**Research Report 213
WATER TEMPERATURES
IN A SHALLOW LAKE
DURING ICE FORMATION,
GROWTH AND DECAY**

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PREFACE

The field research reported in this paper was conducted on a lake near the USA CRREL (formerly USA SIPRE) Keweenaw Field Station, Houghton, Michigan. Numerous individuals including Messrs Bob Boughman, Stanley Bolsenga, Jerry Gregg and Ed Lusk assisted in the field work. Logistics, installation and instrument calibration support for the project was provided by Field Station personnel, especially Mr. William Parrott, formerly Director of the Station.

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SUMMARY

Continuous water temperature measurements were made in a shallow lake in upper Michigan prior to and during ice formation, and during ice growth and decay.

Several full circulations or "overtorns" at 4C were observed during autumn and the temperature throughout the lake just prior to complete freeze-over reduced to a minimum of +0.2C. After a permanent ice cover had formed, the water beneath the ice began to warm up. Within a 25-day period during December the water temperature near the bottom of the lake increased from +0.3C to 3.0C. Quantitative analysis of this heat gain showed that it came principally from the energy stored during the summer in the underlying soils. Evaluation of the effect of solar radiation demonstrated that the sun during December contributed very little heat to the water because of the absorption qualities of the cover of snow and bubbly ice.

During the ice thaw period in April a unique reduction in temperature was recorded throughout the main mass of water. Since the lake is thermally stratified, it was assumed that this cooling could only result from mechanical action in the water. This phenomenon probably takes place as the surface water from melting snow around the area flows into the lake and causes mixing.

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Introduction

Vertical water temperature observations in lakes before and after ice formation have been made by Harrison (1863), Birge and Juday (1914), Yoshimura (1937), Brewer (1958), Scott and Ragotzkie (1961) and others. These observations were made monthly, weekly and occasionally daily. Information on the changes in water temperature during ice formation and decay is lacking because travel on the ice during these periods was hazardous.

In this study, equipment to continuously sense and automatically record temperatures in the air and at various levels in the ice and water was installed at Seneca Lake near Houghton, Michigan. Temperature observations were started in autumn before ice formed and continued until the ice entirely melted in the spring.

Hutchinson (1957) notes that, once a lake is frozen, a series of characteristic events leading to winter heating takes place. The general result of this process is an increase in temperature throughout the main mass of water remote from the ice. This thermal phenomenon was recorded at Seneca Lake where the water temperature near the bottom was found to increase 2 to 3C after ice had covered its surface.

Another change in water temperature, not noted in the literature on heat budgets of lakes, was observed and recorded at Seneca Lake. During the thaw period in April when the ice on Seneca Lake began to break up and thaw, the automatic temperature measuring equipment recorded an abrupt cooling of the water at all levels. This unique record of the cooling of the water during ice decay, and observations made during the periods prior to and after ice formation on Seneca Lake, are the subject of this paper.

Seneca Lake

A number of lakes in the vicinity of the Keweenaw Peninsula in upper Michigan (Fig. 1) were considered before a site was selected. The most important criteria used in the selection were: 1) the availability of electrical power, 2) accessibility, and 3) no commercial and little public activity.

Seneca Lake, located about 32 km northeast of Houghton, Michigan, met the necessary requirements. This lake is oriented NE-SW and is about 150 m wide and 275 m long. The lake was somewhat shallower and more sheltered than desired - the maximum depth is only about 2.2 m and a ridge about 200 m high shields the lake to the northwest. Minor surface streams feed Seneca Lake during the non-freezing period. A small drainage outlet is located on the northeast end of the lake but drainage is extremely small except during heavy rains in summer. After freeze-over there is no apparent flow of water into or from the lake, and it is assumed that no surface or sub-surface influx of water occurs because of the nature of its bed and because

Figure 1. Location of Seneca Lake, Michigan.

there is no measurable change in the water level. The northwest end of the lake is marshy, and extensive probing in other parts of the lake indicated that 50 to 70 cm of silt and mud cover much of the bottom, which is sandy gravel.

Analyses of Seneca Lake water made by USA CRREL soil scientists showed that it is potable water with a total salt content of about 38 ppm.

