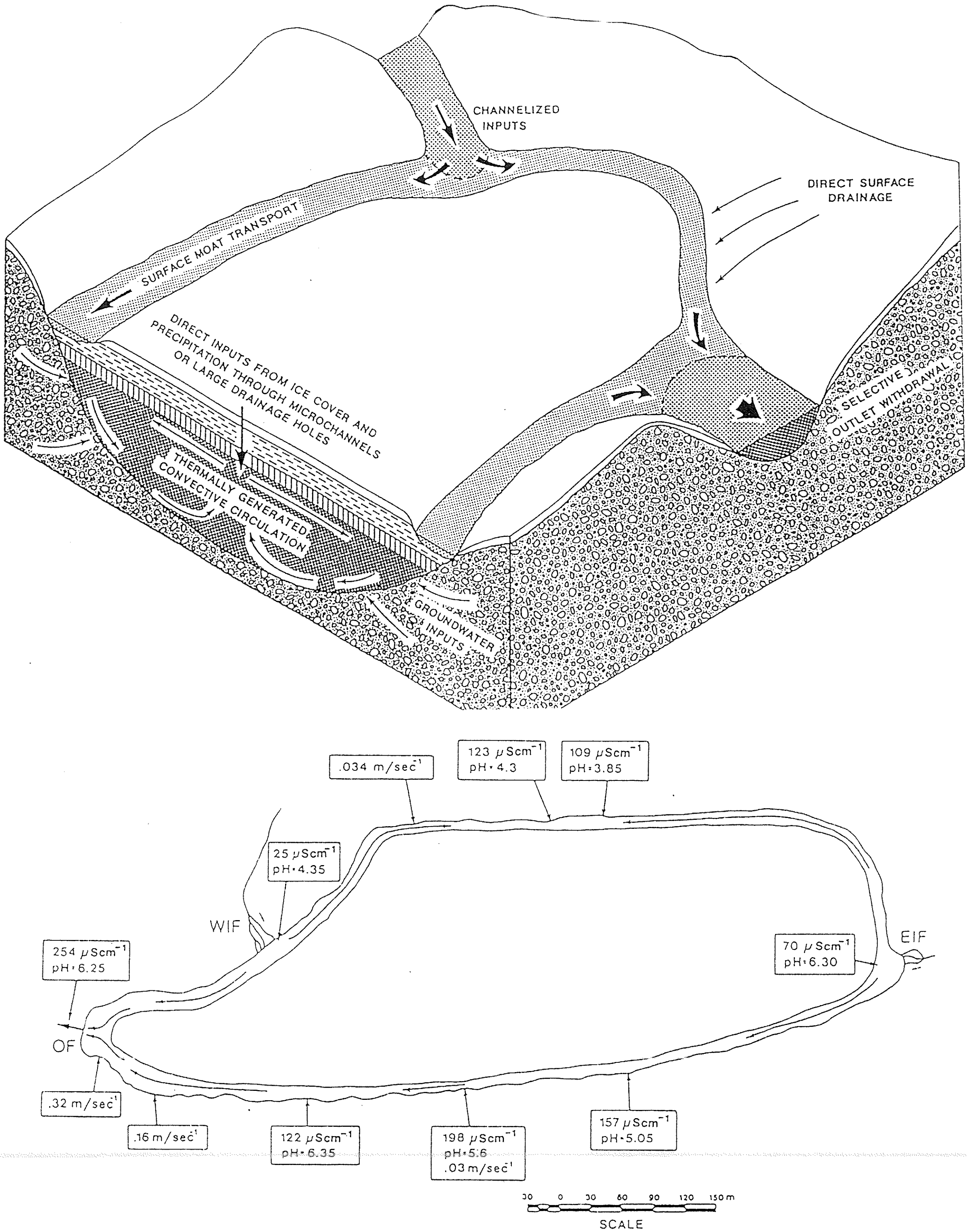
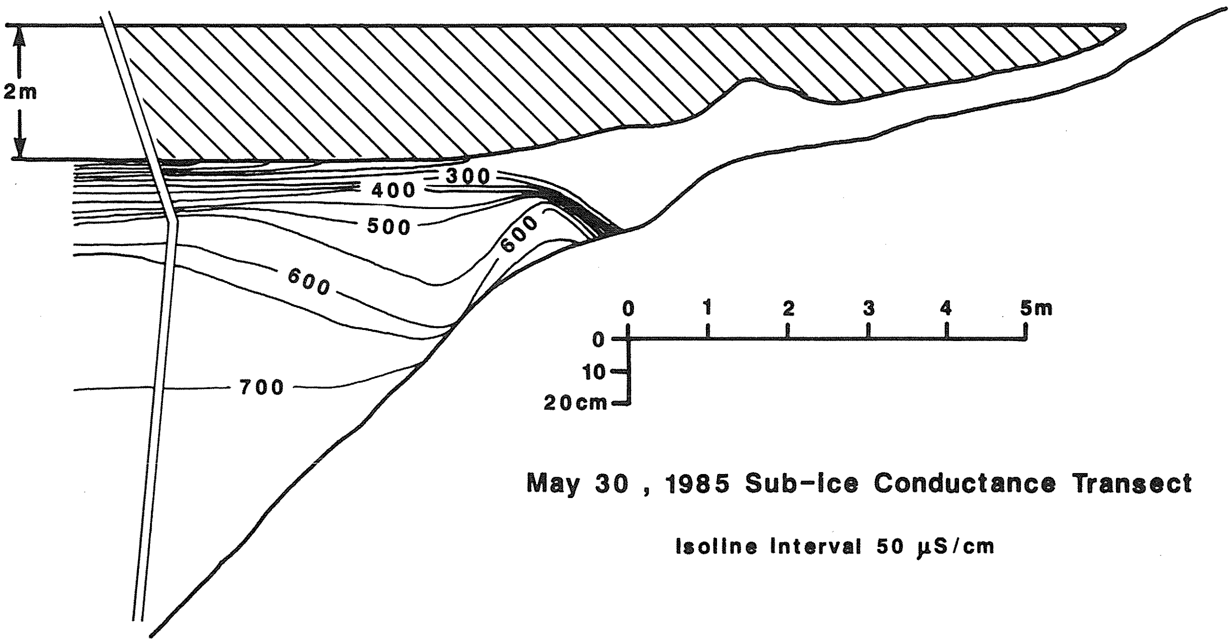
