AN UNREGARDED FACTOR IN LAKE TEMPERATURES.

EDWARD A. BIRGE.

[Notes from the Laboratory of the Wisconsin Geological and Natural History Survey. V.]

In this paper I wish to call attention to one of the factors regulating the distribution of heat in lakes, which seems to have been overlooked hitherto. It is well understood that the heat of the sun is delivered almost wholly to the surface strata of a lake; most of it to the upper meter. This heat is distributed from the surface to the lower strata by various agencies. Chief of these is the wind, which mixes the warmer surface water with the cooler water below. The efficiency of the wind as a distributing agent is opposed and limited by the *thermal resistance to mixture* offered by the decreased density of the warmed surface water. I wish to point out that the effectiveness of this thermal resistance increases as the temperature of the water, which the wind is trying to mix, departs from the temperature of maximum density and decreases as the temperature approaches 4°. A given temperature difference causes a thermal resistance which varies according to the position of that difference on the scale of the thermometer. This variability aids to explain many of the phenomena associated with the distribution of heat.

It is a well known fact that the density of water is at a maximum at 4°, and that it decreases as the water is cooled below or warmed above that temperature. This fact lies at the foundation of all considerations on the distribution of heat in lakes. It is an equally well known fact that the decrease in density corresponding to one degree increase of temperature is not constant but increases as the temperature departs from 4°, either toward 0° or toward a higher temperature. General references to this fact have been made by writers on lake temperatures, but no one called especial attention to it, so far as I am aware, until Groll ('05) showed its application in the production of convection currents. I desire to apply the same fact in the reverse direction and to show its relation to the thermal resistance offered by the warmer upper strata of the lake to the distribution through its mass of the heat received by its surface. Convection currents are far less important agents for distributing heat than are mechanical currents caused by wind. Indeed, it would be difficult to show that convection currents have any such efficiency in carrying heat as to make them worth serious consideration. Currents caused by wind do more work in equalizing temperatures and in carrying heat to the deeper strata than do all other agencies combined. Any factor which seriously modifies or limits their action has corresponding importance in the temperature changes of a lake.

The following table corresponds in part to that given by Groll ('05, p. 48). Column II shows the density of water from 0° to 30°, as given by Landolt and Börnstein.* The numbers show also the weight of a liter of water at the temperature stated. Thus a liter weighs 1.000000 kg. at 4°; at 10° it weighs 0.999727 kg. or 999,727 mg. The numbers in columns III–VI do not stand opposite the numbers of column II but are opposite the spaces between these numbers. Each represents the result of a change of temperature in a unit volume of water, corresponding to the degrees in column I immediately above and below the number in question; or it relates to a column of water whose surfaces have the temperatures immediately above or below.

---

* Physicalische chemische Tabellen, 3rd ed., 1905, p. 37.

I. Temp.	II. Density.	III. Difference.	IV. Rel. Dif. for 1°.	V. Ergs.	VI. Liters for 1 kg. Auftrieb.
0	0.999868				
		+0.000059	7.38	0.0491	17000
1	0.999927				
		+0.000041	5.12	0.0342	24400
2	0.999968				
		+0.000024	3.00	0.0200	41700
3	0.999992				
		+0.000008	1.00	0.0067	125000
4	1.000000				
		—0.000008	1.00	0.0067	125000
5	0.999992				
		—0.000024	3.00	0.0200	41700
6	0.999968				
		—0.000039	4.88	0.0325	25600
7	0.999929				
		—0.000053	6.62	0.0441	18900
8	0.999876				
		—0.000068	8.50	0.0566	14700
9	0.999808				
		—0.000081	10.12	0.0675	12400
10	0.999727				
		—0.000095	11.88	0.0791	10500
11	0.999632				
		—0.000107	13.38	0.0891	9300
12	0.999525				
		—0.000121	15.12	0.1008	8300
13	0.999404				
		—0.000133	16.62	0.1108	7500
14	0.999271				
		—0.000145	18.12	0.1208	6900
15	0.999126				
		—0.000156	19.50	0.1299	6400
16	0.998970				
		—0.000169	21.12	0.1408	5900
17	0.998801				
		—0.000179	22.38	9.1491	5600
18	0.998622				
		—0.000190	23.75	0.1583	5300
19	0.998432				
		—0.000202	25.25	0.1683	5000
20	0.998230				
		—0.000211	26.38	0.1758	4700
21	0.998019				
		—0.000222	27.75	0.1849	4500
22	0.997797				
		—0.000232	29.00	0.1993	4300
23	0.997565				
		—0.000242	30.25	0.2016	4100
24	0.997323				
		—0.000252	31.50	0.2099	4000
25	0.997071				
		—0.000261	32.62	0.2174	3800
26	0.996810				
		—0.000271	33.88	0.2257	3700
27	0.996539				
		—0.000280	35.00	0.2332	3600
28	0.996259				
		—0.000288	36.00	0.2399	3500
29	0.995971				
		—0.000298	37.25	0.2482	3400
30	0.995673				

Column III shows the differences between the successive numbers of column II and indicates the change in density caused by a temperature change of 1°. The significant figures also show the difference in weight, in milligrams, between a liter of water at any given temperature and at a temperature one degree lower. Thus, a liter of water at 10° weighs 81 mg. less than one at 9°; at 25° a liter is 252 mg. lighter than at 24°. These numbers, therefore, express the differences in density and weight which for a temperature difference of 1°, (1) enable a layer of water to set up convection currents if it lies above a warmer stratum, and (2) which enable a stratum of water, warmer above and cooler below, to resist mixture attempted by mechanical agencies.

It is evident that the differences shown in column III for a rise or fall of one degree become greater as the temperature rises above or sinks below 4°. From this fact it follows that a given mass of water—say, a cubic decimeter—which has been cooled one degree below the temperature of the water beneath it, will act with greater energy in setting up convection currents in proportion as the initial temperature was distant from 4°. It also follows that a column of water of unit area and height whose upper surface has a temperature one degree higher than its lower surface, will offer a thermal resistance to mixture greater in proportion as the average rises above 4°; it being assumed that the temperature gradient in the column is uniform.

