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Observations on the superficial sediment temperatures of some lakes in the southeastern United States*

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Summary

Temperatures of the water column and upper 5 cm of sediment were monitored over a yearly cycle in two South Carolina lakes. Occasional supportive data were also obtained for several lakes in north central Florida. Plans are given for a new type of sediment–interface sampler that is useful in obtaining detailed temperature or chemical profiles extending from the sediment surface upward. The sampler was used in the investigation to demonstrate the thermal microstratigraphy near the mud surface.

The deep-water (16 m) temperature for the larger of the two South Carolina lakes changes seasonally from 10·5°C in February to 18·0°C in July. The smaller, shallower (11 m) lake follows an almost identical seasonal cycle but is always 4·0°C cooler because the larger lake receives a heated effluent that has a long-term effect on hypolimnetic temperatures. In both lakes the uppermost sediments are warmer than the overlying water by an average of 0·1 to 1·0°C during the warming period. Heat accretion near the bottom continues but is slower after stratification, probably due to the relatively low temperature (density) differential between water layers in these warm lakes. Cooling in deep water begins long before breakdown of stratification and is apparently caused by cold density currents from the shallows. The coldest water is located in a thin layer just over the sediment. There is evidence from one of the South Carolina lakes and from the Florida lakes that when the density flows begin they at first flow over a warmer water layer that is more dense due to a high electrolyte content derived from the sediment. There is a slight deep water warming in all of the lakes when stratification breaks down. After destratification, the deep water is cooled by turbulence rather than density flows. The surface sediments at this time are consistently warmer than the hypolimnion and remain so through the cooling period. There is strong evidence from one Florida lake that turbulence mixes the upper 3 cm of sediment during the isothermal period.

It is concluded that the sediment–water interface of a warm lake will in general experience greater heat flux than that of a comparable cold lake during the periods of temperature maximum and minimum. Conversely, there is likely to be less heat flux during the warming and cooling periods of warm lakes than of cold lakes. Several expected differences in seasonal patterns of temperature and water movement in the deep water of warm and cold lakes are discussed.

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Introduction

The annual progression of sediment temperatures in lakes is known to conform quite satisfactorily with predictions entirely based on heat flux by conduction (Hutchinson, 1957). In contrast, the progression of temperatures in the water column is controlled much more by turbulence than by conduction. It is consequently reasonable to suspect that the temperatures very near the sediment–water interface will be controlled by a more complex hybrid of mechanisms than those of the water column or sediment. These mechanisms are worthy of special attention for two reasons. First, the superficial sediments contain the benthos, and second, the sediment–water interface is the site of mineral flux between water and sediments.

The annual course of sediment-interface temperatures is best known and perhaps simplest to interpret for dimictic lakes. The classic studies of Birge, Juday & March (1928) as well as more modern work (Stewart & Hasler, 1972; Stewart, 1972) show clear seasonal patterns in the Wisconsin lakes. During summer, the mud surface is slightly cooler than the overlying water, and during the winter it is somewhat warmer, usually by several tenths of a degree. The cooler temperature of the mud surface in summertime is explained by the summer density stratification of the water column, which finds the coldest water on the bottom. In terms of water density, a completely analogous situation prevails during winter in many dimictic lakes, since the warmest temperatures are near 4·0°C, the approximate temperature of maximum density for freshwater. In some dimictic lakes the temperature at the mud surface and even the water above it may slightly exceed 4·0°C. This would suggest some instability, with water near minimum density overlying warmer, less dense water (e.g. Lime Lake, New York; Stewart, 1972). The change in density with temperature is so slight near 4·0°C, however, that an apparent density anomaly may be maintained by an uneven electrolyte distribution, or a small continuous heat input (conduction from deep sediments) and heat sink (ice cover) may be sufficient to maintain a nonequilibrium condition.