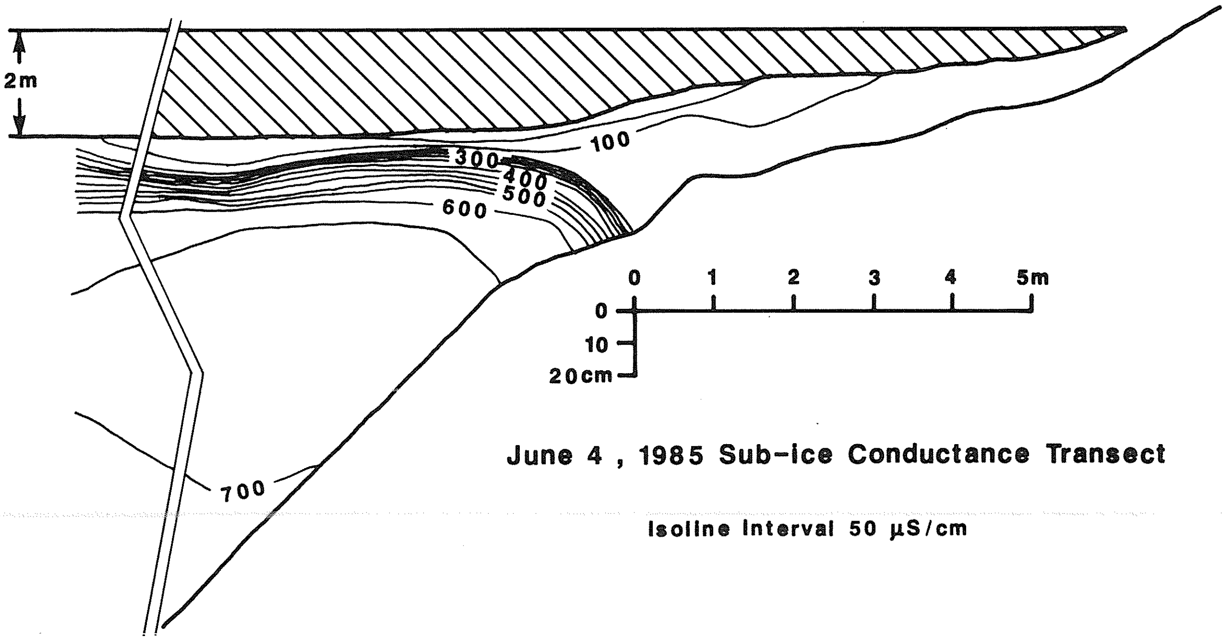