Nor is this difference a small one, as may be seen from column IV. In this column the convection capacity (if I may coin an equivalent for the German word *Auftrieb*), and the thermal resistance to mixture corresponding to the temperature difference of one degree at 4°-3° or 4°-5°, is taken as unity and the relative value is given for the same difference at higher and lower temperatures. At 10° its value is more than ten times as great as at 4°; at 15° it has increased eighteenfold; at 20° more than twenty-five fold; and at 30° it is more than thirty-seven times larger than at 4°.

Groll's paper (p. 48) expresses this fact in relation to convection by stating the number of liters of water which would be needed to make a mass that weighs 1 kg. less than the same mass of water one degree cooler. Such a mass of water is necessary at the given temperature to secure "1 kg. Auftrieb." The number of liters stated is the reciprocal of the numbers in column III. I have repeated his results in column VI; the numbers being slightly changed as the values for density are not quite the same as those employed by Groll.

In order to give a similar picture of the thermal resistance, I have stated in column V the amount of work in decimals of a erg, which would be required to mix a column of water 1 sq. cm. in area, 1 m. high, in which the temperature gradient is uniform and whose upper and lower surfaces differ in temperature by 1°.

The formulas from which these results have been computed have been worked out and furnished to me by Dr. H. C. Wolff of the department of mathematics, University of Wisconsin, whose valuable assistance I wish to acknowledge with thanks. The work done against gravity in mixing a column of water whose density varies with the depth, so that it shall become one of uniform density is

$$(1) \qquad W\,(\text{ergs}) = A \int_0^C f(z) \left[z - \frac{C}{2} \right] dz$$

where A is the area of the cross-section of the column in sq. cm., C the height of the column in cm. and f (z) the function expressing the density in terms of z, the distance from the top of the column. The density of water at 4°C. is to be taken as unity.

If f(z) is a rational integral function of the second degree (1) reduces to the simple form

$$(2) \qquad W\,(\text{ergs}) = \frac{AC^2}{12} [D_2 - D_1]$$

where D_1 and D_2 are respectively the density of the lower and upper strata of the column. This condition is satisfied when the temperature gradient is uniform and when the relation between the density (D) and the temperature (T) is of the form $D = \alpha T^2 + \beta T + \gamma$ where α β and γ are constants. If the temperatures at the surfaces of a column are assumed to be full degrees centigrade, the density can be taken directly from the table and the ergs computed from the equation given above. If $A=1$ sq. cm. $C=100$ cm. and D_1 and D_2 are two of the numbers in column II, then the number of ergs is 833 times the difference between D_2 and D_1. These results are shown in column V.

If it is desired to compute the thermal resistance directly from the temperatures observed, the following formulas will yield approximate results. An empirical relation between the density and temperature of water at temperatures above 4° is

$$D = 1 - \frac{93\,(T-4)^{1.982}}{10^7}. \tag{3}$$

A very close approximation to this is

$$D' = 1 - \frac{6\,T^2 - 36\,T + 47}{10^6} \tag{4}$$

which gives as an approximate value for work

$$W\,(\text{ergs}) = \frac{AC^2}{10^6}\left\{T_m - 3\right\}(T_1 - T_2). \tag{5}$$

Below are given the differences between D and D′, showing the degree of approximation reached by formula (4).

T	D′	D	D−D′
4°	1.00000	1.00000	+0.00000
5°	0.99998	0.99999	+0.00001
10°	0.99971	0.99973	+0.00002
15°	0.99914	0.99913	−0.00001
20°	0.99827	0 99824	−0.00003
25°	0.99710	0.99707	−0.00003
30°	0.99563	0.99567	+0.00004

The values of W, as computed by formula 5 differ in the third decimal place from those derived directly from the tables of density and computed according to formula 2.

Formula 5 also shows that the approximate value of the work done in mixing a column of water is proportional to the temperature gradient $\frac{T_1 - T_2}{C}$, provided that the mean temperature, T_m, remains constant. That is to say, if the temperature gradient of a stratum of water is uniform and the average temperature remains the same, the thermal resistance will rise and fall in proportion to the difference in temperature between the upper and lower surfaces. If, under these conditions, the temperatures of the surfaces are 11° and 8° respectively, the resistance will be three times as great as if they were 10° and 9°; the average temperature being the same in both cases but the gradient being steeper in the first example.

If the temperature gradient is not a uniform one, then the temperature, T, is not a linear function of z. In such cases $f(z)\left[z-\frac{C}{2}\right]$ can be plotted and the value of W found by means of a planimeter.

The fact that the thermal resistance to mixture increases as the temperature rises has important and wide applications. First, it has much influence on the rapid distribution of heat through the lake in the spring as compared with its slow penetration later in the season. Even in our deepest Wisconsin lakes, like Green Lake (72 m.) the temperature of the bottom water goes up to 5°, or even 6°. So, too, the water at all depths of the lake acquires heat most rapidly in spring and early summer. A lake of considerable depth gains little heat after the first of July. Its gains are greatest in April, May, and the early part of June. Yet the surface receives more calories during July and August than during the earlier months. This rapid gain and distribution of heat in spring has forced some students of lake temperatures to conclude that the water is more diathermous in spring than in summer. So Ule ('01, p. 126) says that from the rapid gains of heat in spring we must draw the conclusion that the diathermancy becomes less in the course of the summer. This may or may not be the case, but it never happens to a degree which makes any notable difference; since in all lakes and at all times the upper meter of water receives most of the heat.

But the wind and the currents derived from its influence are mixing agencies which become less efficient as the lake warms, if equal temperature gradients are assumed. At 10° they are 10 times less efficient than at 5°; only one-third as efficient as at 6°; and less than one-half as efficient as at 7°.

When the temperature rises to 15° the resistance is nearly doubled as compared with 10°, and the efficiency of the distributing agents is correspondingly reduced. It is not surprising, therefore, that the distributing agents can work very effectively during the spring and carry the heat received by the surface to considerable depths. It is not surprising also that during the spring they can distribute this heat so rapidly as to prevent the surface temperature from rising so fast as to offer considerable resistance to their action; while they lose a great part of their power as the season advances.

