LAKE ICE FORMATION AS INFLUENCED BY AIR-WATER ENERGY EXCHANGES

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Abstract

Detailed surface radiation and energy balance measurements as well as ambient air and water temperature measurements at several depths were carried out for a small lake in the lower Laurentiens Québec. Measurements were conducted over a five-day period during the fall of 1980 which coincided with the period of the first occurence of ice. The results show that ambient air temperature rather than radiative and turbulent heat exchanges is the dominant factor in lake ice formation.

Introduction

The freezing of lake water at the surface is largely controlled by heat exchange with the atmosphere and the water beneath (Singh, 1973). The heat budget approach then is a convenient and plausible method of explaining and predicting lake ice formation. This approach has been exploited with varying degrees of success in the past (Scott and Ragotzkie 1961, Marcotte, 1974, Tvede 1978). In this study we have attempted to adopt a similar approach with a lot more emphasis being placed on the actual measurement of the basic parameters that influence the thermal regime of the lake.

With the ever increasing use of lakes for recreational purposes, especially for the lower Laurentiens which lies just outside the large metropolis of Montreal, the availibility of this type of information that we expect to provide, becomes all the more important. Besides the study is meant to examine the thermal regime of a small medium-depth lake typical of the hundreds that are found in this area, an aspect which has been neglected thus far. In addition we hope to rekindle renewed interest in a subject that has been on the scientific back burner for a while.

The results which we present in this paper apply to first freeze-up or first appearance of ice crystals on the water surface for the season. This definition varies from that of "first permanent ice" (Allen and Curbird, 1971) which relates to ice once having formed never melted until the next break-up period.

Site, Instruments and Methods

The lake chosen for our study, Lac Croche, is situated in the lower Laurentiens in the township of St-Hippolyte (45°59'N; 79°01'W) which lies about 125 km to the north of Montreal. This particular lake was chosen because of the availibility of support facilities such as power and laboratory space provided by the Biology Research Station of the University of Montreal. The lake is typical of the majority of the hundreds of lakes in the region. It is of structural origin as evidenced by its steep and rocky embankments. It lies at an altitude of about 350 m above sea level and it is surrounded by hilly terrain that rise to 450 m in places. The lake is horse-shoe shaped and has a surficial area of 50,360 square metres. Its average depth is about 4.5 m, with the maximum depth attaining about 11.5 m.

The heat budget approach essentially calls for measurements or estimates of the components of the radiation and energy balances. The radiation balance, using conventional terminology, may be expressed as:

$$Rn = (Q + q) \quad (1 - \alpha) + L\downarrow - L\uparrow \qquad (1)$$

where

Rn = the net radiation of the lake surface ($mwcm^{-2}$)

$Q + q$ = global incoming solar radiation ($mwcm^{-2}$)

α = the allbedo of the lake surface (water ice or snow)

$L\downarrow$ = atmospheric long-wave radiation ($mwcm^{-2}$)

$L\uparrow$ = lake surface long-wave radiation ($mwcm^{-2}$)

The energy balance on the other hand can be written as:

$$Rn = LE + H + G \qquad (2)$$

where

LE = latent heat of evaporation (water) or sublimation (snow and ice) over the lake ($mwcm^{-2}$)

H = sensible heat transfer over the lake ($mw\ cm^{-2}$)

G = the conduction of heat into (+) or out of the lake (-) ($mw\ cm^{-2}$)

All the components of the radiation balance except L↓ were measured directly. Global radiation was measured by a frosted dome solariameter which sensed in the wavelength range 0.3 u to 3.0 u. A similar instrument whose sensor faced the surface was used to measure albedo (α). The lake surface long-wave radiation (L↑) was measured by a Swisteco type unidirectional net radiometer. Net radiation was also measured by a Swisteco type net radiometer. The atmospheric counter infra-red radiation (L↓) was calculated as a residual.