Fig. 1a. & 1b. *Fig. 1a (top) shows meltwater pathways through an ice-covered lake. Fig. 1b (below) depicts an ice moat on Colour Lake with the travel time from EIF (East Inflow) to OF (Outflow) approximately 6 hours. Various chemical parameters are shown at specific locations as are flow velocities. WIF is another inflow. (After Allan, 1986)*



May 30 , 1985 Sub-Ice Conductance Transect

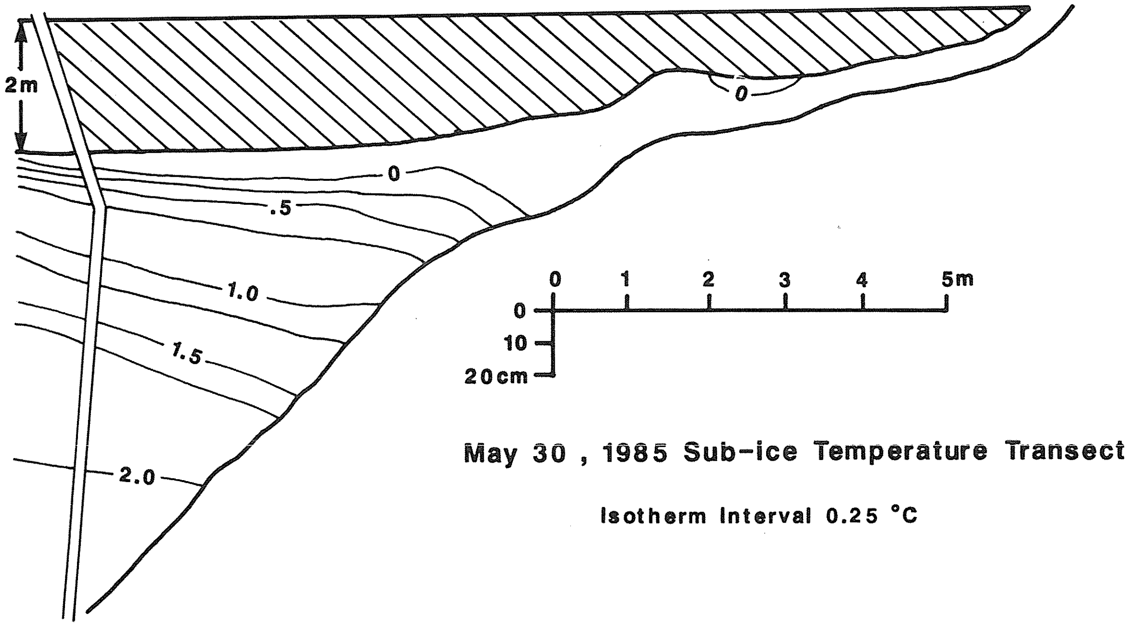
Isoline Interval 50 µS/cm



June 4 , 1985 Sub-Ice Conductance Transect