There are, of course, other factors which work in the same direction, aiding to increase the efficiency of the forces which distribute heat in the early part of the season and checking this distribution as the summer advances. Students of lake temperature, however, have felt that these forces were not adequate to explain the observed facts. I believe that if the increased thermal resistance is also taken into account the phenomena will find a full explanation.

A second point where this principle finds important application is at the thermocline. No one fact in lake temperatures so arouses surprise in the mind of the student as does the ease with which the thermocline can be disturbed and the difficulty with which it can be permanently displaced. Violent winds in summer may raise or depress its surface by several meters in the larger inland lakes, yet it returns to its old position with barely a trace of change. In Lake Mendota the thermocline may be reduced to a temperature amplitude of 2°, or less in late September or October, and may lie within a meter or two of the bottom. This position it may retain for days, if not for weeks, unless an unusually vigorous wind upsets it. No such slight difference of temperature would, or does, persist in the spring. The reason is that the temperatures in the spring are in the region of 6° or 8°, while in the fall they lie at 12° or 14°, and therefore offer much more resistance to mixture.

At the junction of thermocline and epilimnion the fall of temperature is rapid. A decline of 4° or 5° in a meter is not uncommon and this is from a high temperature, 20°, or more. The thermal resistance to mixture is, therefore, very great and it is increased by the processes which tend to cause mixture. When the wind sets up currents in the epilimnion and blows it to the leeward side of the lake, the accumulating mass of warm water presses the cooler hypolimnion downward and outward. The first effect of this process is to condense the isotherms at the very point where the influences tending to cause mixture are greatest. A decline of temperature amounting to 8° or 10° in a meter is thus often produced. In this way is developed a resistance to mixture several hundred times as great as any that is possible in April, or early May, and this lies exactly at the place where it is most effective in preventing mixture. Thus we may explain the fact that the thermocline is but little affected in summer, even by violent and long continued winds.

During early and midsummer the temperature of the epilimnion is not uniform but the surface is always somewhat warmer than the stratum immediately above the thermocline. Since the temperature of the surface at this time is high—from 22° to 25°, or even more—a small temperature difference between the surface and the strata below presents a very great resistance to mixture. This is an important factor among those which keep the thermocline at a practically constant average position during several weeks in summer.

It is obvious that no fair comparison can be made between the ability of the wind to mix the water in summer and that which it may have in late autumn or winter after the surface has fallen below 4°. Many writers have found it hard to believe that the wind is able to mix the water of a lake from top to bottom during the process of cooling below 4°. Richter, for example, ('97, p. 49) finds it necessary to reject the wind as the agent in effecting this cooling, because the wind is not able to disturb the thermocline in summer. He is forced to set up a rather complex theory to account for the fall of temperature in deep water below 4°, and one which is not satisfactory to himself. In a similar way Ule ('01, p. 124) neglects the wind in discussing this process while Groll ('05, p. 54) rejects it for lakes of considerable depth. Yet the resistance to mixture at temperatures below 4° is so small that we need not be surprised that the whole mass of water is readily cooled by circulation to 3°, or even 2°. On the other hand, the rapid increase of resistance to mixture per degree as zero is neared indicates one reason why the temperature curve of inverse stratification is never a straight line, and why, even in larger lakes and at the moderate depth of 20 m. to 25 m., bottom temperatures are rarely so low as 1°. I ought to add that Wedderburn ('09) seems to understand this relation very fully. His paper was received just as this is going to press.

Thus many of the facts of lake temperature find an easy explanation when the principle is accepted that the thermal resistance to mixture increases as the temperature departs from 4°. I have called especial attention to its bearing on those problems for which students of limnology have found only a partial solution. Among these are the rapid warming of the lake in spring and early summer; or stated in a different way, the rapid descent of the isotherms as the lake begins to warm, as compared with the slow penetration later in the season of isotherms representing higher temperatures. Similar problems are the cooling of the lake below 4°; the position, persistence, and stability of the thermocline in spite of disturbance by violent winds. In all of these and other cases which involve the work of the agents for distributing heat, the fact must be considered that a limit is always set to the efficiency of these agents by the thermal resistance to mixture. Water is so nearly a perfect fluid that if its temperature could rise without a change of density the distributing agents in any lake would quickly distribute the warmer surface strata through the whole mass of the water. The most effective means of limiting this distribution is the rapid increase of the rate of decline of density as the temperature rises.

In this discussion it has been assumed that water is a perfect fluid. This is not the case; water is viscous and its viscosity is not without influence on the ability of the wind to mix it. If a lake were composed of a perfect fluid, thermal resistance would be the only force opposing mixture. In a lake filled with a very viscous fluid, like glycerine, viscosity would be far more effective than thermal resistance in opposing mixture.

The amount of the viscosity of water at temperatures between 0° and 30° may be seen from the following table.

Table of viscosity, from Landolt and Börnstein.

Temperature.	Dynes per sq. cm.	Relative viscosity
0°	0.01778	2.23
5°	0.01510	1.89
10°	0.01303	1.63
15°	0.01134	1.42
20°	0.01002	1.26
25°	0.00891	1.12
30°	0.00798	1.00

From this it appears that water has sufficient viscosity to offer some resistance to the action of the wind which attempts to move the particles on each other and thus to mix them. It appears also that the viscosity is very small, but that it is greater at low temperatures and that it increases at a rate which rises as the temperature falls.

Viscosity offers a hindrance to mixture which cannot be stated in terms of ergs. It has been impossible to find a quantitative relation between thermal resistance and viscosity so as to ascertain exactly how much the increase of the latter at low temperature would affect the influence of the wind. Yet it seems clear that it does not have a great influence. The present question is one of the relative influence of viscosity at different temperatures, and viscosity plainly increases far more slowly at low temperatures than thermal resistance diminishes.

If we attempt to mix in a unit of time a column of water, the area of whose base is 1 sq. cm. and whose height is 1 m., viscosity will offer a resistance to be overcome. From the table given above it appears that this resistance is about twice as great at 4° as at 30°. The thermal resistance to mixture for a temperature difference of 1° decreases 37.5 times if the average temperature falls from 30° to 4°. Between 10° and 4° the thermal resistance decreases over ten times, while the viscosity increases by less than 20%, or less than 1-50 as muck Thus it appears that the decline of the thermal resistance i far more rapid in water than is the increase of viscosity, an the increased ratio of decline as the temperature nears 4° i much greater than the ratio of increase of viscosity.