As for the components of the energy balance, net radiation (Rn) was measured directly as described above. So was the flux of heat (G) into or out of the water by means of thermopile plates placed near the surface. The latent heat flux (LE) was estimated by means of the equilibrium version of the combination model written as

$$LE = \alpha' \frac{S\ (Rn - G)}{S + \gamma} \qquad (3)$$

where

α' = an empirical coefficient whose value as used here is 1.26

S = the slope of the saturation vapour pressure curve over water or ice as the case may be ($mb^{o}C^{-1}$)

γ = the psychrometric constant whose value as used here is 0.66 ($mb^{o}C^{-1}$)

The value of 1.26 for α' is supposed to represent potential or free-water conditions as found by Petzold (1980), Stewart and Rouse (1977), and Davies and Allen (1973). The remaining term H was calculated as a residual, exploiting equation (2).

The instruments used to measure the parameters listed above were mounted on a tower which was stationed towards the middle of the lake where it was deepest and which was stabilized by means of a series of anchors and buoys.

At the same time the thermal profile of the lake was measured by means of thermocouples placed at depths of a few centimeters beneath the water surface, at 0.5 m, at 1.5 m, at 5.5 m and at 10 m which depth was close to the depth of the lake at this point. All signals were led back to the laboratory where they were monitored on an interval basis by means of a Fluke 2240B datalogger.

Results

The results that we present here are preliminary and somewhat tentative. As mentioned previously they relate to the period of initial freeze-up or the first appearance of ice for the lake in question. Measurements of selected components of the radiation and energy balances, as they relate to the thermal regime of the lake, especially near the surface, are first examined on a daily basis. These measurements are then juxtaposed so as to more clearly identify trends and the factors that correlate with near-surface water temperature.

Observations relating to the first episode of freeze-up were started early afternoon, November 2, 1980. This period of the day was characterized by sunny skies and extremely calm wind conditions, following the passage of a weak cold front the night before. Air temperature had fallen below the freezing point following the influx of cold air, earlier in the day. This falling off of air temperature was however somewhat moderated during the day in the presence of solar radiation reception ($Q+q$) and absorption (Rn) which allowed for some turbulent heat transfer to the ambiant air (H) in that the greater part of Rn is utilised for H when air and surface temperature are near freezing.

Nonetheless by early afternoon, ambient air temperature had peaked at around 1500 hrs (-1°C), and after which time, with the decline in solar radiation receipt ($Q+q$) and absorption (Rn), turbulent heat transfer (H) and subsequently air temperature plumetted to around -8°C during the night (see Fig. 1 a and 1 b). These factors led to the gradual decline in the lake water temperature near the surface though this decline was somewhat compensated for by the weak conduction of heat from within the lake (-G) and weak turbulent exchange with the ambient air (-H and -LE) with subsequent freezing occuring at around 1900 hrs. Accepting that the extent of supercooling before the formation of ice crystals is between -0.01°C (Schaefer) and -1.2°C (Rymsha and Donchenko) we would expect that skim ice would have appeared at the surface of the lake during the night since a thin layer of skim ice was visible the next morning. This would suggest that the degree of supercooling here is less than -1°C, the lowest temperature attained. This loss of heat which leads to freezing is well reflected in the behavior of the fluxes of $L\uparrow$ and G. With the decline in surface temperature, $L\uparrow$ declined correspondingly, but substantial radiative heat loss ($L\uparrow$) in the presence of cloudless skies led to further cooling at the surface. This cooling at the surface finally led to the flux of G becoming negative during the night with the result that surface cooling was somewhat moderated by the release of heat from the warmer water beneath. The fluctuation in G is most probably related to the release of latent heat of fusion upon freezing.

The temperature of the water at depth however (1.5 m to 10 m) seems to be quite stable and isothermal, since with temperature values near 5°C (above 4°C), overturning due to temperautre and hence density changes do not occur. Slight temperature fluctuations at 1.5 m and even 5.5 m are however observable and this is very likely attributable to heat loss near the surface and subsequent shallow overturning, or to lateral flow.

