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WATER TEMPERATURE DURING THE MELTING OF LAKE ICE

BY

G. P. WILLIAMS

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LA TEMPÉRATURE DE L'EAU DURANT LA FONTE DE LA GLACE
SUR LES LACS

SOMMAIRE

La température de l'eau et l'épaisseur de la glace ont été mesurées durant la période de la fonte à Bennett Bay, White Lake, Ontario. Les températures de l'eau se sont élevées jusqu'à 7.5°C. sous la couche de glace fondante. La chaleur requise pour réchauffer l'eau sous la glace et la fondre entre les deux faces glace-eau a été calculée à différentes périodes et comparée avec la chaleur disponible émanant de radiation solaire qui pénétrait la couche de glace. On a conclu de ces calculs que la radiation solaire pénétrant la glace a causé des températures d'eau relativement élevées observées sous la glace fondante.

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Water Temperature during the Melting of Lake Ice

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Abstract. Water temperature and ice thickness were measured during the ice melt period at Bennett Bay, White Lake, Ontario. Water temperatures were as high as 7.5°C under the melting ice cover. The heat needed to warm the water under the ice and to melt ice at the ice-water interface was calculated for different periods and compared with the heat available from solar radiation that penetrated the ice cover. It was concluded from these calculations that solar radiation penetrating the ice caused the relatively high water temperatures observed under the melting ice.

In a recent paper *Bilello* [1968] reported that water temperature underneath the ice cover in a shallow lake decreased substantially during the ice thaw period. In contrast to *Bilello's* observations, water temperature under an ice cover at White Lake, Ontario, increased substantially during the thaw period with temperatures as high as 7.5°C being recorded. The purpose of this note is to report and interpret these observations.

During 1967 and 1968 water temperature and ice thickness measurements were made during the ice melt period at Bennett Bay, White Lake, Ontario (Figure 1). This bay, about 1.6 km long and 0.8 km wide, has a maximum depth of about 9 meters. Water temperature profiles were obtained once a week with thermistor temperature sensors at three sites located about 100, 200, and 500 meters from shore. Water depth ranged from 3 meters at the site near shore to about nine meters at the site farthest out in the bay.

All calculations presented in this note were made using the water temperature observations obtained at the site 100 meters from shore (Figure 2). Similar temperature profiles were obtained at the other sites (Figure 3).

The heat gain in a column of water of unit area under the ice for 7-day melt periods was calculated as follows:

$$Q_w = \sum \Delta T(\Delta h)(C_w) \quad (1)$$

which equals summation of heat gained in layers of water under the ice (cal/cm²) where

C_w , volumetric heat capacity of water (cal/cm³°C) at the mean temperature of the layer;

ΔT , mean change in temperature within specific layers of the column during 7-day periods (°C);

Δh , thickness of layer (cm). 30-cm-thick layers were used.

The heat contributed by the water for the melting of ice at the ice-water interface was estimated with the following formula:

$$Q_m = k_w \frac{\Delta T}{\Delta Z} \quad (2)$$

where

Q_m , heat contributed by water for melting ice (cal/cm²) during 7-day periods;

k_w , effective molecular conductivity of water (= 0.0014 cal/cm°C sec);

$\Delta T/\Delta Z$, average temperature gradient in 5-cm layer of water immediately below ice-water interface (°C/cm) during 7-day period.

This formula assumes that heat can only be transferred by molecular conduction through the thin stable layer of water at the ice-water interface.

The results of the preceding calculations are presented in Table 1. The sum of Q_m and Q_w represents the total heat supplied to the water during the melt periods.

The heat gained by the water under the ice

Fig. 1. Location of White Lake, Ontario.

during these melt periods could have been supplied from the following sources:

1. snowmelt runoff
2. lake bottom sediments
3. ground-water flow through the bottom sediments
4. lateral flow of heat under the ice from open water near the shoreline
5. solar radiation penetrating the ice cover.

Snowmelt runoff can be eliminated as a major source of heat; runoff from the surrounding land, flowing laterally under the ice, would probably decrease the temperature of the water,

as was the case when observed by Bilello. There are no well-defined streams or creeks flowing into the lake at the site of the observations.

Heat flow from lake bottom sediments in April would be slight because the heat stored in this material would be depleted during the winter months. Bilello estimated that in December heat conducted from bottom material was only about 12 cal/cm²/24 hr. This value agrees reasonably well with *Nybrant's* [1959] values for heat flow from typical bottom material during the early winter for latitudes 50 to 60 N. *Nybrant* considered that heat flow from bottom material in April would be almost negligible.

Fig. 2. Water temperature profiles under ice cover 100 meters from shores.

Fig. 3. Water temperature profiles under the ice cover.