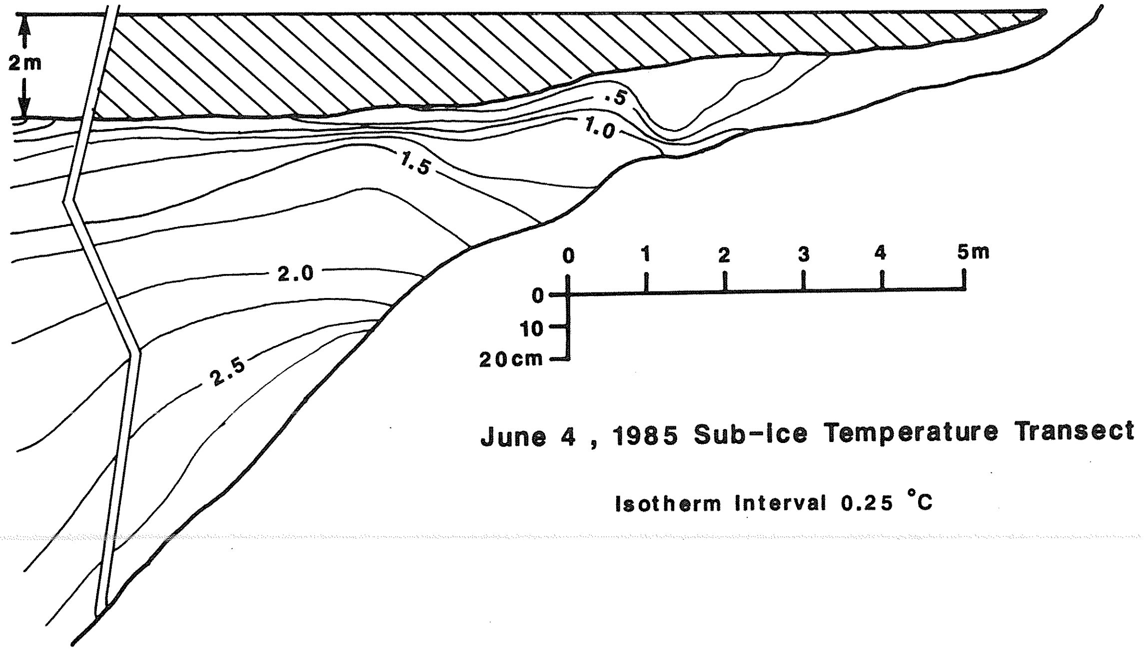
Isoline Interval 50 µS/cm

Fig. 2a. Nearshore conductance transects - landmelt displaces lake water and "layers out" under the ice, over the water column. (After Allan, 1986)



May 30 , 1985 Sub-ice Temperature Transect

Isotherm Interval 0.25 °C



June 4 , 1985 Sub-Ice Temperature Transect

Isotherm Interval 0.25 °C

Fig. 2b. Same location and dates as Fig 2a. Cold, low density meltwater "layers out" under the ice. Signs of warming and sinking on 4 June. (After Allan, 1986)