Warm monomictic lakes, particularly those that do not reach low temperatures during circulation, should be expected to respond differently to seasonal temperature changes affecting the mud surface. The higher deep-water temperatures of such lakes have two important implications for density profiles near the lake bottom. First, due to the rapid density change of water at high temperatures, a given heterogeneity in heat distribution will be considerably more stable if it is not anomalous (i.e., density-inverted) and considerably less stable if it is anomalous. Second, higher decomposition rates in warm lakes may produce electrolytes and deplete oxygen so much more rapidly that substantial density gradients develop near the sediment–water interface. Evidence for such an effect has in fact already been presented for a tropical lake (Lewis, 1973).

The present study was stimulated by the preliminary observation that the sediment surface in some lakes of the southeastern United States can be considerably warmer than the water column during seasonal cooling of the lake. A study was thus undertaken to determine the seasonal pattern of temperature difference between the sediment surface and water column in a warm lake and to interpret this information with regard to the expected differences between cold and warm lakes.

The main body of observations is for Par Pond, a 1130-ha reservoir with an average depth of 6 m and a maximum depth of 16 m. The lake receives a heated effluent, which does not render it qualitatively different for present purposes from the other lakes in the same region. The hypolimnion of Par Pond is, however, about 5·0°C warmer than for a comparable lake not receiving an effluent (Lewis, 1974), hence the effluent cannot be entirely ignored. A second lake from which data were taken, Pond B, is smaller (105 ha) and not so deep (11 m). Both of these lakes have exceptionally low flowthrough, as they receive water only from small streams. The water of both lakes is moderately soft (*c.* 50 μmho cm^{-1}) and poor in nutrients. Additional observations were made on some lakes in north central Florida. These lakes are described by Shannon and Brezonik (1972).

Methods

Prior to June 1973, temperatures were taken with an ARA GT100 thermistor bearing a perforated probe guard. Temperatures were subsequently taken with a YSI 46TUC thermistor with an unprotected steel probe (3·5 mm diameter). The probes were lightly weighted with 200 g so that contact with the sediment could be easily determined but sediment penetration would still be minimal. The weight was attached to one side of the probe so that the probe would tilt rather than penetrate on contact with the sediments. Tests on bottom samples showed that the caged probe would penetrate 1–3 cm and the uncaged one, 2–5 cm. A vertical series was taken at 1- to 2-week intervals for a year in Par Pond and for 10 months in Pond B. In all cases the temperature profiles included one measurement of the sediment surface temperature determined by lowering the probe gently to the bottom. The profiles in Par Pond were taken at eight stations ranging in depth from 7 to 17 m. Pond B temperatures were taken at a single station in the deepest part of the lake.

The information obtained about the sediment-water interface by routine temperature profiles is crude because a thermistor probe cannot be precisely manipulated near the bottom. Except for attempting to core the sediment in such a manner as to leave the overlying 0·5 m of water undisturbed, which would be unnecessarily troublesome for present purposes, there appears to be no widely used method for dealing with submerged interfaces. The Jenkin sampler used by Mortimer (1942, 1971) is obviously the instrument of choice if a sample is to be removed for exacting chemical work, but it is complex and would furthermore have to be handled with great care to prevent temperature changes at the surface. Special samplers of the type described by Schindler (1969) are capable of taking small quantities of water with minimal disturbance but they must be raised and lowered if a series of samples is desirable, and there is no means of repositioning such a sampler exactly once it is raised. Plans were therefore drawn up for a simple apparatus that would permit temperatures and small samples to be taken in series at increments as small as 1 cm, a known distance over the sediments. The design is shown in Fig. 1.