The next day, november 3, there was a return to warmer air temperatures with a rapid rise from -8°C at 800 hr to about 0.5°C at 1300 hr (see Fig. 2 b). This temperature

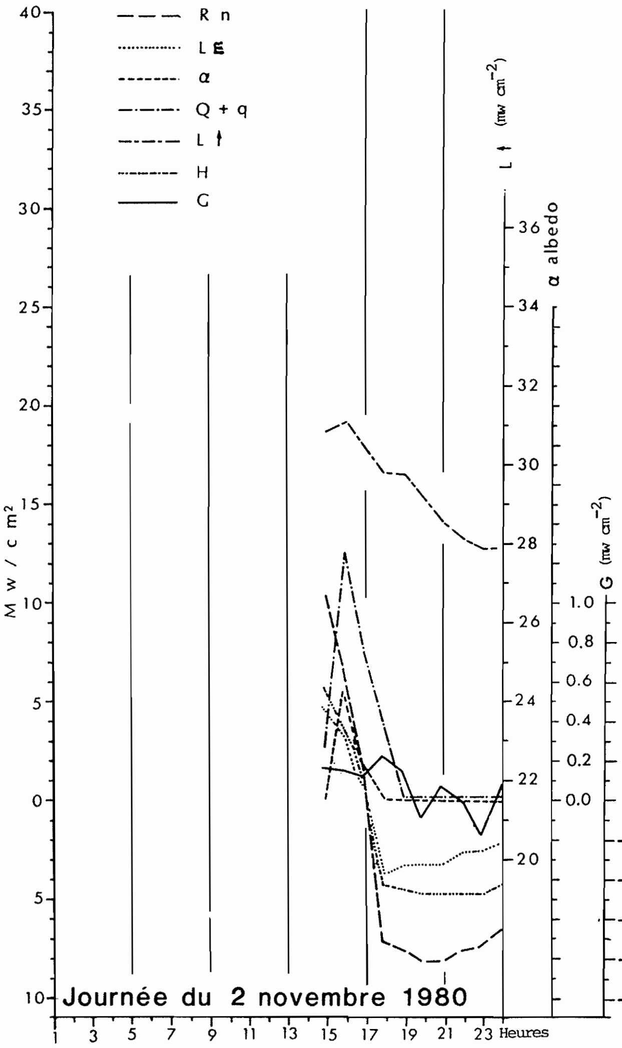

Fig. 1 a: Radiation and energy balance parameters. Nov. 2, 1980.

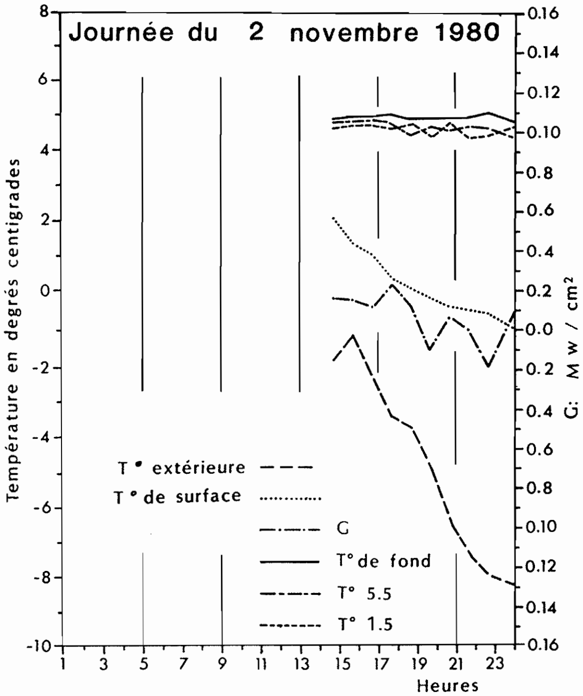

Fig. 1 b: Thermal regime of lake, november 2, 1980.