It is impossible to say how much must be added to the num bers in column V if it is desired to express by them not only the work done against gravity but also that against viscosity in mixing a unit column of water in a unit of time. But i is clear that the addition, whatever it may be, cannot be more than doubled between 30° and 4°.

This is not the place for a complete discussion of the various factors aiding or opposing the distribution of the surface water through the lake, but it may be pointed out that since the influence of the wind will vary as the square of its velocity, the greater amount of wind in the spring will more than compensate for any increase in viscosity. The average velocity of the wind in Madison in July is about 8.3 miles per hour and in April 11.6 miles. The ratio of the squares of these numbers is about as 1 to 2, showing that the mixing power of the wind in April is about twice as great as in midsummer.

Literature Cited.

Groll, '05: Der Oeschinensee. Max Groll. *Jahresber. der Geog. Gesellschaft von Bern,* xix: pp. 1–78; 7 figs.; 2 maps.

Richter, '07: Seestudien. E. Richter. *Geog. Abhld. herausgegeben von Prof. A. Penck in Wien.,* vi, H. 2: pp. 1–72; pl. I–II. Wien, 1897.

Ule, '01: Der Wurmsee (Starnbergersee) in Oberbayern. Eine Limnologische Studie. Willi Ule. *Wissenschaft. Veroffentlich. des Vereins für Erdkunde zu Leipzig,* v: pp. i–vi, 1–212; pl. 5; figs. 15 and atlas of 8 plates. Leipzig, 1901.

Wedderburn, '09: Temperature Observations in Loch Garry (Invernessshire). With Notes on Currents and Seiches, E. M. Wedderburn. *Proc. Roy. Soc. Edinburgh,* xxxix, pt. ii: pp. 98–128; figs. 1–6. Edinburgh, 1909.

PLATE LXIV.

EXPLANATION OF PLATE LXIV.

Plate LXIV, from Groll, '05, represents the change of density in water due to rise of temperature and gives in graphic form the facts of column III, p. 991. The degrees are given at the bottom of the plate and the loss of weight, in grams per liter for each rise of 1, is platted on the vertical scale. The ordinates show the difference in weight between a liter of water at any given temperature and at 4°.

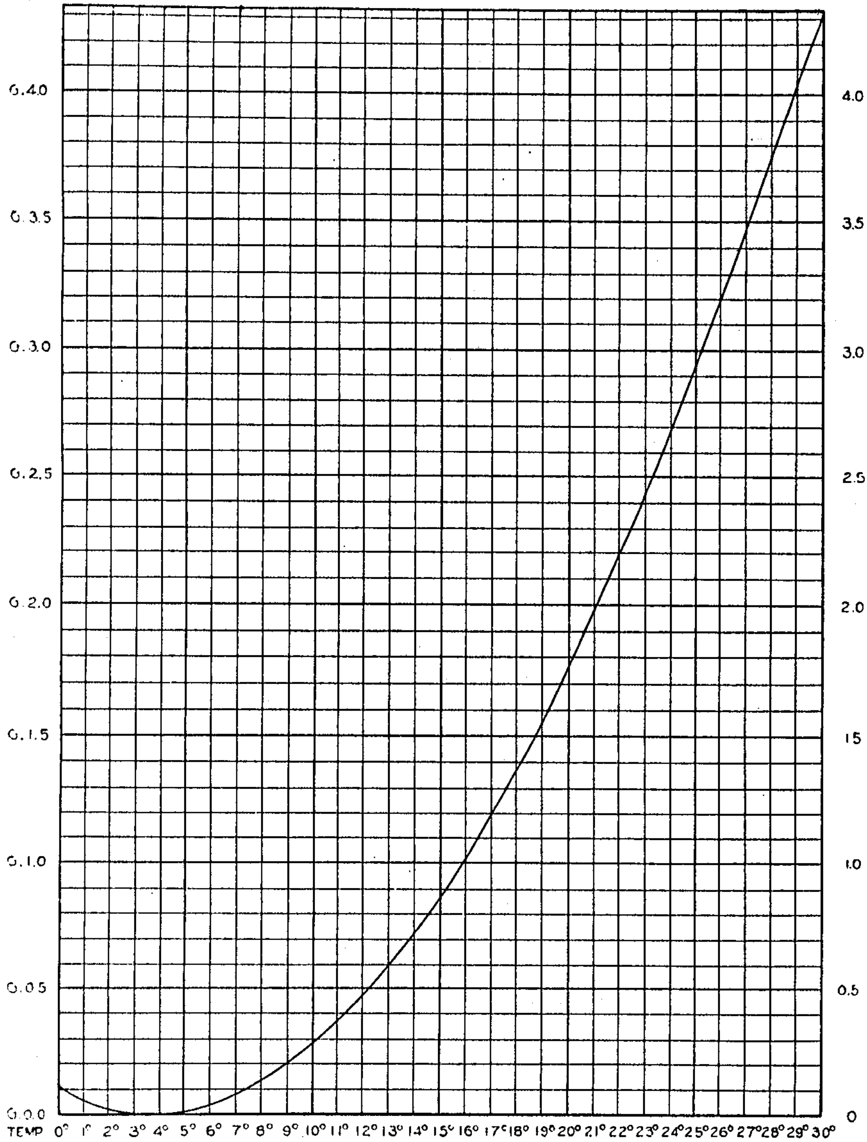
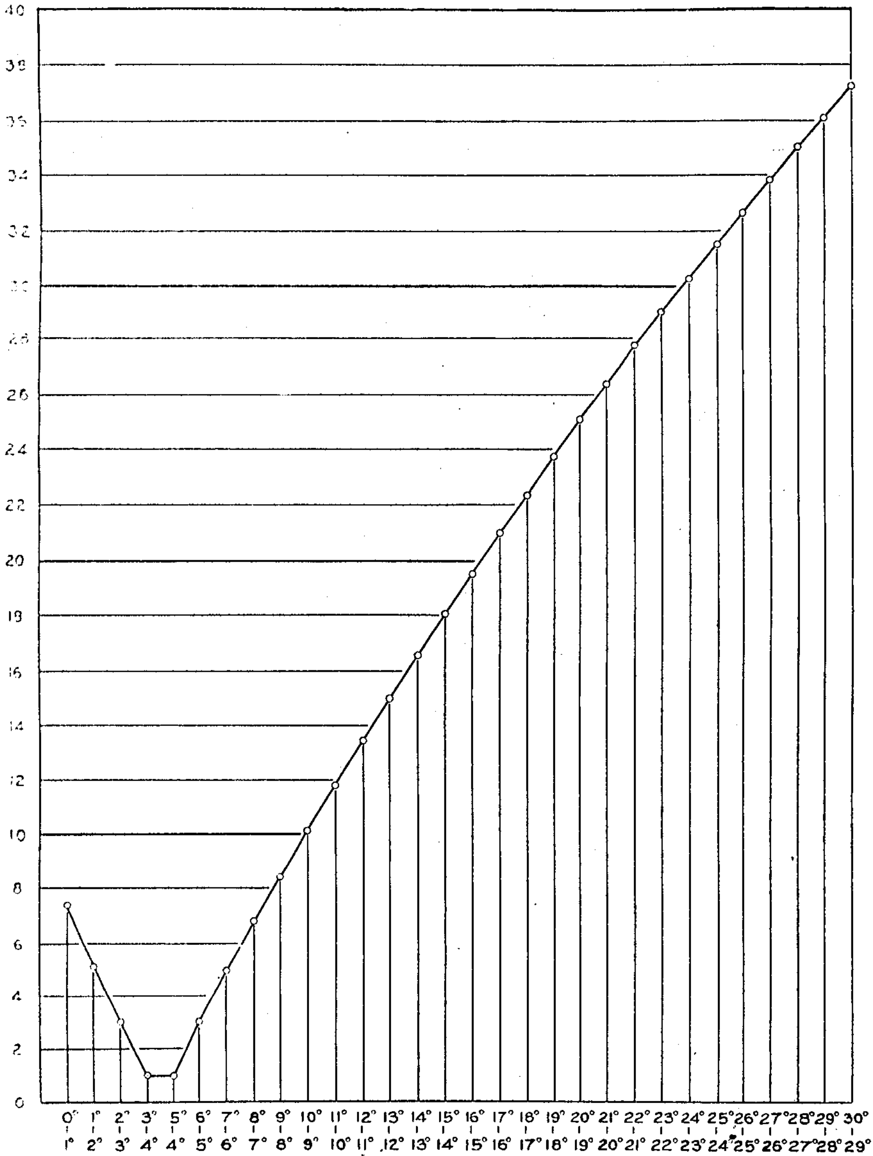