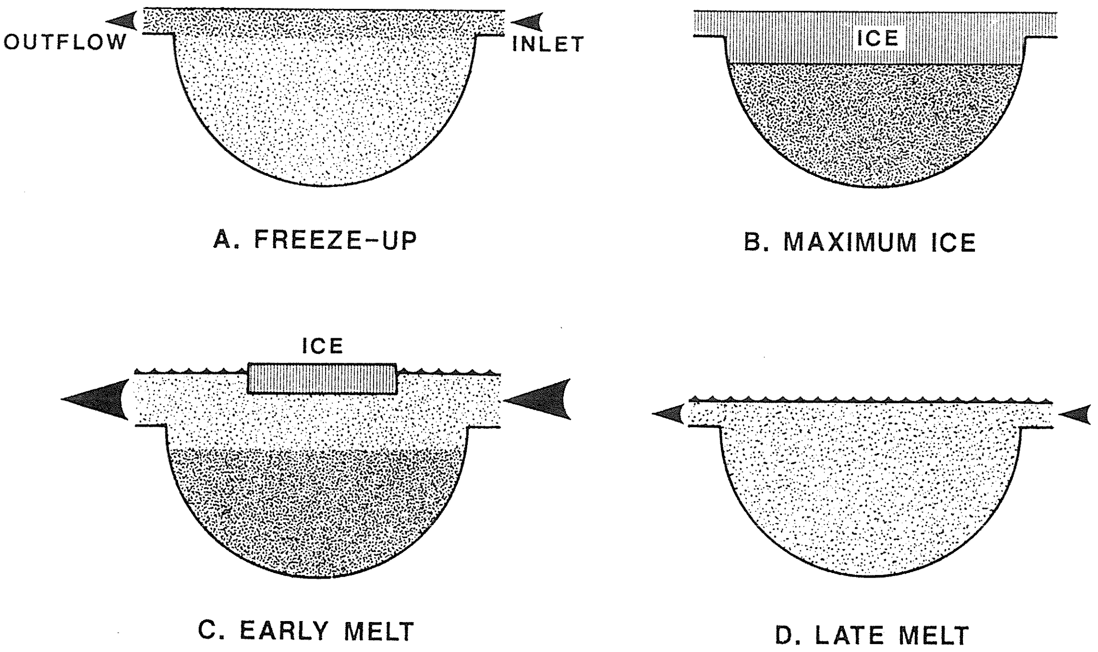


Fig.3. Ice cover limits lake-atmosphere interactions by cutting off the unfrozen water column from atmospheric turbulence. Most years, high arctic lakes circulate during a short ice-free season as is shown in this schema of the annual cycle. (After Schindler et al., 1974)

years all summer (see below), they rather effectively isolate lakes from their catchment even though there is some sub-ice circulation.

A variant of the above occurs when all or part of the ice cover becomes flooded during the early melt. Then, if holes or fissures develop, turbulent vertical streams of cold, dilute meltwater can penetrate to great depths in the otherwise stratified lake. This is illustrated in Fig. 4. Calculations of the head developed by such water on a thick ice sheet are given in Adams and Allan, 1987. This is a short-lived (1-2 days) condition following which the lake re-stratifies.

The references mentioned in this section and Welch (1991) provide useful quantitative illustrations of ice-meltwater interactions.

B. PRESENCE/ABSENCE LAKE ICE, WATER CIRCULATION AND TEMPERATURE

The growth and decay of an ice cover greatly influence the chemical and physical properties of high arctic lakes (Adams and Allan, 1987; Welch, 1991). These properties affect circulation in the lake and are affected by it. One of the most important ways which the ice cover controls circulation is protecting the unfrozen water body from the turbulent atmosphere. This helps preserve the quite fragile temperature and chemical profiles in the unfrozen water column.

In most high arctic lakes, most years, the gradual extension of interaction between catchment (and atmosphere) and unfrozen lake, described above, culminates at the end of a short ice-free season. At this time, wind-induced turbulence usually causes vertical mixing and lake turnover. This is implicit in stage D of the schematic series shown in Fig. 3.