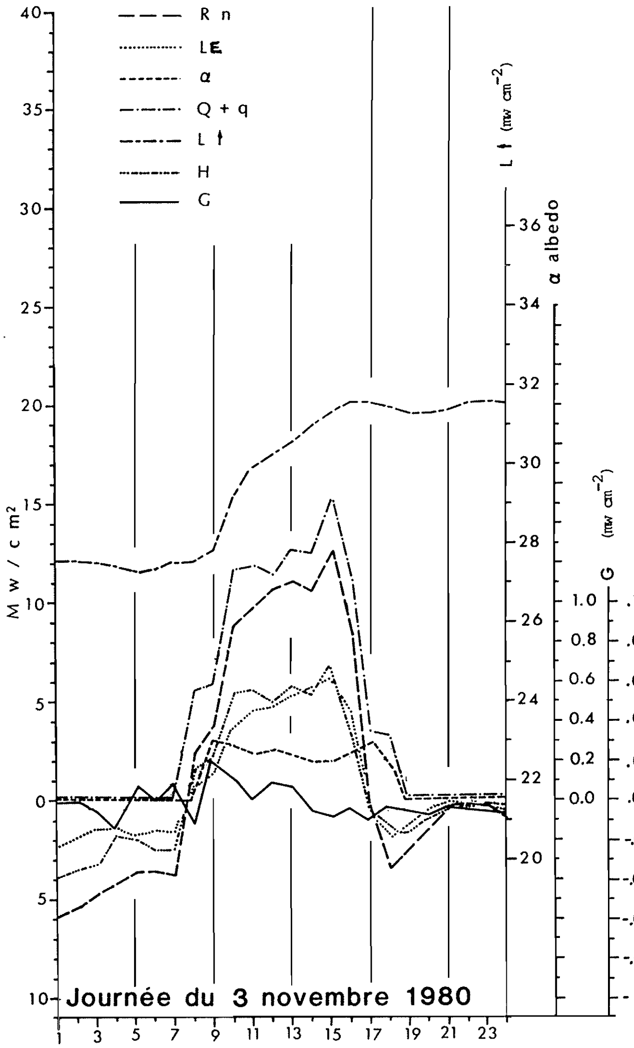

Fig. 2a: Radiation and energy balance parameters, november 3, 1980.

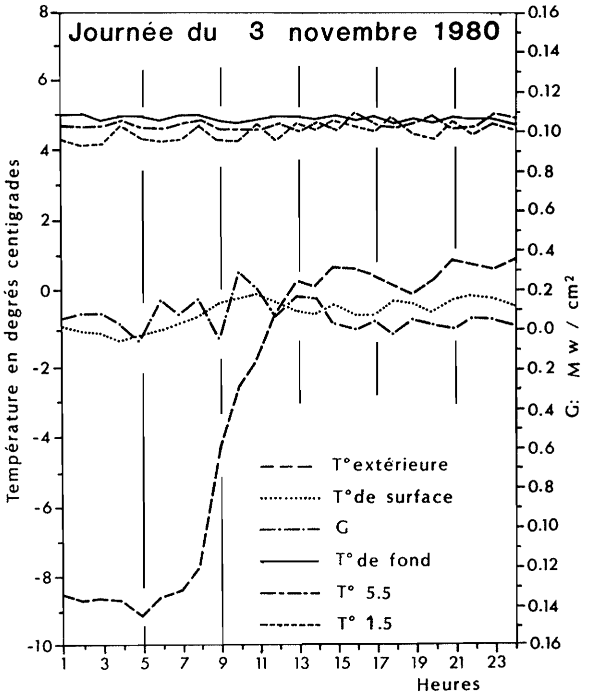

Fig. 2 b: Thermal regime of lake, november 3, 1980.

rise was mainly due to the advection of a warm south-westerly wind ahead of an advancing warm front and partly to local sensible heat transfer (H). Skies were overcast with thin cloud predominating. The albedo of the frozen water surface is around .20 and most of the absorbed solar radiation is used for sensible (H) and latent heat transfer (LE) (see Fig. 2 a). The high value of H in relation to LE is attributable to the cold air temperatures and the frozen water surface. The result is that the amount of heat conducted into the water body (G) is very weak and its value except for the morning is negative (flux directed towards the surface), because of the temperature gradient between the warmer water beneath and the colder air above. In fact the input of heat at the surface from advective and radiative sources, is lost mainly through long-wave terrestrial radiation ($L\uparrow$) which in return produces very little change in surface temperature.