Equipment and installation

In the fall of 1959 copper-constantan thermocouples were installed on and near a raft anchored about 45 m from shore in water 200 cm deep (Fig. 2). An aspirated, shielded thermocouple on a boom measured air temperature 100 cm above the water surface. This thermocouple was attached to a movable support so that when snow and ice accumulated on the lake the sensor could be reset at 100 cm above the snow or ice surface.

Seven other thermocouples used to measure water temperature were held in position by fine nylon threads midway between the posts of a 50 cm wide frame made of plastic pipe. The equipment was located 1.5 m away from the raft to isolate the sensing elements from extraneous temperature influences. The thermocouples were placed prior to freeze-up, at the depths listed below (water-line equals zero):

no. 7 - zero	no. 3 - 100 cm
no. 6 - 10 cm	no. 2 - 150 cm
no. 5 - 20 cm	no. 1 - 180 cm
no. 4 - 50 cm

Figure 2. Instrumented raft and shelter with recorders on shore.

The lead wires were encased in a waterproof, heavy-duty hose which led from the raft to a shelter on the beach. The shelter (Fig. 2) was heated to prevent freezing of the recording equipment. Temperatures for each level were recorded continuously on a Leeds and Northrup potentiometer-recorder. Print-out rate was approximately one observation per minute and a complete cycle was repeated about every 20 minutes.

A temperature-measuring circuit at Seneca Lake consisting of a primary ice bath, thermally buffered by a second ice bath which completely surrounded the primary bath, was installed in January 1960 (Fig. 3). * The primary ice bath which housed the reference junction thermocouples was insulated within a Dewar vessel and remained undisturbed. The Dewar vessel was placed in the second larger ice bath insulated with foamed polystyrene. A continuous read-out of the temperature between the reference junction and a monitoring thermocouple in a separately maintained ice bath was checked regularly. No differences were encountered during the periods under study confirming that the reference junction temperature remained at 0C.

At least twice a week throughout the winter the sensors and recording equipment were checked for proper operation. About twice a year an additional check on the equipment was made by means of a portable potentiometer. The reading obtained by this method and those provided by the automatic system correlated perfectly.

* Mr. B. Lyle Hansen of USA CRREL suggested and designed this double insulated reference junction ice bath.

Figure 3. Reference junction ice bath.

Results and discussion

Interesting changes in water temperature were observed in Seneca Lake during the spring, fall and winter seasons of 1960. The specific periods of time of the investigation were: 1) prior to the first appearance of ice; 2) during the formation of a "permanent" ice cover; 3) while the lake was "permanently" ice-covered; and 4) during ice decay and lake clearance.

The period prior to first appearance of ice. Forel (Hutchinson, 1957) points out that a lake in a temperate region under continental climatic conditions experiences full circulation (overtturn) at or near the temperature* of maximum density twice a year - in the spring after the ice melts and in early fall before freeze-over. Since Seneca Lake is shallow, more than two full circulations in temperature are usually recorded each year.

A record of the temperature regimes in the fall of 1960 at Seneca Lake is shown in Figures 4 and 5. In Figure 4, two temperature traces are presented, one in the air 100 cm above the surface and the other in the water 50 cm below the surface. Only the temperatures recorded at 0600, 1200, 1800 and 2400 each day are given because additional detail was not required in the analysis. Note that the time lag between air and water temperatures for associated peak highs and lows is about 24 hours. The full temperature circulations are shown in Figure 5 where the water temperature throughout the depth of the lake decreased to less than 4C on 24 October and again on 5 November 1960.

The thermal stratification in Seneca Lake as defined by Hutchinson (1957) is as follows: the temperature decreases vertically upward when the water is

* Termed 4C hereafter.

Figure 4. Air and water temperatures prior to first ice, Seneca Lake.

Figure 5. Water temperature profiles prior to first ice, Seneca Lake.

colder than 4C and decreases vertically downward when the water is warmer than 4C. Hutchinson notes that exceptions in the second case can occur when slight temperature reversals, due to sensible heat loss or evaporation, are observed at the surface.*

* Exceptions in the former case also occur, as shown by the slight temperature reversals observed at Seneca Lake (Fig. 5). These temperature variations in the top 50 cm of water are apparently due to increase in sensible heat gained from solar radiation.