The essential component of the interface sampler shown in Fig. 1 is a plexiglass tripod that assumes a stable position at the sediment surface without disturbing the interface at the point where the temperatures or samples are to be taken. The legs of the tripod form an equilateral triangle measuring 1 m on each side at the bottom. The platform stands 60 cm above the sediment and bears a hole through which the thermistor cord and attached aspiration tube can be lowered. The thermistor probe itself is too large to pass backwards through the hole, hence the entire apparatus can be lowered into position or raised to the surface by the thermistor cord. A collar is attached to the thermistor cord about 60 cm above the probe so that the probe can be lowered through the hole only a sufficient amount to bring the thermistor tip and aspirator tube to the sediment–water interface or a few centimetres below it. The collar can be adjusted (a Hoffman screw clamp serves the purpose) so that the slight additional penetration of the legs in very soft sediments can be offset, or discs can be attached to the tripod legs to prevent penetration. The interface sampler costs very little and is easily made. It is useful on lakes as deep as 20 m in all but the roughest weather.

The aspiration tube should be small if the source of the water sample relative to sediment surface is to be precisely known and the solute-temperature profile is to remain undisturbed. Although this paper deals principally with the thermistor applications of the interface sampler, the aspiration tube was field tested under a number of conditions. The ideal tubing size proved to be $\frac{1}{8}$ inch I.D. For lakes 5–20 m deep, this size of tubing will supply approximately 20 ml min^{-1} at about 0·6–0·7 atm vacuum. The tube must of course be flushed when the collection depth is changed. If the tube is lowered into the sediment it will clog.

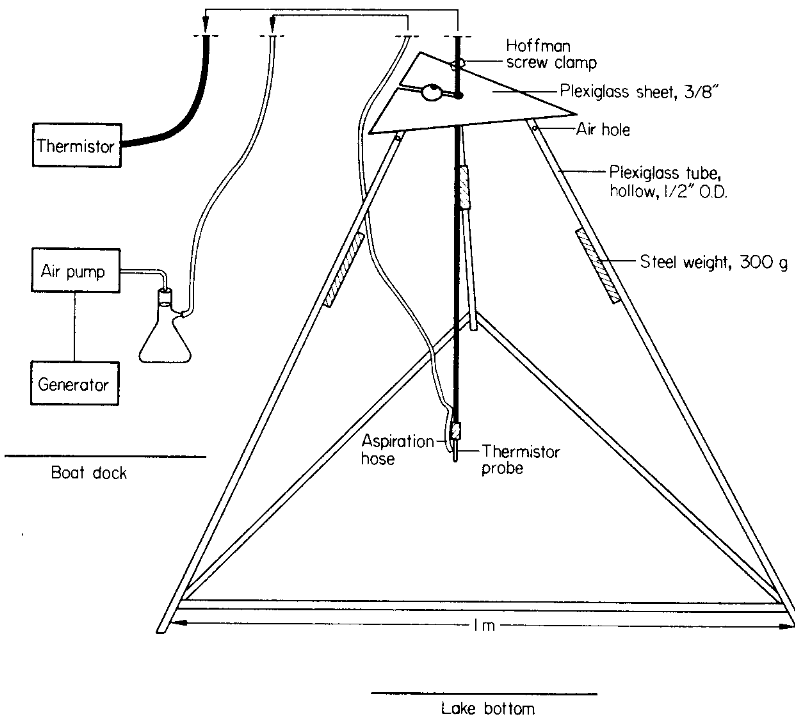

Fig. 1. Plans for the interface sampler described in the text.

The only potentially exasperating requirement of the interface sampler is that the boat remain stationary. It is ordinarily possible to achieve stability with the boat oriented broadside to the wind and anchored from both ends. The sampler is then lowered from the lee side of the boat until the lake bottom is reached. A meter stick is clipped to the cord so that the probe can be lowered by known increments toward the mud–water interface.