Ramifications of the presence/absence of ice cover in late summer can be illustrated from observations on Colour Lake during years in which the ice cover did **not** completely melt at the end of the summer. Figure 5 shows water column temperature profiles for springs following summers in which the lake became ice-free (as envisaged in Fig. 3) and for springs following summers in which the lake remained ice-covered. The latter, "residual ice" years, were appreciably warmer. One of the effects of the turnover of a lake in the short ice-free season of the high arctic is a cooling of the water body through contact with the atmosphere. Such turnover and associated large-scale cooling does not

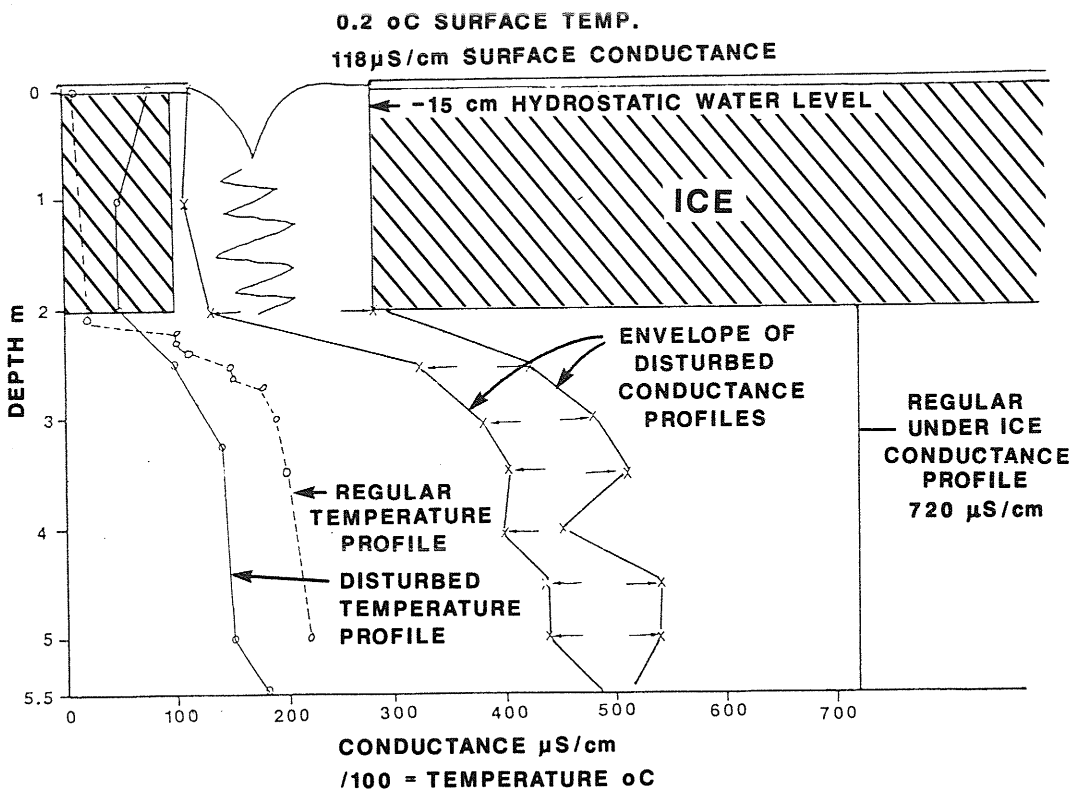


Fig. 4. Effect of Waterhole Vortex on Conductance and Temperature Profiles, May 27, 1985. (After Allan, 1986)

occur in residual ice years.

Retention of an ice cover through one summer results in the development of a very distinctive "residual" cover during the following winter (e.g., Fig. 6). This affects exsolution of solids and gases from the ice into the lake which in turn affects lake stratification and other aspects of ice-water interaction (Adams *et al.*, 1989).

CONCLUDING REMARKS

The growth and decay of an ice cover has important implications for chemical, physical, hydrological and biological processes in a lake. In polar regions, where ice covers are thick and persistent, these implications are more obvious than in lakes at lower altitudes. The unusual chemistry of Colour Lake, Axel Heiberg Island has the effect of highlighting some of the implications even further. We hope that the illustrations provided in this paper will draw the attention of researchers on other lakes to the importance of ice cover in limnology.