In view of these factors the water surface remained frozen (see Fig. 2 b) with its temperature fluctuating around -1°C in response to the varying heat additions and losses discussed above. At depth the temperature is still rather stable and isothermal between 5 m and 10 m. But at 1.5 m, there is a fair amount of fluctuation of the temperature which most likely is related to overturning, seeing that the temperature is close to the threshold value of density of 4°C.

The following day, 4 November skies were completely overcast, with thick clouds predominating. As a result, radiative input of energy ($Q+q$) is very weak and whatever energy is abosrbed (Rn) is utilised mainly for turbulent sensible (H) and latent heat (LE) transfer, since the flux of heat into the water (G) fluctuates around zero (see Fig. 3 a). Note that with the increase in air and water temperatures towards the afternoon, the flux of LE exceeds that of H. As a result it is the advective component, as influenced by air mass movement, which plays the major role in determining the temperature of the lake near the surface. There was a light (5 to 8 km/hr) southerly wind on this date and air temperature continued to rise and by early afternoon had reached about 5°C. This caused water temperature to also rise steadily, with somewhat of a lag, and by midday the frozen lake had returned to the liquid state. Note the decrease in albedo (α) from .20 to .15 with the change from ice to water.

It would also seem that the timing of the disappearance of the ice is tied to the circulation within the lake. In the presence of a negative heat regime near the surface, the lake water temperature beneath (1.5 m) continued to decline and by late morning had approached the critical density value of 4°C, at which time an abrupt overturning took place. Water at 1.5 m was replaced by warmer water from beneath and the temperature at this depth quickly rose to about 7°C at midday. This time in fact coincided with the disappearance of the ice at the surface. This overturning also caused water temperature to increase slightly at 5.5 m and water temperature at depth (10 m) to decrease to the maximum density value of around 4°C.

At night despite the absence of solar radiation heat input, air temperature continued to rise due to advection effects, and this kept surface water unfrozen. In fact, surface water temperature continued to rise throughout the night. The abrupt temperature fluctuations which occurred throughout the depth of the lake at around 2000 hrs is most likely attributable to lateral flow.

The following morning (5 November) the skies had cleared with the arrival of a high pressure system. This also brought along with it cooler air temperatures. Radiative input ($Q+q$) and absorption (Rn) were extremely high for this time of year (see fig. 4a) A fair portion of $Q+q$ was reflected (α) near sunrise because of the angle of incidence of the sun's rays. However later in the morning a sizeable amont was absorbed (Rn) when the value of α decreased. Most of this energy was however dissipated through LE and H. Nonetheless a fair amount of this absorbed energy was conducted into the lake (G) and this may have caused the lake surface temperature to decline less slowly than ambient air temperature (see Fig. 4b). The water temperature variations at depth (5.5 m and 10 m) may well again be due to lateral flow.

In plotting the variables examined above over time (1 to 6 November), we observe that surface water temperature does not display the diurnal cyclical variations typical