The water temperature profiles (Fig. 5) for October and November 1960 show the temperature to be near-isothermal between 50 and 180 cm below the surface. Dutton and Bryson (1960) note that soundings at temperatures above +4C in Lake Mendota, Wisconsin, in the fall, tend to become isothermal. They suggest that the cause of this isothermal state is similar to the process described by Proudman (1953) for promoting vertical turbulence near the sea-surface. Dutton and Bryson (1960) define the process as thermal instability and describe it as follows: As the surface water cools, its density increases and the water tends to sink, displacing the warmer water at depth, which then rises to the surface where it is cooled. They also state that the process is probably brought to its full effectiveness by the action of the wind on the surface.

An interesting study on surface cooling of water was conducted by Spangenberg and Rowland (1961). Through schlieren photography they were able to record the convective currents induced by evaporative cooling. Their photographs showed that water from the cooled surface-layer formed a network of very narrow ridges, an inch or two apart, that periodically became unstable. The water plunged in vertical sheets and reduced the cooled surface layer to a thin film.

The vertical temperatures in Seneca Lake appeared isothermal as the water warmed and cooled (Fig. 5), even during periods of calm. Detailed examination of the temperature profiles recorded 20 minutes apart also showed an immediate time-response regarding uniform temperature change with depth. Spangenberg (personal communication) explained this phenomenon as follows: "The data upon which the temperature profiles [Fig. 5] were based do not indicate strictly isothermal conditions. They show a temperature stratification consisting of alternately stable and unstable or neutral layers. In the region below the 50-cm depth where the temperature is most nearly constant, all the data show a layer with an unstable temperature gradient several orders of magnitude greater than that required to initiate thermal convection, based upon the stability criteria as predicted by Rayleigh, Jeffreys, Low and others. Since the temperature differences necessary to initiate thermal convection in thick layers such as these are extremely small, even at temperatures near +4C where the expansion coefficient is at a minimum, vigorous mechanical overturning due to convection currents is probably continuous, and the mixing motions originating in the lowermost unstable strata, when considered with other possible mixing motions originating in the unstable layers above, establish a high heat transfer coefficient and maintain a near-uniform temperature as heat flows continuously between the bottom and the top of the pond."

Isothermal conditions in Seneca Lake continued during the cooling (or warming) transition across +4C and after the temperature fell below +4C. This thermal condition is not uncommon in shallow lakes during the late autumnal circulation. It has been observed by Brewer (1958) at Imikpuk Lake, Alaska, and by Hutchinson (1957) at Linsley Pond, Connecticut. This phenomenon probably is peculiar to shallow lakes, in this case to depths of 180 cm.*

Since further cooling of the surface water at temperatures below +4C decreases its density, the convective processes due to thermal instability (as described earlier) no longer apply. During this time, the surface of the lake is exposed to the atmosphere so that the isothermal state at these temperatures can be attributed to mechanical mixing resulting from wind action. During spring thaw we show that thermally stable water again recools at depth to temperatures below +4C even though wind action is negligible due to a cover of thick ice. This phenomenon and its probable causes will be discussed later.

* Studies on the temperature regime of deep lakes observed during the winter are given for Bratsk Reservoir by Bulatov (1966), for Lake Michigan by Noble (1965) and for Lake Vetter, Sweden, by Liljequist (1941).

The period during formation of a permanent ice cover. Depending upon the intensity and duration of freezing temperatures at the surface and the size and depth of a lake, ice may form quickly or, perhaps, not at all. During the transition period between autumnal cooling and a permanent ice cover, Seneca Lake usually experiences several periods of ice formation and clearance. For example, the following ice conditions were observed during November and December 1960:

- 7 Nov - Ice along part of the shore line, approximately 2.5 cm thick.
- 10 Nov - Lake almost frozen over, ice 2 cm thick.
- 15 Nov - Ice appears thick and firm.
- 16 Nov - Lake free of ice.
- 18 Nov - Ice 8 mm thick.
- 21 Nov - Ice considerably deteriorated.
- 23 Nov - Lake free of ice.
- 29 Nov - 80% of lake frozen over, ice 2 cm thick.
- 2 Dec - Lake permanently covered, ice 15 to 20 cm thick.
- 7 Dec - Lake remained covered with ice.

