On the Thermal Stratification of Sea Water and its Importance for the Algal Plankton.

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With Three Figures in the Text.

IN a previous paper (1924) the writer considered the factors which bring about the mixing of surface water, warmed by the sun, with the cooler water below. Observations were cited to show that in the English Channel, between May and September, a warm surface layer may exist, which differs from the deeper water in being more alkaline and poorer in phosphates ; both these differences are due to the activity of the phytoplankton. The reduction in phosphate proceeds in the upper well-illuminated layer till none is left. No further increase in phytoplankton is then possible till phosphate is set free by decomposition or supplied by mixing with the deeper water. The phenomena of thermal stratification are consequently of great importance in the study of the phytoplankton.

Such stratification has been considered at length by Birge and Juday (1911) in their limnological studies. Birge (1910) designates the upper warm and the lower cold layers the " epilimnion " and " hypolimnion " respectively. These terms connoting very different biological habitats are undoubtedly useful, but from their derivation are not strictly applicable to sea water. It is suggested that the terms " epithalassa " and " hypothalassa " should be used to denote these layers in sea water, the region between them being denoted by the well-established term, thermocline, introduced by Birge in 1897.

The epithalassa usually persists throughout the summer months ; though the rough seas of June, 1922, almost destroyed it, yet it became apparent again in August. Its stability is, in fact, surprising, but Birge (1910) has given reasons which render the persistence of the epilimnion intelligible. These apply equally to the epithalassa as shown by the figures which follow.

The effectiveness of the resistance to mixing, due to increase of temperature, is not proportional to the temperature gradient simply, but depends also on the departure of this temperature from that of the maximum density of the water.

The decrease in density as water is removed from the temperature of maximum density is not constant, but increases. Groll (1905) pointed out the bearing this has upon the origin of convection currents. Wind, however, appears to be the chief factor concerned in the mixing of warm

TABLE

$t°$	D^t	$\Delta \times 10^5$	Relative Δ for 2°.	Δ relative to fresh water.	Ergs salt water.	Ergs fresh water.
−2	1·02845	8	1·00	2·50	680	—
0	1·02837	13	1·62	4·05	1083	833
2	1·02824	19	2·38	5·95	1583	267
4	1·02805	24	3·00	7·50	1997	267
6	1·02781	28	3·50	8·75	2332	766
8	1·02753	32	4·00	10·0	2665	1241
10	1·02720	36	4·50	11·25	2998	1682
12	1·02684	40	5·00	12·5	3332	2116
14	1·02644	44	5·50	13·75	3665	2507
16	1·02600	48	6·00	15·0	3997	2899
18	1·02552	51	6·39	16·0	4248	3266
20	1·02501	54	6·75	16·9	4498	3607
22	1·02447	58	7·25	18·1	4831	4009
24	1·02389	61	7·62	19·05	5046	4273
26	1·02328	64	8·00	20·0	5331	4589
28	1·02264	67	8·37	20·95	5581	4881
30	1·02197	—	—	—	—	—

surface water with cold bottom water. During the summer the density differences between the top and bottom are far greater than during the spring and autumn; it is this fact and not only the diminished force of the wind in summer that permits of the establishment and persistence of the epithalassa.

Birge has tabulated, for fresh water, temperatures from 0–30° C., densities at 1° intervals, the density differences for 1° and the relative differences for 1° C., taking that from 4° to 3° and from 4° to 5° as unity. He also tabulates, for temperatures from 0°–30°, the number of ergs.

work done against gravity in mixing a column of water of one square centimetre area, one metre high, whose upper and lower surfaces differ in temperature by 1° the gradient being uniform. This may be calculated from the equation :—