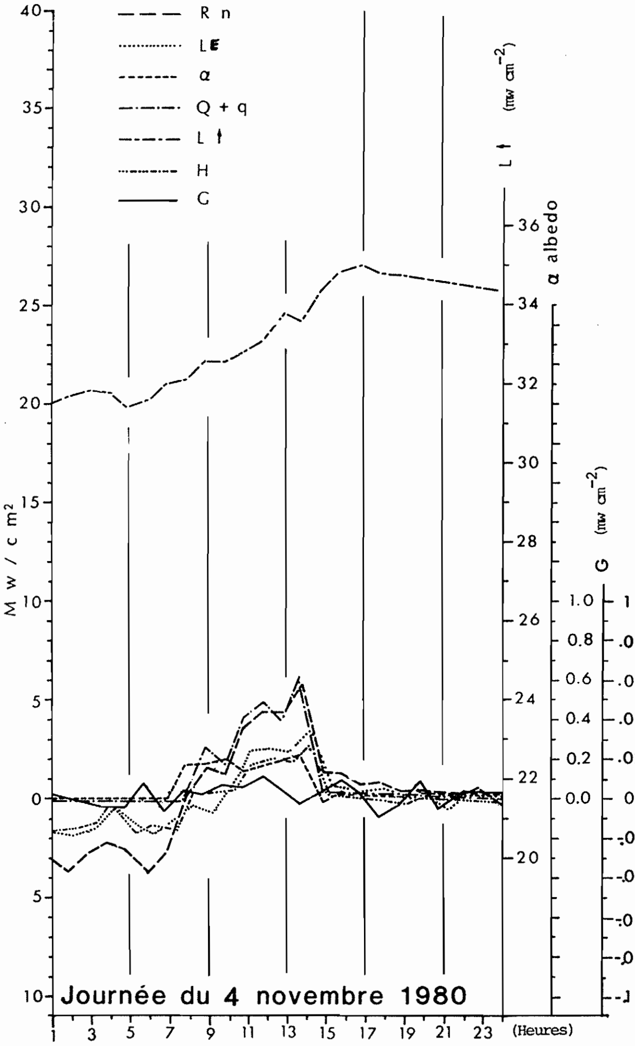

Fig. 3 a: Radiation and energy balance parameters, november 4, 1980.

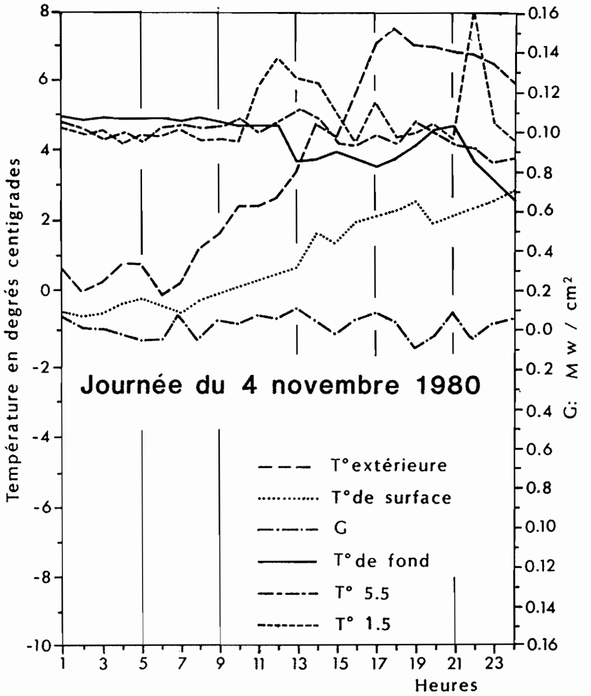

Fig. 3 b: Thermal regime of lake, november 4, 1980.