0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
TEMP 0° 1° 2° 3° 4° 5° 6° 7° 8° 9° 10° 11° 12° 13° 14° 15° 16° 17° 18° 19° 20° 21° 22° 23° 24° 25° 26° 27° 28° 29° 30°
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0

PLATE LXV.

EXPLANATION OF PLATE LXV.

In plate LXV the facts of column IV, p. 991, are shown graphically. The numbers at the bottom of the plate give the temperatures of the upper and lower surfaces of a column of water having unit area and height. Ordinates express the relative thermal resistance to mixture, that at 3°–4° and at 5°–4° being taken as unity.


40
38
34
32
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0° 1° 2° 3° 5° 6° 7° 8° 9° 10° 11° 12° 13° 14° 15° 16° 17° 18° 19° 20° 21° 22° 23° 24° 25° 26° 27° 28° 29° 30°
1° 2° 3° 4° 4° 5° 6° 7° 8° 9° 10° 11° 12° 13° 14° 15° 16° 17° 18° 19° 20° 21° 22° 23° 24° 25° 26° 27° 28° 29°

ON THE EVIDENCE FOR TEMPERATURE SEICHES.

EDWARD A. BIRGE.

[Notes from the Laboratory of the Wisconsin Geological and Natural History Survey. VI.]

The term *temperature seiche* was introduced by Watson ('04) in discussing certain periodic oscillations of temperature in the deep water of Loch Ness. He thought that these oscillations show that the isotherms of the lower water "are swinging as a whole about a transverse central axis." His explanation conceived a swinging of the hypolimnion*, as if the thermocline were the upper surface of water in a trough, above which floated a layer of lighter oil, representing the epilimnion. In 1907 Wedderburn ('07 a) reported experiments on a trough thus arranged, showing the possibility of a seiche, such as that postulated by Watson. Watson computed the period of a seiche in the hypolimnion of Loch Ness and found that it agreed with the observed period of the oscillations of temperature. His paper reported only the temperatures found at the depth of 200 feet, where the maximum oscillations occurred, and no profitable criticism of his theory could be made until the whole series of temperature records was published. This was done

* I employ two new words in this paper, which seem convenient in writing of the temperature and other phenomena of lakes. These terms are *epilimnion*, for the upper warm layer of water which develops in the lake in summer, and *hypolimnion*, for the lower colder water. These two parts of the lake differ widely in their temperature changes, as well as in their chemical and biological phenomena. It seems advisable, therefore, to assign definite names to them. The word *thermocline*, first used by me in 1897, is the equivalent of Richter's term *Sprungschicht*, or the *discontinuity layer* of Wedderburn. It lies at the top of the *hypolimnion*.

by Wedderburn ('07), who printed all of the observations and also (pp. 420–427) repeated the theory in more detail. The next year Wedderburn ('08) recapitulated the theory and says that after the epilimnion has been established the variations of temperature in the lower water are "principally due to the temperature seiche." Our ideas regarding the change of temperature in the hypolimnion will be greatly changed—or rather revolutionized—by this theory, if it is correct. An examination of the evidence for it is, therefore, not out of place.