Results

The information obtained from routine thermal profiles in Par Pond is summarized in Fig. 2. Figure

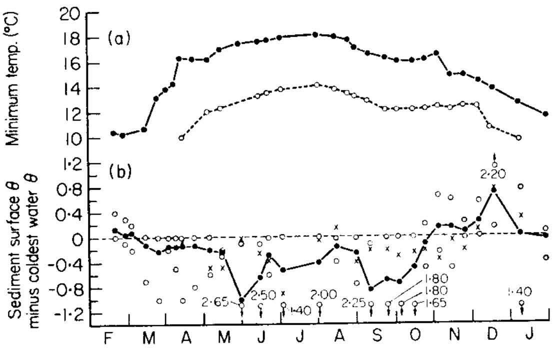

Fig. 2. Seasonal temperature trends near the bottom in Par Pond and Pond B. (a) Minimum temperature of the water column at the deepest point on the lake (Par Pond, 16 m (●); Pond B, 11 m (○)). (b) Differences between the minimum water temperatures at a number of stations and the superficial sediment temperatures at the same stations. Solid line shows mean for eight Par Pond stations. ○, Par Pond (range); ●, Par Pond (mean); ×, Pond B.

2(a) shows the change in minimum water temperature, which was always found near the bottom in the deepest water (16 m). The difference in temperature between the coolest water at a given station and the temperature of the sediment surface at that station was computed for each of the eight Par Pond stations on each of the sampling dates. The means of these differences and their ranges are plotted against time in Fig. 2(b).

Figure 2(a) shows that the seasonal deep-water temperature cycle includes a short temperature minimum at about 10·5°C during February and early March followed by steady hypolimnetic warming from late March to the end of May. Hypolimnetic warming is more extensive than in most regional lakes due to the addition of a heated effluent. The seasonal pattern for Pond B is similar except the temperatures are about 4·0°C lower.

Hypolimnetic warming in Par Pond slows by the end of May and the minimum temperature remains at 17·5–18·0°C until the last half of August. There is subsequently a gradual decline in the minimum temperature until November. The most rapid decline in minimum temperature occurs during December and January in both Par Pond and Pond B.

The seasonal change in minimum temperature is quite similar but not identical to the concurrent change in heat content of the lakes. Attention is focused here on the minimum temperature because the temperature of the superficial sediments is more directly related to that of the overlying water than to the heat content of the entire water column.

Figure 2(b) shows that during stratification, when the deep water is warmest, the sediment surface is consistently cooler than the overlying water. There is considerable variation between stations. This variation is partly explained by inaccuracies in the determination of minimum water temperatures and probably by internal water movements leading to nonequilibrium conditions as well. It should also be noted that the stations vary somewhat in depth, hence seasonal changes occur sooner at some stations than others. The average difference during stratification between the top 5 cm of sediment and the overlying water ranges between 0·1 and 1·0°C.

At the end of August the deep water begins to cool, but the superficial sediment remains cooler than the overlying water. The sediment therefore cools at about the same rate as the overlying water during this early portion of the cooling period. During the last half of October the sediments begin to achieve parity with the overlying water and subsequently become consistently warmer than the overlying water. The superficial sediments are warmer than the overlying water during midwinter but the difference is very small. In early spring the sediments are once again cooler than the water.

In Par Pond during the early phases of cooling as the sediment surface first became warmer than the overlying water, the thermistor frequently seemed to reach a zone of increasing temperature before actually entering the sediments. This observation suggested that some warmer water near the sediment resisted mixing due to its greater electrolyte content and thereby remained warmer than the overlying water. These observations were indefinite, however, due to the difficulty of manipulating the probe in a precise manner. The bottom sampler described in the foregoing section was designed to alleviate this difficulty. The sampler was unfortunately not ready until January.