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REFERENCES

Adams, W.P. and C. Allan, 1987. Aspects of the chemistry of ice, notably snow, on lakes. In: Seasonal Snowcovers: Physics, Chemistry, Hydrology (H.G.Jones and W.J.Orville- Thomas, eds.), NATO ASI Series C: Mathematical and Physical Sciences, Reidel Publishing, Vol.211, 393-466.

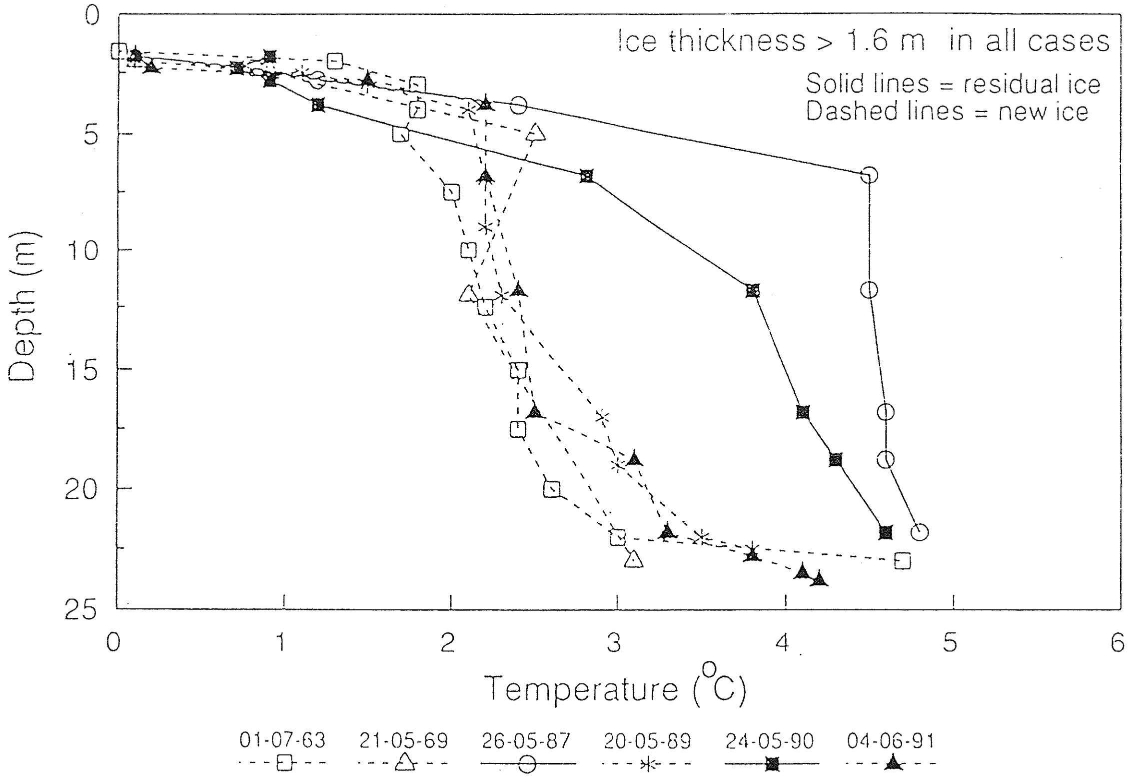

Fig. 5. Water temperatures, Colour Lake. "Residual ice" years, those following summers when the lake did NOT become ice-free, were warm. (After Doran et al., 1993)