$$W(\text{ergs}) = \frac{Ah^2}{12}(D_2 - D_1)$$

where A denotes the area and h the height, D_1 and D_2 being respectively the densities of the lower and upper strata of the column.
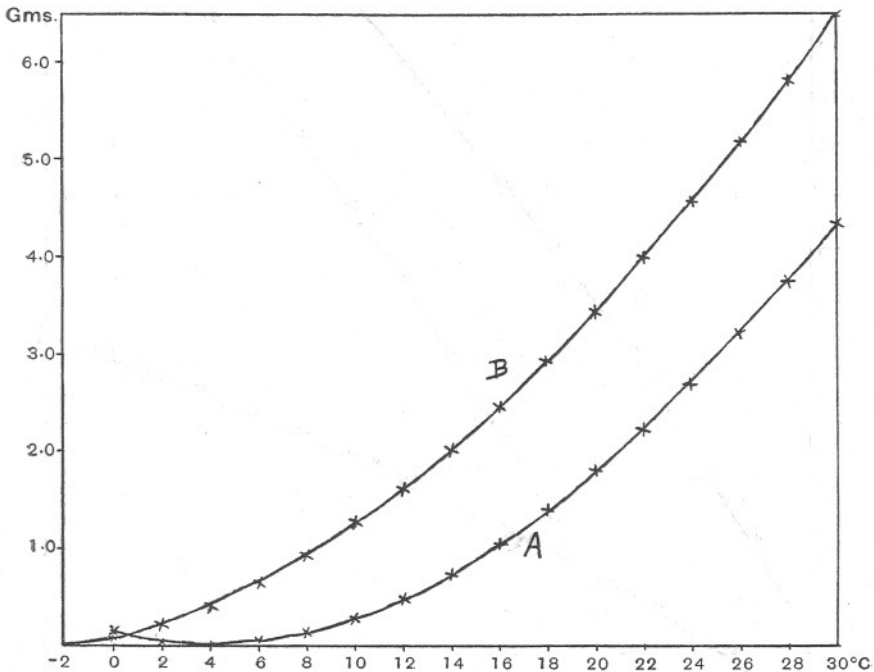

FIG. 1.—The curves represent changes in density due to rise of temperature. The ordinates show difference in weight, in grams, between a litre of water at temperature t° and 4°, curve A, and between t° and −2°, curve B, which is for water of salinity 35·3°/$_{oo}$. For example, in B, $D_{\frac{-2}{4}} = 1\cdot02845$ and $D_{\frac{14}{4}} = 1\cdot02644$, viz. 2·01 gms. less per litre, as may be read off on the curve.

The number of ergs is, therefore, 833 times the difference between the densities.

In order to apply these density changes to sea water calculations have been made of the density of sea water of 35·3°/$_{oo}$ salinity, such as is found in the west of the English Channel, at a series of temperatures from −2° to 30°. The freezing-point of such sea water
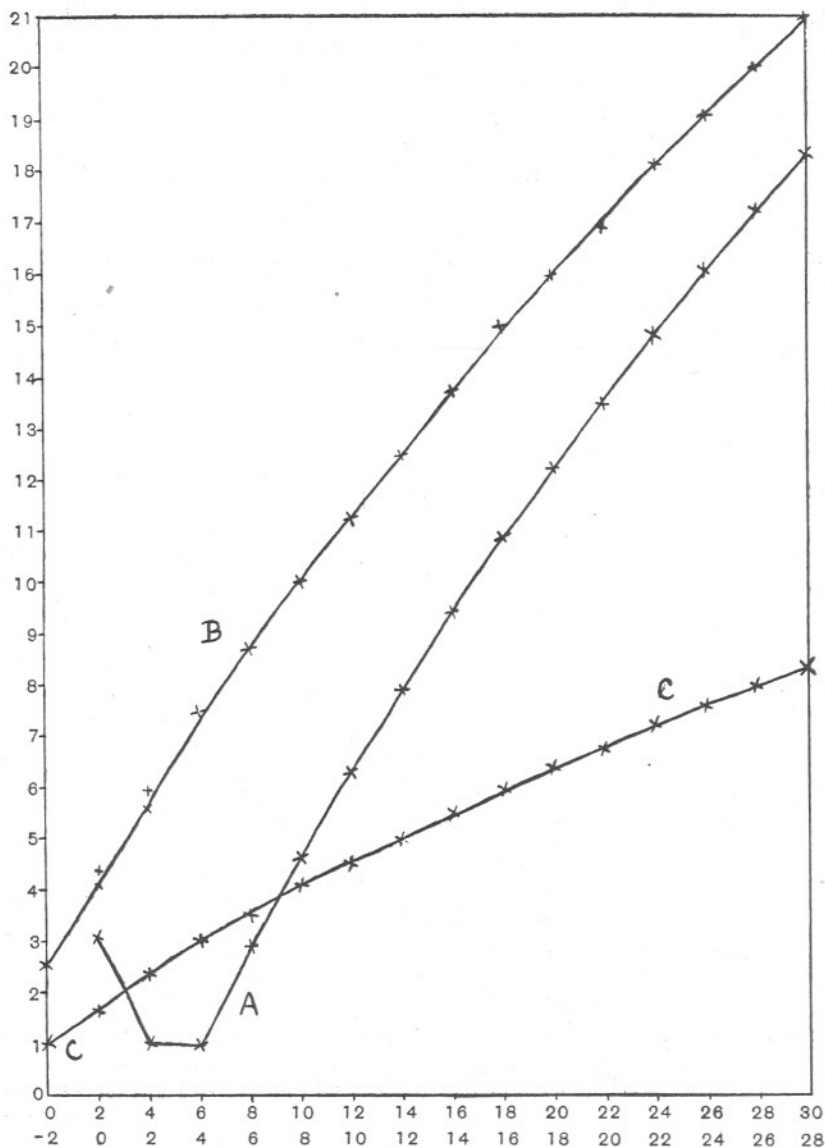
Fig. 2.—The ordinates indicate relative thermal resistance to mixing, and are in reality
ratios of the change in density over the given ranges of 2° C. relative to that
of water from 4° to 2° or from 4° to 6° as unity, viz. the ratio of $(D\frac{t-2}{4}-D\frac{t}{4})$
to $(D\frac{4}{4}-D\frac{2}{4})=(D\frac{4}{4}-D\frac{6}{4})$. Curve A is for pure water, curve B for water of
$S=35\cdot3°/_{oo}$. Curve C is the ratio for $(D\frac{t-2}{4}-D\frac{t}{4})$ relative to $(D\frac{-2}{4}-D\frac{0}{4})$
for the water of curve B. The abscissæ represent the temperatures of the
upper and lower surfaces of a column of water of unit area and height, but
for pure water the temperatures 4° over 2° and 2° over 0° should be inverted.