Wedderburn's paper of 1907 is by far the most complete one on this subject and my remarks are based mainly upon it. It does not appear that the observations of 1903, which were employed by Watson, can be profitably discussed in detail, since they were taken at intervals of about twelve hours—morning and afternoon—and so give no detailed picture of the movements of the water or of the wind. Wedderburn, however, gives an admirable series of temperatures, taken in Loch Ness in 1904, chiefly from a yacht anchored near Fort Augustus at the southwest end of the lake. Besides very numerous series of temperatures, taken at less frequent intervals, observations were made every two hours, day and night, from Aug. 1 to Aug. 24. I do not know any similarly complete series of lake temperatures from any other source. It is from this series that Wedderburn draws his chief illustrations of seiches, and to this I shall refer.

In discussing the question of temperature seiches it should be said that no one doubts the presence of oscillations "in the lower layer independent of movements progressing in the upper layer" (Wedderburn, '07, p. 422), or of temperature changes resulting from them. These have been frequently observed; they are always going on and are very numerous and complex. The undecided questions are (1) whether there are present in the hypolimnion stationary waves, series of pendular movements of the whole mass of this water, and (2), if so, what are the extent and importance of such movements. It is plain that there is no general or *a priori* reason why such temperature seiches should not exist; on the contrary, they might be expected to be present. The action of the wind, depressing the hypolimnion on the lee side of the lake and raising it on the windward side, furnishes the conditions for starting a seiche. But as the wind declines or ceases and the hypolimnion swings back toward its former position, does it continue its movement, rising above the normal at the lee side of the lake, and then falling so as to start a series of pendular oscillations? Or is the return so slow and the hypolimnion so loaded by the epilimnion that movement practically ceases when the isotherms have returned to the horizontal position? If the first question is answered in the affirmative, then what are the extent and influence of such pendular oscillations? These questions are to be answered on the basis of observation. If periodic movements of considerable magnitude can be shown which, started by the wind, are thenceforward independent of the wind and of the movements of the epilimnion, then the case is proved.

I must confess that I find the evidence adduced by the Loch Ness observers insufficient to prove their case. Neither Watson nor Wedderburn seems to have carefully discriminated movements directly associated with wind from those which are possibly independent of it. All movements of the surface of the hypolimnion are apparently referred to indiscriminately as seiches. Even the greatest temperature changes are listed as seiches, which, if they were such, would involve a vertical swing of the water amounting to 200 feet, or more. An amplitude of 100 feet is said by Wedderburn to be quite ordinary. Many of the movements in July, 1904, as well as all of those of August, seem to be regarded as seiches. Certainly there must have been some movements which were correlated with the wind, and it would seem that Watson and Wedderburn should analyze the complex movements of temperature in and below the thermocline and should point out which are due to seiches and which are of other types. Yet no attempt is made to do this and I cannot see that either author furnishes any criterion by which to discriminate temperature changes due to a seiche from those due to other movements of the hypolimnion.

It should also be noted that the position of the yacht, (Fig. 1) where the temperatures were taken, was singularly well adapted to show movements of the water caused by wind and ill adapted for recording seiches. It lay close to the shore, about 300 yards from the southwest end of the lake and in 300 feet of water. The main lake extended, like a broad river, for 20 miles to the northeast. Every northeast wind must fill this end of the lake with warm surface water, and

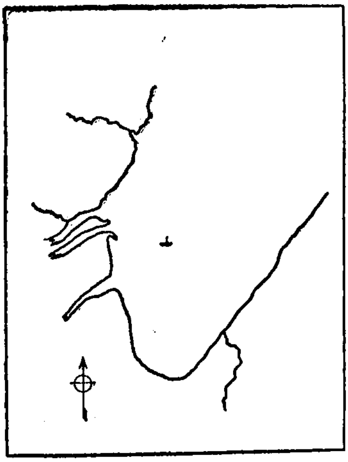


Fig. 1. Sketch map of the south-west end of Loch Ness, showing position of yacht used as observing station. Scale, 1.5″=1 mile.

every southwest wind must blow it out again. The yacht lay so close to the shore that the underwater movements induced by wind must readily affect the temperatures. Every student of lake temperatures will also notice the fact that the yacht lay at one side of the outlet of the small bay that forms a pocket at the end of the lake. Any wind that pushed the water at all obliquely against the southeastern shore would fill this pocket and thence the warm water would gradually work out toward the yacht, moving up toward the northern shore.

The observations of August, 1904, are far more valuable in this discussion than all of the others combined, since they were taken at frequent intervals day and night; the thermocline was present; and the force and direction of the wind were recorded. I shall, therefore use these in my discussion, especially as Wedderburn's illustrations are almost wholly taken from them.

The diagram of temperature movements which Wedderburn gives ('07, p. 421) is not easily read. I have, therefore, platted on a different scheme and a larger scale his observations from noon of Aug. 14 to noon of Aug. 21, (Plate LXVI). This period includes three of the five major movements of the thermocline which came in August, and also includes the swing that looks to me most nearly as I suppose a great seiche would appear. The rise of temperature in the hypolimnion, shown in the center of the diagram (Aug. 17), is that chosen for special illustration and discussion by Wedderburn. It seems to me plain that this great swing of the isotherms was not a seiche, as defined by Watson. Examination of the diagram will show that during Aug. 16 the wind was constantly from the southwest, off shore, and the isotherms steadily rose as the warmer surface water was blown away, until in the afternoon the epilimnion practically disappeared. At 4 a. m. of Aug. 17 the wind shifted to east and then to northeast and blew from that quarter for nearly 20 hours. Under its influence the warm surface water returned to fill the end of the lake, crowding down the hypolimnion. After some ten hours of this wind, the filling extended out to the yacht and caused a sudden and great rise of temperature. Then as the northeast wind dropped and was followed by calms and southwest breezes, the displaced hypolimnion swung back toward its normal position and the isotherms rose with it. This is my reading of the movement, nor can I see ground for a different interpretation. It is certainly clear that the movement was by no means independent of conditions in the epilimnion but, on the contrary, was directly associated with changes of wind which must shift the epilimnion and so tend to cause the movement of temperature in the hypolimnion. These forces also seem wholly adequate to effect it and there is no need of supposing a seiche in order to explain it.