In January the superficial sediments and overlying water were considerably less different in temperature than earlier, and the new sampling device revealed that although the upper 4 cm of sediment were warmer than the water above there was no warm water layer over the bottom. A typical January profile is shown in Fig. 3(a). The insert shows an

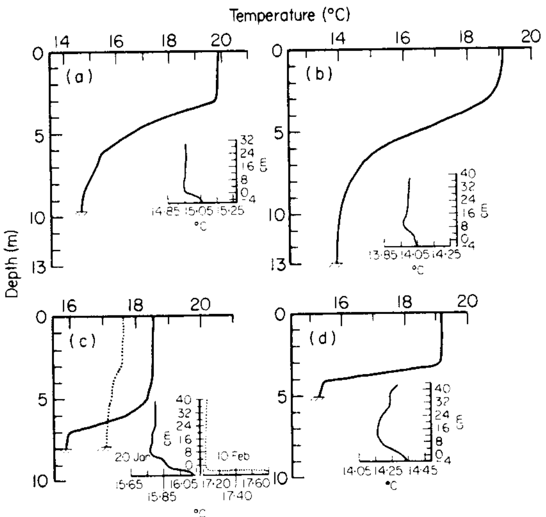

Fig. 3. Temperature profiles of Par Pond and three north Florida lakes. The insert in each case shows the detailed profile adjacent to and 4 cm below the sediment as determined with the interface sampler described in the text. (a) Par Pond, South Carolina. Station 6; 28 January 1974. (b) Lake Magnolia, Florida. 19 January 1974. (c) Lake Santa Fe, Florida. 10 February (....); 20 January (——). (d) Lake Johnson, Florida. 19 January 1974.

expanded-scale view of the sediment–water interface as obtained by the interface sampler. The inversion in temperature shown in the figure begins just at the mud–water interface, not above it. By this date considerable cooling of the lake had occurred, as is obvious from Fig. 2(a). The thermocline visible in Fig. 3(a) is artificially induced by the thermal effluent, but does not prevent deep mixing during cold windy weather (Lewis, 1974). It was therefore considered likely that any warm water layer overlying the sediments which might have been visible a month or more earlier in Par Pond would have been eliminated by deep turbulence by middle January. Some more southerly lakes were therefore visited during January on the supposition that the seasons would be sufficiently retarded to provide examples of lakes in earlier stages of cooling.

North Florida lakes visited on 19–20 January had cooled some at the surface but clearly had not destratified. The thermal profiles of three of these lakes appear in Fig. 3. The temperatures are about the same as those for Par Pond 10 days later (Fig. 3(a)). This might seem somewhat contradictory, since the Florida lakes were purportedly not so far along in seasonal cooling. Par Pond, however, has a higher maximum heat content, hence the profile shown in Fig. 3(a) represents a great deal of heat loss and deep mixing, whereas the January profiles from Florida lakes do not.

The Florida lakes showed a definite temperature inversion in the sediment during January. The inversion in fact appeared to extend above the sediment several centimetres (Fig. 3). The superficial sediments in all of the Florida lakes are unconsolidated, hence there is some chance that the inversion coincides with the distribution of extremely loose or flocculent bottom material. It is, nevertheless, evident that after the onset of cooling a considerable inversion extends well above the consolidated sediment into and perhaps beyond the sediment–water boundary. The aspiration tube had not been added to the thermistor probe at this time, so the conductance profile was not obtained.

Temperature data were again taken on Lake Santa Fe in early February after a period of cold weather. These data, which appear in Fig. 3(c) along with the January data for the same location, show that the lake destratified between the two sampling dates. Since the volume of the epilimnion in this lake is considerably larger than that of the hypolimnion, there was an obvious rise in temperature near the bottom at destratification. A similar change of smaller magnitude is also visible in the late October and early November temperatures for the deepest part of Par Pond (Fig. 2(a)).

The rise in deep-water temperature in Lake Santa Fe at destratification was accompanied by a disappearance of the uppermost portion of the temperature inversion (Fig. 3(c)). The sediment temperature 3 cm below the interface remained warmer than the overlying water, despite the considerable increase in temperature of the deep water and the sediments as well. Water samples aspirated at 2-cm intervals over the bottom showed that there was no detectable electrolyte gradient above the sediment on 10 February.