TABLE 1. Heat Supplied to the Water during Melting of the Ice Cover on White Lake

	Period of Observations	Q_m cal/cm ²	Q_w cal/cm ²	Total cal/cm ²
1967	30 March- 6 April	55	414	469
	6 April-13 April	410	584	994
1968	27 March- 3 April	572	500	1072

There was no evidence that heat from ground-water flow through bottom sediments was sufficient to increase water temperature significantly. Water temperature profiles under the ice cover before the active thaw period were typical for lakes at this latitude with no indication of substantial heating of the bottom water layers by ground-water flow (March 30 profile, Figure 2).

Solar radiation warming the open water near the shoreline could result in lateral flow of water under the ice cover. During the periods of observation the area of open water near the shore was not extensive, varying from 1 to 2 meters in width. Calculations indicate that heat from this source did not contribute effectively to the observed increase in water temperature under the ice cover.

Some approximate calculations were carried out to determine whether the heat available from solar radiation that penetrated the ice cover would be sufficient to explain the increase in temperature. The amount of radiation penetrating the ice cover was estimated from the following formula:

$$I_x = I_0 e^{-\lambda x} \quad (3)$$

where

I_x , solar radiation penetrating to depth x (cm)
cal/cm²;

I_0 , solar radiation received at the ice surface
(cal/cm²);

λ , extinction coefficient (cm⁻¹).

Incoming solar radiation during the weekly observation periods was estimated from short-wave radiation recorded at Ottawa about 40 miles east of White Lake. The percentage of incoming solar radiation reflected from the surface was assumed to be 30%, a reasonable value for melting ice.

Two values of extinction coefficient were used, 0.01 and 0.02, which are about the range of values measured by Scott [1964] for clear spring

ice in Wisconsin lakes. These values are considered reasonable, for during both seasons the ice covers were essentially clear for the lower two thirds of their thickness but had some air bubbles entrapped in the upper layers.

The calculated amounts of radiation penetrating the ice cover for the melt periods are given in Table 2.

These values compare reasonably well with the previously calculated total heat ($Q_m + Q_w$) gained by the water during the observation periods. It is concluded, therefore, that solar radiation penetrating the ice caused the relatively high water temperatures observed at White Lake.

Water temperature under a melting ice cover will be highly variable because of variations in the extinction coefficient of ice. The percentage of radiation that penetrates different thicknesses of snow and ice for different extinction coefficients is illustrated in Figure 4. The range shown for extinction coefficients is based on values reported in the literature [Geiger, 1965; Scott, 1964; Lyons and Stoiber, 1959]. Figure 4 shows that a large proportion of the incoming solar radiation will penetrate clear ice of considerable thickness, whereas the amount penetrating bubbly ice or snow-covered ice may be almost negligible.

Field observations tend to confirm that water temperatures under melting ice will vary depending on the amount of solar radiation that can penetrate the ice. The maximum water temperature measured by Bilello under a melting lake ice cover that was two thirds bubbly ice was about 2.0 to 3.0°C. In contrast, water temperatures as high as 7.5°C reported in this note and elsewhere in the literature [Hill, 1967] are probably not uncommon if significant amounts of solar radiation can penetrate through melting lake ice. In permanently ice-covered lakes, bottom temperatures as high as 25°C have been attributed to solar heating

Fig. 4. Per cent radiation penetrating ice covers for different extinction coefficients, λ .

[Wilson and Wellman, 1962]. Some of the implications of solar heating for the stability of the water under the ice have been discussed by Woodcock [1965].

The rate at which ice clears from a lake can be influenced by the solar heating of water under a melting ice cover. Wind may cause a free ice sheet to oscillate both horizontally and vertically and mix the water below [Bilello, 1968], resulting in an increased rate of melting. If the wind action continues and the ice is thin, it will start to break up and melt rapidly by mixing freely with the water previously warmed by solar radiation. In 1968 at Bennett Bay the water was cooler by about 2°C to a considerable depth (April 9th profile, Figure 2) immediately after the ice had cleared from the bay, indicating that several centimeters of ice were melted by mixing with water under the ice. Wind speeds of 10 to 14 mph at a height of 2 meters were re-

TABLE 2. Calculated Radiation Penetrating the Ice Cover during Melt Periods

	Period of Observations	Mean Ice Thickness (cm)	I_0 (cal/cm ²)	I_x (cal/cm ²)	
				$\lambda = .01$	$\lambda = .02$
1967	30 March-6 April	48	1660	1030	600
	6 April-13 April	35	2000	1410	962
1968	27 March-3 April	48	1890	1170	680

corded during the 24 hours prior to the final clearance of ice from the bay.

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