Figure 6 shows a trace of the air temperature and of the water temperature 50 cm below the surface during this period of alternating ice formation and decay. When ice partially covered the lake the trends in water temperature did not follow directly the changes in air temperature as they had done before ice appeared. For example, between 10 and 15 November, the air temperature increased from -3°C to $+6^{\circ}\text{C}$, whereas the water temperature remained relatively unchanged near $+1^{\circ}\text{C}$. The alternating formation and melting of ice during this period resulted in a constant water temperature.

Figure 6. Air and water temperatures prior to a permanent ice cover, Seneca Lake.

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Figure 7. Water temperature profiles prior to a permanent ice cover, Seneca Lake.

It is interesting to note that on 15 November the lake ice appeared "thick and firm," but 24 hours later the lake had cleared. The ice, although reportedly firm, may have been considerably rotted by the above-freezing temperatures on 13 and 14 November. A similar situation occurred on 21-23 November, but on this occasion the surface of the ice on the 21st had obviously deteriorated.

The water temperature throughout this period of ice formation and decay remained below 4°C. Four representative profiles of the water temperature (Fig. 7) show near-isothermal conditions between 20 and 180 cm throughout the period. The water temperature reached +3°C on 21 November and on 30 November cooled to its lowest annual temperature (+0.1 to +0.2°C), which was recorded at all depths.

Mixing at temperatures as low as +0.3 to 0.4°C has also been observed in deep lakes such as Lake Vetter in Sweden (Liljequist, 1941). However, isothermal conditions in such deep lakes persist only to depths of about 25 m, the temperatures increasing below this level with depth, to 4°C or less. The results obtained at Seneca Lake show that, prior to the formation of a permanent ice cover, mechanical mixing continues throughout a shallow lake until near-freezing temperatures are reached.

The period during which the lake was "permanently" covered with ice. After a "permanent" ice cover had formed over Seneca Lake, the water beneath the ice began to warm up. Figure 8 shows that although the air temperature during most of December 1960 remained below freezing, the water temperatures gradually increased. Typical water temperature profiles at approximately weekly intervals clearly show this increase in temperature (Fig. 9). A quantitative analysis of the amount of heat accumulating in Seneca Lake between 2 and 26 December was made through use of vertical temperature profiles similar to those shown in Figure 9. The profiles for 2 and 26 December were obtained from water temperatures observed on those dates.

Figure 8. Air and water temperatures under a permanent ice cover, Seneca Lake.

Figure 9. Water temperature profiles under a permanent ice cover, Seneca Lake.

The gain in heat (cal/cm^2) in a column of water of unit area in which there is assumed to be no horizontal loss or gain in heat was computed as follows:

$$Q_w = \left(\sum_{i=1}^8 \Delta T_i \right) \Delta h \cdot C_v \quad (1)$$

where Q_w is positive and

ΔT = mean change in temperature (between 2 and 26 December) within specific layers of the column ($^{\circ}\text{C}$)

Δh = thickness of the layer (cm)

C_v = volumetric specific heat at the mean temperature of the column ($\text{cal/cm}^3 \text{ } ^{\circ}\text{C}$); or $C_w \cdot \rho_w$

in which

C_w = specific heat of water at mean temperature of the column ($\text{cal/g } ^{\circ}\text{C}$) and

ρ_w = density of water at mean temperature of the column (g/cm^3).

Substituting numerical values for a mean temperature of $+1.5^{\circ}\text{C}$ gave

$$Q_w = (14.4)(20)(1.006) = +290 \text{ cal/cm}^2.$$

Temperature increases throughout the main mass of water after freeze-over have been recorded by numerous investigators since Harrison (1863).

Yoshimura (1937) reports the warming of the deep layers under the ice in a Scottish lake in 1879 as observed by J.Y. Buchanan and gives the following three causes for it:

- a) Solar radiation
- b) Heat exchange between the water and the mud on the bottom of the lake, and
- c) Inflow of warm water.

Likens and Ragotzkie (1965) and others give two other possible sources of heat flow from the sediments in winter: d) Oxidation of organic matter, and e) The geothermal gradient. Estimates and discussions on the amount of heat involved in each of these sources follow.