Discussion

Seasonal temperature change near the sediment is partly controlled by morphometry. Small deep lakes are less likely to show turbulent transfer of small amounts of heat to the bottom during stratification than large shallow lakes. The following discussion specifically concerns the sequence of events at the mud–water interface in relatively shallow lakes. The deepest portions of deep lakes differ in that they are much better buffered against seasonal temperature changes than the lakes considered here.

The warming period

The warming of deep water occurs twice during the year in a warm monomictic lake—once during the spring prior to stratification and once just at destratification. The latter warming is coincident with heat loss for the lake and will be considered separately.

During the heat uptake period of a lake the deep water is warmed rapidly at first, before stratification becomes evident, and then more slowly as resistance to mixing becomes stronger due to uneven heat distribution. In the lakes of this study the slow accretion of heat well below the thermocline continued far into the summer. Such an extensive deep-water warming period is not typical of comparable dimictic lakes, probably because the deep water of such lakes is considerably colder so that the vertical density gradient is more marked during stratification.

Throughout the lengthy deep-water warming the sediment remains cooler than the overlying water. Heat is transferred to the upper sediments by conduction at a rate dependent on the steepness of the thermal gradient at the mud–water interface. In fact if the time course of deep-water temperatures is expressed in terms of Fourier waves (Birge *et al.*, 1928) and the thermal diffusivity is known (Hutchinson, 1957, p. 505), the progression of temperatures at any depth below the sediment can be predicted. The variable of greatest interest is therefore the progression of temperature at the mud–water interface.

The temperature of water just above the sediment during the heating period reflects the efficiency of vertical heat transfer from the surface by turbulence. Heat is transferred less efficiently to greater depths, partly because the energy of mixing is degraded over depth by friction, and partly because there is a density gradient opposing the descent of warm water. The deep-water temperature gradient is particularly important in warm lakes since water changes density most rapidly at high temperatures. Thus in warm lakes, while there may be less density difference between the main water layers, and consequently more heat passing the thermocline, there is also more resistance to the equal distribution of this heat in the deeper water. It is therefore reasonable to expect a more pronounced heat gradient in deep water and a more prolonged, steady movement of heat to the bottom in warm lakes than in cold lakes.

Turbulence terminates abruptly at the mud–water interface. Since the sediments receive heat mainly by conduction, whereas the overlying water is being steadily warmed by turbulence, the superficial sediments are always cooler than the water during the heating period. The temperature differential between superficial sediments and overlying water is thus simply a residual heat deficit caused by the inefficiency of heat transfer across the mud–water boundary.

Warming of the superficial sediments proceeds almost as rapidly as warming of the overlying water even though the sediments are always somewhat cooler than the water. This is due to the accelerated movement of heat into the superficial sediments by conduction whenever the heat differential across the interface is high. Turbulence could also play a direct role by stirring the upper sediments, but this is possible only during the earliest phases of heating when there is no density gradient in the water column.

The summer equilibrium

The heating of the deepest water in Par Pond and Pond B becomes asymptotic in June and July, hence this period can be classified as the summer equilibrium, or the time of maximum heat content. Careful examination of the water temperatures near the bottom for this period shows, however, that heat transfer to deep water continues, even though its rate is much reduced. During July 1973, when the heat accretion reached its minimum, the deepest water of Par Pond warmed 0·30°C. This warming must in part explain the continued differential in temperature between deep water and the adjacent sediments during July. Since a truly stable hypolimnetic temperature is not established in these lakes, the equilibrium that would be established by conductance between a thermally uniform hypolimnion and the underlying sediments is never observed.

The cooling period

An apparent enigma is created by the failure of the superficial sediments to become warmer or at least as warm as the overlying water when the lakes begin to cool. The minimum temperatures for Par Pond and Pond B decline markedly between the first of August and the middle of October, but the superficial sediments are even cooler. The switch to a consistently positive heat gradient at the sediment surface occurs rather abruptly in both lakes about the same time as a slight rise in minimum temperature (October–November). An explanation requires the recognition of two separate cooling mechanisms—density flow and turbulent mixing. Cooling of deep water in the lakes of this study occurs primarily by density flow in late summer and early fall and primarily by turbulent mixing in late fall and early winter. The transition between these two cooling phases is marked by the fall increase of minimum temperature in deep water, which is caused by the breakdown of thermal stratification. The two cooling mechanisms will be considered separately as they have greatly different effects on the course of events near the bottom.