If this temperature change was caused by an on-shore wind, it is obvious that the sudden downward sweep of the isotherms, corresponding to the great change of temperature in the deeper water, does not represent a corresponding and equally rapid vertical movement of the water, or indeed any considerable vertical movement at all. If this and similar temperature changes are due to seiches, then the vertical movements of the isotherms, as platted on the diagram, represent equally well the vertical movements of the water. Wedderburn does not hesitate to accept this result. He assigns an occasional amplitude of 200 feet to the temperature seiche ('07, p. 426) and thinks that an amplitude of 100 feet is nothing out of the ordinary. He also states ('07, p. 422) that on August 17 the temperature rose 8.3° F. in 15 minutes at a depth of 100 feet. This change, if due to the lowering of the surface of the thermocline, means a movement of at least 50 feet in the same time, and in the course of the general temperature movement of this day there would have been a depression of the thermocline amounting to over 100 feet during two hours. I find it difficult to believe in such great movements of the hypolimnion. They are so large and so rapid that they should cause serious disturbances at the surface of the water, which have never been observed. But if the explanation of these temperature changes, which I have given above, is accepted, no such violent and rapid movements of the hypolimnion need be assumed. As the space between the yacht and the shore was gradually filled with warm water, forced to the end of the lake by the wind, the colder water was crowded downward and outward. The front of this growing mass of warm water gradually moved out into the lake as new additions were made to it, and when it reached the observing station the thermometer recorded a very sudden and great rise of temperature, which however, involved no corresponding movement of the water but only a comparatively small displacement, chiefly lateral.

The complex phenomena, caused by wind, with their resulting temperature changes, cannot be readily analyzed from observations made at a single point, but before we can accept temperature seiches as their cause, there must be observations sufficient in number and position to exclude other and more easily received explanations.

In like manner may be seen that all of the considerable rises of temperature in the deeper water of Loch Ness during August were preceded or accompanied by a northeast or on-shore wind. The relation is plain in the movement of Aug. 15, as is shown on the diagram. The similar movement of the isotherms on the night of Aug. 22–23 coincided with an on-shore wind. The same is true of the movements on Aug. 11 and the night of Aug. 19–20, although they need separate discussion. The decline of temperature at a depth of 50 feet on Aug. 8, referred to as a seiche by Wedderburn ('07, p. 422) was accompanied by southwest or off-shore wind and by a fall of surface temperature certainly due to this wind. The similar drop of temperature at 50 feet on Aug. 14, also referred to by Wedderburn, coincided with a shift of wind from northeast to southwest and the temperature rose again when the wind turned, at 10 p. m., to the northeast. Thus every considerable shift of temperature in and below the thermocline during August was precisely that which might have been predicted as probably resulting from the meteorological changes; the position of the observing station and the direction of the wind being known. So far from the evidence showing that these major oscillations are independent of changes in the epilimnion, they coincide with such changes and with meteorological forces directly adapted to cause them.

I do not mean to say that we are able thus to account for every change of temperature at every depth in this series of observations. We are ignorant of the underwater currents in Loch Ness, and of the minor effects of the winds; and their major effects are matters of inference rather than of observation. We know that these effects are numerous and complex. When a mass of warm water is once established at the lee end of a lake it often shifts and moves about in an irregular and quite incalculable fashion. It is acted upon by numerous forces, each quantitatively unknown, including not only wind currents but convection currents, as well as underwater currents set up in the past, and the numerous and doubtful interactions between this warm mass and the cold outer water crowding in upon it. But if seiches are to be asserted as the main factor in temperature changes in the hypolimnion, the temperature phenomena must be clearly analyzed and it must be shown which of them are due to the immediate influence of wind, which to irregular movements of the hypolimnion, and which to stationary waves or seiches.

There remain to be considered the movement of midnight Aug. 19–20 and also that of Aug. 11, which though of smaller amount is a similar case and open to similar explanation. Wedderburn does not refer to these movements of the isotherms, although they appear more like temperature seiches than any of the other swings of temperature in August. This is especially clear in the movement of Aug. 19–20. Reference to the diagram will show that on Aug. 19 a northeast wind began at 2 a. m. and caused a slight but obvious descent of the isotherms at 6 and 8 a. m. After 10 a. m. there was little, or no wind recorded during the day; at 8 p. m. it was northeast again, followed by light southwest breezes and calm during the night. Between 6 and 8 p. m. began a rapid descent of the isotherms, culminating at midnight. They remained about stationary during four hours, or more, then swung back to their former position, and later, on Aug. 22, to a still higher level under the influence of a southwest wind.

In this case there is plainly an on-shore wind associated with the rise of deep water temperatures. It is plain also that the rise is greater than would have been expected from the amount of wind and that it came later than in the other cases. Thus the descent of the isotherms seems not wholly but to some degree independent of the movements of the epilimnion and their rise is practically independent of the wind. It is also to be noted that the 45° isotherm began to move downward some four hours before the 50° isotherm. The question is not one of association of these movements with an on-shore wind, but of the adequacy of the wind to produce so great a swing of the isotherms, which, with a much smaller amount of wind than on Aug. 17, is a swing of the same general order of magnitude as that.

I believe that this movement was a secondary effect of that of Aug. 17 and that it was directly caused by underwater currents set up by the northeast wind of Aug. 19 and which continued to move slowly after the wind died away. It must be remembered that conditions on Aug. 19 were very different from those on Aug. 17. When the northeast wind began on the former date, the southwest wind, extending through the preceding twenty-four hours, had blown all of the warm water from the southern end of the lake. Several hours and much wind were, therefore, necessary to bring it back. But on Aug. 18 there was little wind; a large mass of warm water remained at the yacht and there was doubtless much more in-shore. It required, therefore, only a small amount of northeast wind to put the deeplying warm water into motion again. I suppose that the mass of warm water, accumulated by the wind of Aug. 17, moved out to the observing station, causing the rise of temperature before midnight of Aug. 19–20, and then was either crowded back or pushed past the station, causing the fall of temperature in the early morning of Aug. 20. I am very glad to admit that this movement looks like a temperature seiche, but the evidence that it is such is by no means complete, or even adequate. We do not know how much warm water lay in the southwest end of the lake on Aug. 19, nor do we know the extent or shape of the mass. We do not know that there was any corresponding movement of temperature in a reverse direction on Aug. 19–20 at the other end of the lake, or indeed that there was any movement of temperature at all. So far as the facts at hand give evidence, there is no reason which requires us to conclude that the disturbance of Aug. 19 was a different kind of phenomenon from that of Aug. 15, 17, or 22; in each of which not only is the qualitative relation to the wind distinctly marked but the quantitative relation seems adequate.