Solar radiation: For solar radiation to contribute a substantial amount of heat to the water beneath an ice cover the ice must be almost clear. More than half of the total incoming solar radiation is reflected from the snow and ice surface and much of the energy in the infrared wave lengths is absorbed in the surface layer (Fig. 10). Most, if not all, of this absorptivity represents light scattering due to reflection and refraction in the snow-bubbly ice layers.*

Ice cores removed from Seneca Lake during 1960 (Fig. 11) show that about 2/3 of the ice is bubbly. This bubbly ice, found in the upper portions of the ice sheet, is formed by the freezing of slush produced by water, either seeping from below or overrunning from the sides, saturating the snow above the ice-snow interface. During the period 2 to 26 December the average thicknesses of cover were: 8cm snow, 15cm bubbly ice, and 4 cm clear ice.† In addition to the

* Lyons and Stoiber (1959) point out that in the visible range the absorptivity coefficients for bubble ice are as much as two orders of magnitude greater than those for clear ice. Greenbank states (Welch, 1952, p. 81): "7½ inches of clear ice transmitted 84% [of the incident light] as against 22% for 7½ inches of partly cloudy ice." Thomas (1963) further points out the significant role crystal size and orientation of ice and snow play in the absorption of visible radiation.

† This bubbly ice (sometimes called snow-ice or white-ice) has been studied in Canada by Andrews (1962), in the United States by Ragle (1963), and in the Scandinavian countries by Ager (1962) and Palosuo (1965).

Figure 10. Approximate evaluation of the distribution of incoming radiation at Seneca Lake 2 - 26 December 1960.

Figure 11. Ice core removed from Seneca Lake.

bubbly ice, the effectiveness of solar radiation was much further decreased by the snow cover through reflection, absorption and low conductivity.*

An approximate evaluation was made of the distribution of incoming radiation for Houghton, Michigan, between 2 and 26 December 1960 (Fig. 10). The average incoming solar radiation for this location was 110 langley's per day, according to the December issue of the National Summary (U.S. Department of Commerce, 1960). Of this incoming radiation about 80 ly/day would be in the visible range, and only about 15 ly/day of this amount would be retained because of surface reflection. The infrared radiation of 30 ly/day would be absorbed in the upper layers of the snow. Of the energy in the visible spectrum (15 ly/day), 5 ly/day would be absorbed by 8 cm of snow, and 5 ly/day by 15 cm of bubbly ice. None would be absorbed by the 4 cm of clear ice, leaving a net incoming energy of about 5 ly/day to the water. Temperatures measured at the snow/bubble-ice interface averaged about -1C, indicating a continuous upward conduction of heat from the ice/water interface. The net loss in heat results in an ice growth of about 0.2 cm/day or 5 cm in the period under study. This amount of growth agrees with the observed increase in ice thickness (from 20 to 25 cm) on Seneca Lake during the period in question.

The above values are reasonable estimates; no precise computations are possible unless actual radiation measurements in the snow, ice and water are available. Nevertheless, the foregoing rough analysis demonstrates quantitatively that solar radiation contributed only a small amount of heat to the water in Seneca Lake during December 1960.†

Heat exchange between the water and the mud on the bottom of the lake: A considerable amount of heat is accumulated in the soil layers beneath the lake during the summer. An evaluation of the heat budget of lake sediments in shallow lakes was made by Bryson and Bunge (1956) and Newman (Hutchinson, 1957). However, it appears that the heat stored in the material beneath the sediment was not taken into account in these evaluations. Calculations similar to those made earlier to determine the increase in heat in a column of water were made to estimate how much of this heat in the sediments and soils underlying the lake is available during 2 to 26 December.** Unfortunately, temperature measurements were not made in the soil beneath Seneca Lake prior to, or during, ice formation. It was, therefore, necessary to construct the probable temperature profiles which existed within the soils during December 1960.

* Wilson, Marshall and Zumberge (1953) state that even a cover of 1 in. of light snow can prevent solar radiation from being adequately absorbed by the ice surface for rapid thermal expansion. Harrison (1863) states that the temperature increase he observed in the water beneath the ice cover of a lake in Connecticut could not have been produced to any notable degree by the sun's rays, because the ice was opaque with air bubbles and also covered with snow.

† It should be noted that the effectiveness of solar radiation through ice sheets as noted and observed by G. A. Birge (Hutchinson, 1957) still remains an open question. Shirtcliffe and Benseman (1964) in a study of permanently ice-covered Lake Bonney, Antarctica, concluded that the primary heat source producing water temperatures of +7.5C at a depth of 10 to 15 m was solar radiation. This lake, however, is highly saline at these depths and Hobbs and Mason (as quoted by Ragotzkie and Likens, 1964) report that the ice of Lake Bonney is quite transparent below the first meter.