differs by only a few hundredths of a degree from $-2°$. For the calculations the formulæ and constants given in Knudsen's Hydrographical Tables were used.

In the table (see p. 694) are recorded the densities obtained as described, together with, under $\triangle$, their differences for intervals of 2° C. The fourth column shows the values of $\triangle$ for 2° intervals, relative to that
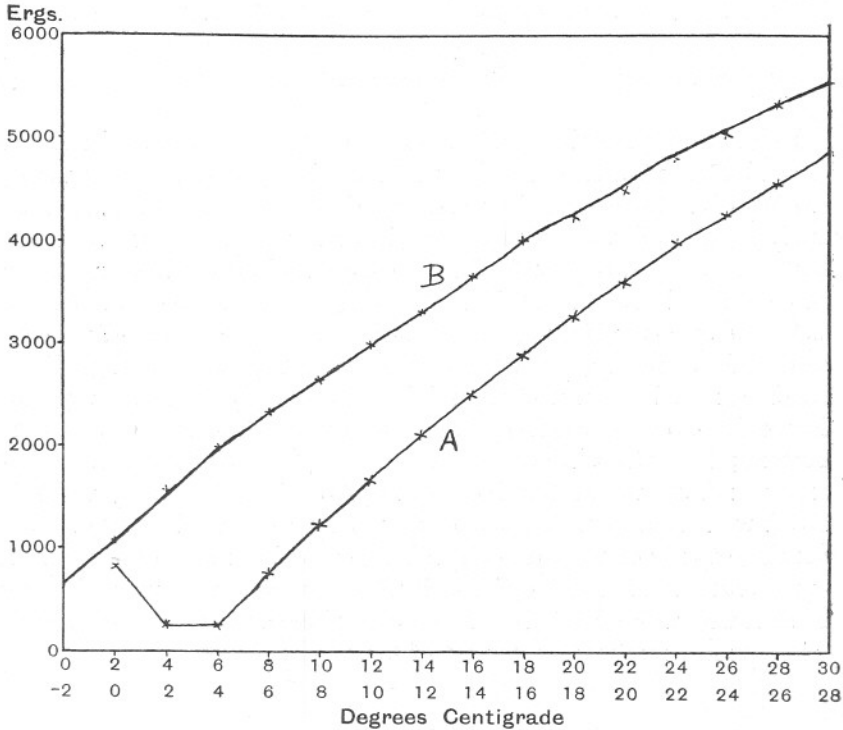
Fig. 3.—The ordinates show ergs of work done in mixing columns of water, one metre high and one square metre in area, whose upper and lower surfaces differ by 2° C., the upper being the warmer. The abscissæ indicate the temperatures of the surfaces. Curve A is for pure water, modified from Birge. In it the temperature figures 2° over 0° and 4° over 2° should be read 0° over 2° and 2° over 4°. Curve B is for water of $35\cdot3°/_{oo}$ salinity.