Thus after a review of the clearest evidence for temperature seiches, adduced by Wedderburn, I am forced to give my vote for the Scotch verdict of "not proven". I am quite ready to accept seiches of any period or amplitude that can be proved, but I cannot see that we ought to accept seiches of 200 feet amplitude, or even of any amplitude, on the evidence presented.

It is unfortunate for the establishment of the seiche theory that Loch Ness is so long. The period of its oscillation, about two days, is so great that it must be difficult to find considerable movements which are not interfered with by the changes of weather and it is correspondingly difficult to eliminate the possible effects of wind. Still further, the fact that even in August the epilimnion may practically disappear, as it did on Aug. 16, adds to the difficulties of analysis of observations. A smaller lake of similar shape with an oscillation period of a few hours and with a much warmer epilimnion would offer far better opportunities for settling the question of the presence of temperature seiches, of their magnitude, if present, and of their importance in the temperature changes of the hypolimnion. Loch Ness, of course, has an advantage over a smaller lake in possessing a hypolimnion of enormous mass, so great that the loading due to the epilimnion may well be inadequate to damp the temperature seiches, if such are started.

If I may hazard a doubtful opinion, I would say that I believe that such seiches may be found to exist. I believe also that in most lakes they will be of small extent and of small influence upon the temperature. Great and rapid changes of temperature in the hypolimnion are due mainly to definite movements of its water, directly caused by the shifting of the epilimnion under the action of the wind. Minor changes and the slow rise of temperature in the hypolimnion seem to be caused chiefly by the irregular currents which result from the major movements and which may persist long after their direct cause has disappeared.

Literature Referred To.

Watson '04: Movements of the Waters of Loch Ness, as indicated by Temperature Observations. E. R. Watson. *Geog. Jour.*, xxiv: pp. 430–437; Figs. 1–3. London, 1904.

Wedderburn '07: The Temperature of the Freshwater Lochs of Scotland, with special reference to Loch Ness. With Appendix containing Observations made in Loch Ness by Members of the Scottish Lake Survey. E. M. Wedderburn. *Trans. Roy. Soc. Edinb.*, xlv, pt. ii: pp. 407–489; Figs. 1–15. Edinburgh, 1907.

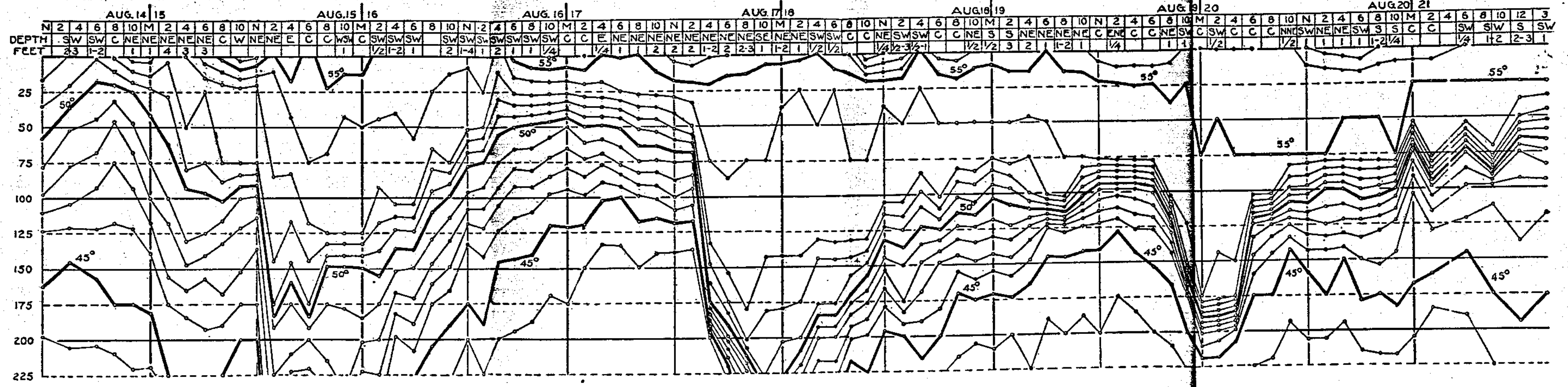
Wedderburn '07a: An experimental Investigation of the Temperature Changes occurring in Fresh-Water Lochs. E. M. Wedderburn. *Proc. Roy. Soc. Edinb.*, xxviii, pt. i; pp. 2–20; figs. 1–14. Edinburgh, 1908. (Issued separately, Dec. 1907.)

Wedderburn '08: Notes on the Temperature of the Water in Loch Ness. E. M. Wedderburn. *Geog. Jour.*, xxxi: pp. 41, 52–56; figs. 1–3. London, 1908.

EXPLANATION OF PLATE LXVI.

This plate shows the movement of temperature in Loch Ness, Aug. 14–21, 1904. In the heading of the diagram, the first line gives the hour of the day; N represents noon, M, midnight. The second line gives the direction of the wind and the third gives its force. Temperatures are recorded in Fahrenheit degrees and depths in feet. The data are taken from Wedderburn '07, pp. 472–474. In this paper the temperatures are recorded for intervals of 25 feet. From these data the position of the full degrees has been platted, assuming a uniform temperature gradient in each 25-foot stratum. These points are indicated by small circles, and the successive positions of each degree are connected by straight lines. The lines representing 45°, 50°, 55° are made heavier than the others.

Thus the diagram represents the movements of the isotherms in the water, as influenced by sun, wind, and currents.


AUG. 14
15
AUG. 15
16
AUG. 16
17
AUG. 17
18
AUG. 18
19
AUG. 19
20
AUG. 20
21
DEPTH
FEET
25
50
75
100
125
150
175
200
225
55°
50°
45°