** A similar but theoretical approach to this problem was made by Kolesnikov (1953) for ice-covered reservoirs in Russia.

Figure 12a. Ground temperatures observed at Ottawa, Canada. (After Crawford and Legget, 1957.)

Figure 12b. Estimated ground temperature beneath Seneca Lake.

Utilizing the water temperatures observed during this month, and such information as the comparative thermal diffusivities of the underlying material, the mean annual temperature, and the 1960 mean late summer temperature at Seneca Lake, an approximate annual ground temperature envelope was drawn (Fig. 12b). A plot of measured temperatures versus depth in the mud in the middle of Oumalik Lake, Alaska, during August 1951 (Livingston *et al.*, 1958) is also shown in Figure 12b. The Alaskan values are of course lower by 7 to 8°C than those given for Seneca Lake but the corresponding curves for August are very similar.

Within the envelope, estimated temperature profiles for 2 and 26 December 1960 are shown. Sinusoidal temperature - time curves, with amplitudes and phases based on known temperature curves in soil, were drawn for several depths. From these curves the temperature profiles for the two particular dates were obtained. The procedure is very approximate, but the final curves are probably not much in error.

Ground temperatures observed by Crawford and Legget (1957) at Ottawa, Canada (a site similar to Seneca Lake in latitude and climate) were used for comparison (Fig. 12a). The annual ground temperature envelope and the observed temperature profiles for 15 November and 15 December are similar to those for Seneca Lake on 2 and 26 December. The major difference is that the temperature range for Ottawa is wider than that for Seneca Lake. This is because the surface measurements at Ottawa were made at the air (or snow)/ground interface, whereas those for Seneca Lake, at the mud/water interface,

were modified by the water. The ground temperature profiles close to shore around Seneca Lake no doubt differ from those directly beneath the lake (Fig. 12b). Heat stored in the upper 200 cm of exposed soil around the periphery of the lake during the summer actually may contribute some additional but unaccounted energy to the water after freeze-over. It should be noted that the temperature 5m below the bottom of Seneca Lake agrees with measurements taken at similar depths in a copper mine at Calumet, Michigan (Ingersoll, Zobel and Ingersoll, 1954).

The soil temperature profiles beneath Seneca Lake on 2 and 26 December (Fig. 12b) were used to estimate the amount of heat released through a column of soil of unit thickness assuming no horizontal loss or gain in heat. The underlying material consisted of 20 cm mud, 40 cm silt, and below that sandy gravel. The curves for 26 December and 2 December intersect at 8 cm depth, indicating a change in the direction of heat flow at that depth. The heat gain and loss in the underlying soils then were considered separately and computed from the following equation:

$$Q = \left(\sum_{i=1}^n \Delta T_i \right) \Delta h \cdot C_v \quad (2)$$

where

n = 2 for top mud layer, 3 for second mud layer, 5 for silt layer and 35 for sandy gravel

Q = gain or loss in heat in soil (cal/cm²)

C_v = volumetric specific heat = $\rho_d(C_m + w C_w)$

where

ρ_d = dry density of soil (g/cm³)

C_m = specific heat of mineral grains at mean temperature of the mass (cal/g C)

w = water content of soil (% of dry weight).

The other variables were defined earlier.

The specific heat and density values for the various soils were obtained from Kersten (1949). The 75% water content in the mud (20 cm deep) was taken from values observed by Hart and Steinhart (1965) from mud samples from the bottom of Lake Superior. The numerical values and the results of each layer follow:

1. Q_m = gain in heat in mud, mean mass temp = +2C
 $= (3.7)(4.0)(0.88)(0.17 + 0.75 \times 1.006) = +12 \text{ cal/cm}^2$
2. Q_m = loss in heat in mud, mean mass temp = +5C
 $= -(7.3)(4.0)(0.88)(0.17 + 0.75 \times 1.004) = -24 \text{ cal/cm}^2$
3. Q_s = loss in heat in silt, mean mass temp = +9C
 $= -(17.0)(8.0)(1.36)(0.18 + 0.35 \times 1.002) = -98 \text{ cal/cm}^2$
4. Q_g = loss in heat in sandy gravel, mean mass temp = +10.5C
 $= -(33.0)(8.0)(1.76)(0.19 + 0.20 \times 1.001) = -181 \text{ cal/cm}^2$

The total amount of heat released through a column of mud, silt and sandy gravel beneath the lake between 2 and 26 December is 303 cal/cm². This heat balances that required to heat the column of water (i.e., 290 cal/cm²) and the mud adjacent to the water (12.0 cal/cm²), a total of 302 cal/cm², during the same period.