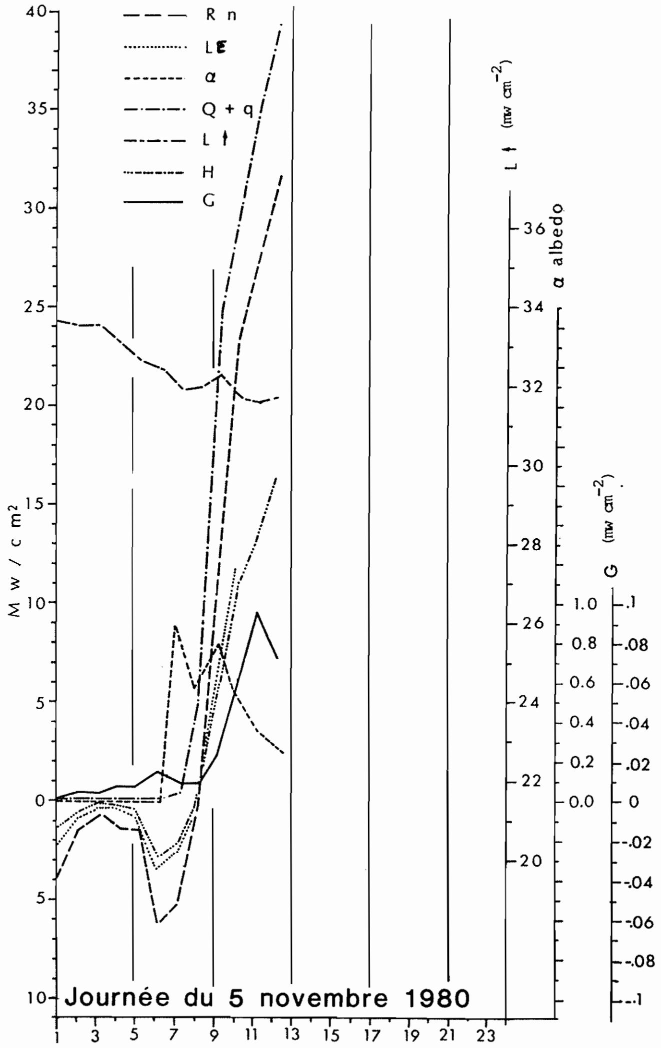

Fig. 4 a: Radiation and energy balance parameters, november 5, 1980.

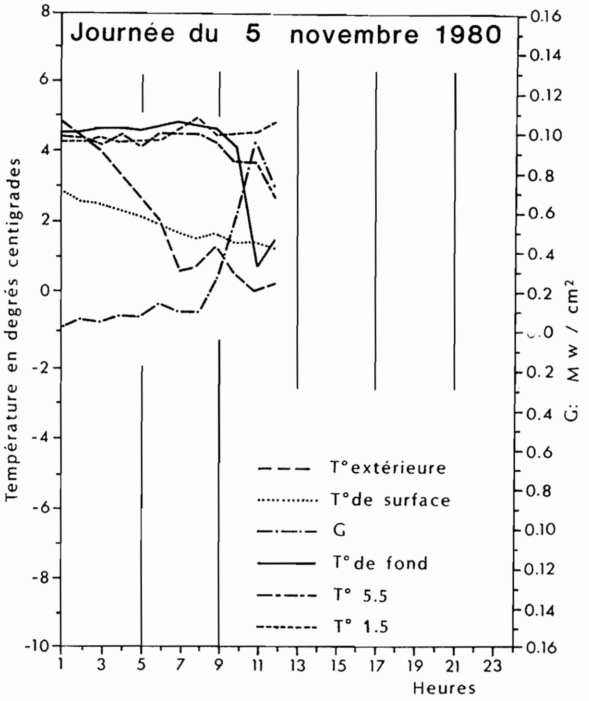

Fig. 4 b: Thermal regime of lake, november 5, 1980.

of radiation receipt $(Q+q)$ and absorption (Rn) and of turbulent heat transfer (H and LE). The only radiative components whose variation follows that of surface water temperature are $L\uparrow$ and G. However in both cases there is a cause and effect ralationship in that surface temperature determines the intensity of $L\uparrow$ as well as that of G through its influence on the magnitude and direction of the temperature differential in the layer of water near the surface $(\Delta T / \Delta Z)$. Therefore the instantaneous values of $(Q+q)$ and Rn would serve as poor predictors of lake ice formation. However their cumulative totals over time can most certainly be used not only in this regard, but also for the prediction of lake ice evolution over the winter.

It would seem then that air temperature is the most likely parameter to be used to predict lake ice formation, at least on an instantaneous basis. Of course this predictive power would increase if air temperature were to be accumulated over time exploiting the degree-day concept (Rodhe, 1952; Bilello, 1964, Mackay, 1960; Spence 1971; Broissia et al 1980).

Summary and Conclusion

It would appear that the climatic parameter that seems to most significantly incluence surface water temperature and hence freeze-up is air temperature, at least for short time intervals. In fact air temperature, whose variation seems most influenced by air mass movements, appears to be the major forcing factor not only with respect to surface water temperature but also with regards to heat conduction into or out of the lake (G) and to long-wave radiative loss and also to the internal circulation within the lake. Radiation receipt $(Q+q)$ and absorption (Rn) though of lesser influence, however seem to mitigate the effect of air temperature in several instances. Predictive models then that consider air temperature and solar radiation variation on a cumulative basis would seem to offer the best possibilities for lake-freeze-up prediction. Other factors such as windiness, that was of little consequence here, may also be important, especially as regards type of ice formed.