Density flows

Decline in the deep-water temperatures of Par Pond and Pond B occurs long before there is any breakdown of stratification. The only reasonable explanation for this decline is the generation of density currents by late summer cooling of water in the shallows. The downslope movement of this water would account for incremental cooling observed in water adjacent to the bottom prior to destratification. Mortimer & Mackereth (1958) documented the existence of a similar flow in Torneträsk, except that the water moving downslope was warmer than overlying water because the lake temperature was below 4·0°C. Talling (1963) also noted the probable existence of cool density flows in Lake Albert. The likelihood of such currents in warm monomictic lakes would seem to be even greater than in cold lakes such as Torneträsk due to the relatively large density changes that accompany modest heat loss in warm lakes.

Cooling of deep water by density flows provides ideal circumstances for the formation of temperature inversions near the lake bottom but entirely above the sediment. At the beginning of the cooling period, electrolytes will be most concentrated near the mud–water interface, particularly if the interface is anoxic (Mortimer, 1941, 1942). The electrolyte profile could thus cause the cool dilute water moving downslope to flow over warmer water adjacent to the bottom without creating an unstable density inversion. Evidence for a phenomenon of this type has been described for a Philippine lake (Lewis, 1973). If a cool density flow does move above more saline water, a temperature inversion should be detectable near the lake bottom but above the sediment. There is no evidence for such an inversion in Par Pond, although this does not rule out the phenomenon since the thermal microstratigraphy of the lower water column is not known for early fall. There is indirect evidence for a thermal inversion above the sediment in Pond B and direct evidence for the same phenomenon in the Florida lakes. The Pond B sediment surface became warmer than the overlying water for a brief period in August just as the cooling began. This is precisely the time of year that one would expect cool density flows to be held away from the sediment surface by warmer but more saline water adjacent to the bottom. The subsequent disappearance of the inversion is also to be expected, since cool density flows would eventually dilute the underlying water or become so much cooler than the saline layer that the inversion would be unstable. The complicating possibility of groundwater flow in deep water cannot be ruled out from the data at hand, but the coincidence of incremental deep-water cooling with the cool nights of late summer suggests that cool density flows from the shallows are important in at least the South Carolina lakes.

A thermal inversion extending above the mud surface would seem to be entirely feasible from a theoretical viewpoint. The shallow warm lakes of the southeast must release considerable amounts of electrolytes as they become anoxic in summer. It is not unusual for the interstitial waters of superficial sediments from Georgia lakes to have triple the conductivity of the water column (J. E. Schindler, personal communication). If the dissolved solids in water just overlying the sediments were to increase by 50 ppm, water from the shoreline at about 12°C could be as much as 0·30°C cooler without being denser than the electrolyte-laden bottom layer. Temperature inversion in the lower water column may therefore prove to be a common feature of the early cooling period in warm lakes.

As cooling of the deep water proceeds by movement of cool density currents, the sediments become progressively cooler. Except for the brief period in Pond B during late August, in fact, the sediments appear to be even cooler than the overlying water. The superficial sediments can be cooled only by contact with cooler water, presumably density flows. Such flows must hug the bottom after they have effectively diluted any saline layer overlying the sediments. The cool superficial sediments are thus in contact with an even cooler water layer, but this water layer cannot be distinguished from the upper sediments on a routine temperature survey because it is relatively thin. It is also possible that the density flows become sufficiently cool to draw some of the interstitial water from the upper sediments by density inversion, and this might account for the rapidity of cooling in the upper sediments before destratification.