Inflow of warm water: The small surface streams leading to the lake were all frozen over by 2 December and no outflow of water was observed at the lake's one outlet. It was not possible to determine the existence of any warm underground inflow of water into Seneca Lake but weekly observations of the lake water level and ice lift by survey methods indicated that little, if any, water was being added to the system.

Oxidation of organic matter: In a small ice-covered lake in Wisconsin, Likens and Ragotzkie (1965) estimated that the heat gain due to oxidation of organic matter would be no more than $0.1 \text{ cal/cm}^2 \text{ day}$, and constitutes a minor contribution toward heating the lake. This value was based on the assumption that the water near the bottom is saturated with dissolved oxygen at the time of freeze-up. Therefore, the total heat (2.7 cal/cm^2) from this source for the period in question is a negligibly small fraction of the total energy required to heat Seneca Lake.

Geothermal gradient: Geothermal heat flow values of 0.93 and $0.95 \times 10^{-6} \text{ cal/cm}^2 \text{ sec}$, observed by Birch and Roy at locations on the Keweenaw Peninsula in Michigan, are presented by Lee and Uyeda (1965). This represents about $0.08 \text{ cal/cm}^2 \text{ day}$ or a total of 2.16 cal/cm^2 for the period 2 to 26 December. This contribution also is only a very small fraction of the heat required to increase the temperature of the water.

The preceding discussion and calculations show that the predominant heat source is the energy stored in the soils beneath the lake during the previous summer (see Ruttner, 1952, p. 37).

Direct solar radiation does not substantially contribute toward heating the water below the ice sheet of a shallow lake in a temperate zone.

The period during ice decay and lake clearance. After the water at the bottom of Seneca Lake warmed to maximum density ($+4^\circ\text{C}$) and 0°C was maintained at the ice/water interface the temperature profile remained essentially unchanged throughout the winter. The relatively stable water temperatures recorded during a winter are typified by those observed at the 50- and 150-cm depths (Fig. 13) during the period 1-10 April 1960. Note that the data for Figures 13 and 14 were obtained from observations made during the winter of 1959-60, instead of 1960-61 as presented earlier. The temperature measurements made during April 1961 became unreliable when both containers for the ice of the reference junction developed leaks.

Although the temperature remained nearly constant with depth there are undoubtedly vertical water motions beneath the ice similar to those observed in Tub Lake, Wisconsin, by Likens and Ragotzkie (1965). The energy source generating these motions is the heat continuously released by the warmer underlying soil between December and April (Fig. 12b). After no additional energy is required to heat the water beneath the ice sheet to capacity (i.e., after 26 December) any surplus energy probably is partly lost to the atmosphere via the cover of ice and snow but also would effectively retard the growth of ice.

Beginning 11 April 1960 the air temperature remained mostly above freezing (Fig. 13). On 14 April, the ice around the shore began to break up with an ice-free area extending 1.5 to 3 m from shore. The water at this time suddenly began to cool at all depths. Scott (1964) presents data on the variations in mean temperature of the water for lakes in Wisconsin over the winter of 1962-63. At Spruce and Mystery Lakes he observed cooler water in March than in February. These spot measurements probably reflect the same phenomena as observed in this study, because the measurements coincided with a period of above-freezing air temperatures (U.S. Department of Commerce, March

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Figure 13. Air and water temperatures prior to and during ice decay, Seneca Lake.

Figure 14. Water temperature profiles prior to and during ice decay, Seneca Lake.

Figure 15. Schematic cross section of Seneca Lake during thaw period (not to scale).

1963) when ice melting was no doubt in progress. Temperature decreases in the spring of 1961 in Tub Lake, Wisconsin, were also recorded by Likens and Ragotzkie (1965). These observations are significant because this cooling apparently has not been previously emphasized and because the physical processes causing it are in question.