Further analyses are at present being conducted to relate the evolution of the winter ice cover with respect to the climatic variables listed above and snowfall. The results of these analyses will be reported in the not too distant future.

Aknowledgements

We would like to thank the Quebec Ministry of Education (FCAC: CAFIR, U. de M.) for its financial support, the personnel at the Biology Station, Université de Montréal. St.Hyppolite for its logistique support and M. Guy Frumignac for the cartographic assistance towards the completion of this report.

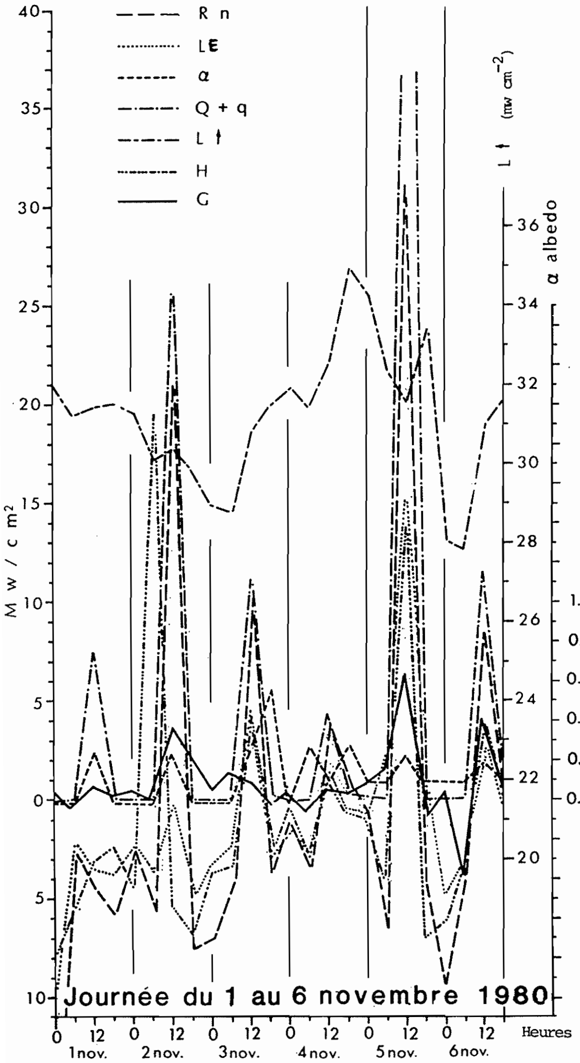

Fig. 5 a: Radiation and energy balance parameters, november 1-6, 1980.

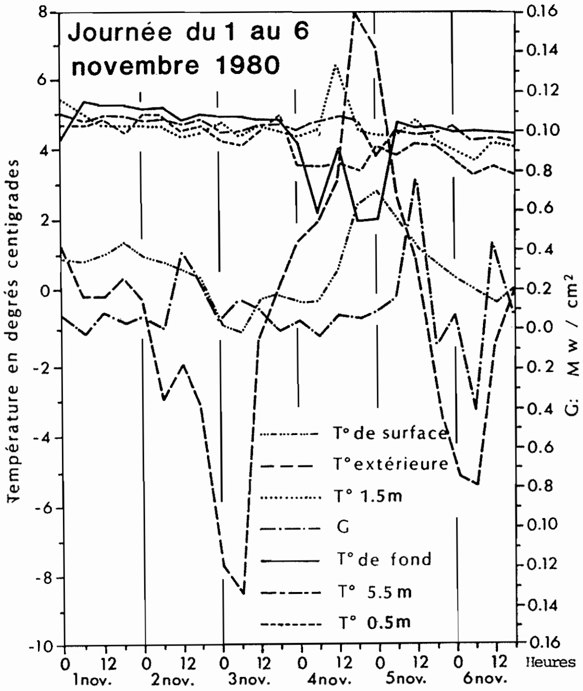

Fig. 5b: Thermal regime of lake, november 1-6, 1980.

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