for $35\cdot3°/_{oo}$ salinity water between $-2°$ and $0°$. The fifth column records the values of $\triangle$ relative to that for pure water over the range 2° to 4° or 4° to 6° as unity. The sixth column sets forth the work done in mixing a water column as already described for sea water, but with 2° temperature gradient. Also to obtain whole numbers the area taken was one square metre instead of one square centimetre. In the seventh column the corresponding values for fresh water have been quoted from Birge's

paper, but as he calculated on a 1° gradient the figures given here are the sums of his values taken in pairs. The value for $\triangle$ between $-2°$ and $0°$ is tabulated opposite $-2°$ and similarly for the other values.

In Fig. 1 (p. 695) are plotted the temperature-density curves for both fresh and salt water, 35·3°/$_{oo}$ salinity. Fig. 2 (p. 696) shows the values of $\triangle$ relative to salt and fresh water, also values of $\triangle$ for fresh water modified from Birge's data, which are for 1° intervals. In Fig. 3 (p. 697) the results of columns 6 and 7 are plotted, the temperatures of the tops and bottoms of the columns being abscissæ, as in Fig. 2, while the ordinates represent ergs of work required for mixing.

From Fig. 1 it may be seen that, on account of the complication introduced by the position of maximum density being at 4° for fresh water, the rate of decrease in density per degree rise in temperature is far less for fresh than for salt water, but the rate becomes more nearly the same the higher the temperature. This is more clearly brought out by Fig. 2, from which it may be found that the mixing of, for example, a column of fresh water 10° at its upper surface and 8° at its lower is only about 47 per cent as difficult as mixing salt water of the same temperature and gradient. Again it may be seen that the mixing of a water column 12° top, 10° bottom, is 4·5 times as difficult as if the same column were 0° top, $-2°$ bottom ; but if the temperatures were 16° to 14° respectively the resistance to mixing would have increased to 5·5 times. In Fig. 3, which is based upon Fig. 2, the resistance to mixing is shown by plotting the number of ergs of work done in mixing one cubic metre of water with upper and lower surfaces differing by 2° in favour of the upper. It may be seen that throughout the whole range plotted the mixing of fresh is effected more readily than is that of salt water.

SUMMARY.

1. A table has been drawn up showing the values of D_4^t for water of 35·3°/$_{oo}$ salinity from t$=-2°$ to t$=30°$. In it the values of $\triangle=(D_4^{t-2}-D_4^t)$ are shown as are also the values of $\triangle$ relative to $(D_4^{-2}-D_4^0)$ as unity. In addition the values of $\triangle$ relative to $(D_4^4-D_4^2)=(D_4^4-D_4^6)$ for fresh water are tabulated. From the foregoing the number of ergs of work required to mix completely one cubic metre of water, with upper and lower surfaces having initial differences of 2°, have been calculated for sea water over the range $-2°$ to $+30°$. For comparison Birge's values for fresh water are quoted.

2. The rate of decrease in density with increase in temperature in-

creases for both salt and fresh water, according as the actual temperature becomes further removed from the temperature of maximum density. Thus the relative value of $\triangle$ as defined above becomes 5·0 for water at 14° to 12° and 6·0 for 18° to 16°, while $\triangle$ relative to fresh water for the latter temperatures has the value 15·0. Owing to the differences in the temperatures of maximum density more work is required to mix a cubic metre of salt water than of fresh water, for 16° top to 14° bottom the number of ergs required are, for example, 3997 and 2899 respectively.

3. It results that the mixing of the surface water with the deeper is less readily brought about in summer than in winter, both on account of the lesser amount of wind and the increased differences in density. The warm surface layer, or epithalassa, gets depleted of phosphate by the phytoplankton, and as long as it persists the phosphate in the deeper layers is not fully utilized. The stability or otherwise of the epithalassa is consequently of great importance.

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