Four vertical temperature profiles observed during this crucial period of ice break-up are shown in Figure 14. Unfortunately, the thermocouple at 180 cm did not operate properly so the profiles do not extend beyond 150 cm. The temperatures observed on 12 April represent the general thermal conditions existing beneath the ice sheet throughout the winter. The profile observed 4 days later (16 April), during a period of peak air temperatures and probable ice decay, clearly shows cooling of the water at all depths. The profile taken on 19 April, two days before the lake was almost free of ice, shows an increase in water temperature, which continues rapidly as shown by the profile taken on 23 April after all the ice was gone.

Several processes which may cause the sudden decrease in water temperature in the lake are shown graphically in Figure 15:

1. Near-freezing water released at the underside of the ice sheet as the ice melts.
2. The ponding of melt water on the surface of the lake ice. This water occasionally flows downward through cracks in the ice.
3. The gravity flow of snow melt water ($< 4^{\circ}\text{C}$) from around the lake.

The fact that the density of water decreases from $+4^{\circ}\text{C}$ to 0°C inhibits the influence of the cool water available at the surface on the water at lower depths. Nevertheless, the water did cool at all levels in Seneca Lake (Fig. 14, 16 April). Since the temperature profiles taken during this period (Fig. 14) show that the lake is thermally stable, natural convection is improbable. Hutchinson (1957), however, notes that Woodcock and Riley observed remarkable patterns in ice on small lakes on Long Island, New York, apparently indicating the existence of thermal convective cells over the centers of which melting is initiated. It is possible that as melted water is continuously available at the ice/water interface, the colder water may, by conduction, interact with the warmer water immediately below it and cause cooling at depth. However, mechanical processes are believed to be the principal cause for the changes in temperature. The water provided by processes 1 and 2 may not generate sufficient speed to cause substantial mixing, whereas the flow of cool water from melting snow on the sides of the lake could develop enough speed as it enters the lake to explain the mixing. The fact that this water could carry suspended soil particles, thereby increasing its density, would support this idea.

Wind may cause the free ice sheet to oscillate both horizontally and vertically and thus mix the water below. Sustained wind speeds of 20 to 25 mph were recorded at Seneca Lake on the 14th and 17th of April 1960, so that this mechanical mixing was not unlikely.

The amount of heat released during this cooling cycle of the water is of interest since most of it is undoubtedly expended in melting the underside of the ice sheet. This deduction is based on the fact that the temperature of the incoming melt water (approximately 1 to 2C) is about the same as the mean temperature of the water beneath the ice sheet (1.5C) and does not thermally contribute to the system, and since the air temperatures are much higher than the water temperatures, the heat released by the water is not being lost to the atmosphere. The assumption, consequently, is that the decrease in water temperature is mainly due to ice melt and can be quantitatively defined as follows:

The loss in heat in a column of water of unit thickness, assuming no horizontal loss or gain in heat at a mean temperature of +1.5C, between noon 13 April and midnight 16 April 1960 was computed as -148 cal/cm² (see eq 1). This computation only considers water depths of from 20 cm (at the ice/water interface) to 180 cm (maximum depth of temperature measurements). Approximately 50 cm of water (to the bottom of the lake) was not included; if included it would add about 75 cal/cm² to the total. This means that about 2 to 3 cm of ice (at a latent heat of 80 cal/g) would be melted from the underside of the ice sheet between 13 and 16 April.

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13. ABSTRACT

Continuous water temperature measurements were made in a shallow lake in upper Michigan prior to and during ice formation, and during ice growth and decay. Several full circulations or "overtorns" at 4C were observed during autumn and the temperature throughout the lake just prior to complete freeze-over reduced to a minimum of +0.2C. After a permanent ice cover had formed, the water beneath the ice began to warm up. Within a 25-day period during December the water temperature near the bottom of the lake increased from +0.3C to 3.0C. Quantitative analysis of this heat gain showed that it came principally from the energy stored during the summer in the underlying soils. Evaluation of the effect of solar radiation demonstrated that the sun during December contributed very little heat to the water because of the absorption qualities of the cover of snow and bubbly ice. During the ice thaw period in April a unique reduction in temperature was recorded throughout the main mass of water. Since the lake is thermally stratified, it was assumed that this cooling could only result from mechanical action in the water. This phenomenon probably takes place as the surface water from melting snow around the area flows into the lake and causes overturning.

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