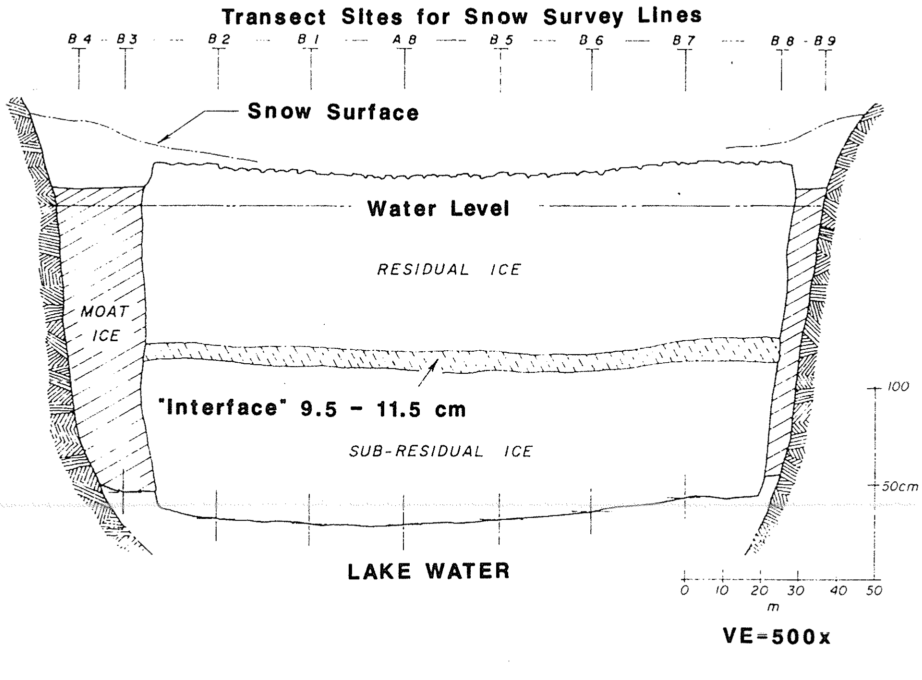

Fig. 6. Retention of ice through one summer also results in a distinctive cover the next year. This has implications for the "direct inputs" and "thermally-generated circulation" aspects of ice-water interactions mentioned in Fig. 1a.

Adams, W.P., P.T. Doran, M. Ecclestone, C.M. Kingsbury, C.J. Allan, 1989. Observations of a rare second-year lake ice cover in the Canadian high arctic. Arctic, 42, 4, 299-306.

Allan, C., 1986. Observations of the role of snow and ice on the chemistry of an arctic lake. Proc. Eastern Snow Conference, 43, 123-138.

Buttle, J. and K.Fraser, 1991. Hydrochemical fluxes in a high arctic wetland basin during spring snowmelt. Arctic and Alpine Research, 24, 2, 153-164.

Doran, P.T., W.P. Adams, M. English, 1992. Thermal impact of residual ice covers on a high arctic lake (in prep.).

English,M., S.Schiff, M. Ecclestone, W.P. Adams, M. Hinton, L. Pezzutto, R. Elgood, C. Allan and D. Pierson, 1991. Seasonal changes in the hydrochemistry of land drainage: Colour Lake catchment, Axel Heiberg Island, NWT. Proc. Northern Hydrology Symp., NHRI Symposium Series 7, Saskatoon, Saskatchewan, 75-88.

Heron R., 1985. Decay of a high arctic lake ice cover. Ph.D.thesis, McMaster University, Hamilton, Ontario, 189p.

Schindler,D.W., H.E. Welch, J. Kalff, G.J. Brunskill and N. Kritsch, 1974. Physical and chemical limnology of Char Lake, Cornwallis Island(75° N). J. Fisheries Research Board of Canada, 31, 585-607.

Welch, H.R., 1991. Comparisons between lakes and seas during the arctic winter. Arctic and Alpine Research, 23, 1, 11-23.

Wharton, R.A., C.P.McKay, G.D. Clow and D.T. Andersen, 1991. Perennial ice covers and their influence on Antarctic lake ecosystems. In: Lakes of the McMurdo Dry Valleys (W.Green and E.I.Friedmann,eds.). Antarctic Research Series, American Geophysical Union, 1-30.