Turbulent mixing

The breakdown of the thermocline is coincident with a rise in deep-water temperature due to the redistribution of surface heat by turbulence. After this transition, the sediment surface is exposed to a much greater amount of wind-generated turbulence. Subsequent cooling occurs by the transfer of cold water from the surface to the depths by convective or wind-generated turbulence. This accounts for the abrupt change in the sediment-water temperature differential. Since cooling is induced by heat loss of the entire water column rather than by a thin underflowing cold water layer, it is possible by routine use of a thermistor to distinguish the temperature of the superficial sediment from the temperature of the water that is cooling it. Prior to the onset of turbulent mixing, the sediment surface must also be warmer than the water cooling it, but this can only be demonstrated if special techniques are used for working close to the interface.

The winter equilibrium

The period of thermal minimum is similar in its brevity to the period of thermal maximum. Heat flux continues during this period, so the lake does not reach a stable minimum temperature as would a dimictic lake under ice. The barriers to mixing at this time are minimal, hence the superficial sediments are most affected by turbulence. This may explain the observations on Lake Santa Fe in February (Fig. 3(c)), which indicate that the top 3 cm of sediment were isothermal with the water above, while an abrupt temperature increase occurred below this depth. In a significant but infrequently cited paper, Gorham (1958) argues convincingly that the uppermost layer of sediments is actively stirred in Esthwaite Water and other such lakes of moderate depth during the mixing season. The observations on Lake Santa Fe are accounted for if the cold water over the sediment is actually mixed with the upper few centimetres of sediment while the deeper sediments are cooled only by conduction.

Conclusions

Limnological literature is strongly oriented toward lakes having deep-water temperatures near 4·0°C. Warm monomictic lakes, which generally have higher hypolimnetic temperatures, predominate in the tropics and lower temperate latitudes, hence they have a global importance second only to the more numerous dimictic lakes of the north-temperate latitudes. It therefore seems worthwhile, whenever possible, to stress the categorical differences between these lake types. The importance of several such differences has become evident in the course of this study. Perhaps most obvious is the absence of ice cover in warm lakes. Because ice is an almost perfect shield against wind-generated turbulence, winter temperatures at the bottom of dimictic lakes are, unlike those of warmer lakes, essentially static for a considerable portion of the year. The bottoms of dimictic lakes may also be better shielded against turbulence during stratification due to the much greater temperature differential between epilimnion and hypolimnion. This is partly a matter of depth, since a very deep lake of any kind is unlikely to experience much deep-water heat flux during stratification. During the transition between ice cover and stratification in dimictic lakes, deep turbulence and the consequent heat transfer are likely to be more marked than in warmer lakes since the stabilizing effect of small thermal gradients is greatest at high temperatures. In addition, the temperature of the sediment surface will in general be less radically changed by breakdown of stratification in warm lakes, since there is less temperature differential between epilimnion and hypolimnion. Warm lakes are thus likely to experience greater deep-water heat flux than cold lakes during periods of maximum and minimum heat content and less deep-water heat flux than cold lakes during the heating and cooling periods.

The higher deep-water temperatures of warm lakes are also likely to affect events at the mud–water interface in ways unrelated to wind-driven turbulence.

The high base temperatures of warm lakes provide optimum conditions for the formation of thermal density flows. Although such flows may prove to be only a minor consideration in the total heat exchange of lakes, their potential effect on temperatures and chemical conditions near the sediment–water interface is exceedingly important. Sediments of warm lakes may also prove to be more prolific producers of electrolytes due to accelerated decomposition at high temperatures, hence biological modification of density gradients near the bottom may be more significant in these lakes.

The annual course of events near the bottoms of lakes is poorly known even for the most familiar lake types. This is somewhat surprising in view of the great interest in the formation and composition of lake sediments. Further investigation is almost certain to turn up observations of great relevance to the movement of heat and electrolytes in lakes and simultaneously provide a description of the benthic habitat and the conditions for decomposition of recently-sedimented organic matter.

Acknowledgments

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