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SOME PHYSICAL FACTORS WHICH MAY INFLUENCE THE PRODUCTIVITY OF NEW ENGLAND'S COASTAL WATERS

BY

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Of recent years physical oceanographers have gradually gained a more satisfactory understanding of the circulation problem. While it is true that most of this advance has resulted from studying the deep, oceanic currents, nevertheless, the newer principles also can be applied to the more difficult conditions found near the coast. More and more the physical investigators are working independently from the marine biologists. It is hoped that the following discussion of factors causing variations in the temperature and salinity of coastal waters off New England will demonstrate the biological significance of some of the modern physical investigations, and also perhaps help to bring the two branches of oceanography closer together again.

In general, coastal areas and oceanic areas differ fundamentally as far as the vertical distribution of salinity is concerned. Over the continental shelf the salinity usually increases with depth and, therefore, adds to the thermal stability of the water-column; while off shore in the deep water it decreases with depth and thus partly counteracts the stability resulting from the vertical temperature gradient. The fact that the salinity is at a maximum near the bottom on the continental shelf shows conclusively that the coastal circulation has an off shore component at the surface and an in shore component beneath.

The coastal waters, because of their relative freshness, are at most times of year less dense than the corresponding layer off shore and consequently a current is maintained which, for some reason not clearly understood, tends to have its greatest strength just outside the 100 fathom curve. This contour in general also corresponds roughly in position to the boundary between the two contrasting water-masses. The lateral transfer across the current, off shore at the surface and in shore along the bottom, supplies salt to the coastal waters which, because of land drainage, would otherwise gradually decrease in salinity. Off New England, coastal water can be defined as having a salinity of less than 34 ‰, while higher values indicate an oceanic origin.

* Contribution No. 221.

If the continental shelf were more regular in depth and width, and in the absence of fluctuations in the oceanic currents, the necessary interchange between coastal and off shore waters would probably proceed at a steady, slow rate and a continuous current would flow along the 100 fathom curve. However, uneven bottom topography and major barriers such as Nantucket Shoals and Cape Hatteras tend to prevent a continuous and steady southward movement along the edge of our continental shelf. In addition, a number of deep troughs allow saline, off shore waters to work inward along the bottom in certain areas almost to the shore line. A notable example occurs in the Gulf of Maine where only a few miles east of Cape Cod salinities as high as 34.2‰ are found at the bottom. In general, however, wherever the continental shelf is straight and regular, as off New Jersey, the cross current components are less pronounced and there is less possibility of sudden fluctuations in the in shore conditions.

The exchange of waters across the 100 fathom curve is partly brought about by small scale mixing processes which result in a rapidly changing temperature-salinity correlation across the boundary between the coastal and the oceanic waters. In addition, there are frictional movements having a much larger scale which from time to time cause considerable volumes of relatively fresh water to move off shore near the surface. These intermittent movements are of course accompanied by a corresponding bottom invasion of more saline water, although the compensation can occur at some quite distant part of the continental shelf. From the standpoint of a biologist, the irregularity and strength of these large scale mixing mechanisms are of great significance, for they are capable of causing the death of large numbers of the population living near the edge of the shelf.

There are at least two different causes for the sudden, large scale, off shore movements of coastal water. During the autumn and early winter, especially if the inflow from rivers is for some reason particularly weak, the density of the waters over the continental shelf may become identical with that of the corresponding layer beyond the 100 fathom curve. In this case the coastal currents will die away and the winds are then free to force large masses of the relatively fresh, but cold, water off shore. It is indeed surprising that our coastal waters do not blow off to sea much more often than they do. Apparently their very great stability prevents the winds during most of the year from breaking down the local gradient currents. As long as a current is maintained along the 100 fathom curve, the in shore waters are in some way confined. No doubt bottom friction also plays an important role.

A second and more effective mechanism seems to depend on the large, frictionally driven eddies that from time to time develop along the northern edge of the Gulf Stream. These powerful eddies are often as much as 60 or 80 miles in diameter and thus can extend the whole distance from the edge

of the continental shelf to the Gulf Stream. They are known to occur north of the Gulf Stream at any point between Cape Hatteras and the Grand Banks, but they are most likely to be found off New York and off the Gulf of St. Lawrence. The structure of these eddies is as yet not well understood, nor is it known how long they persist. However, there is little doubt that, at least in their early stages, they can absorb large amounts of coastal

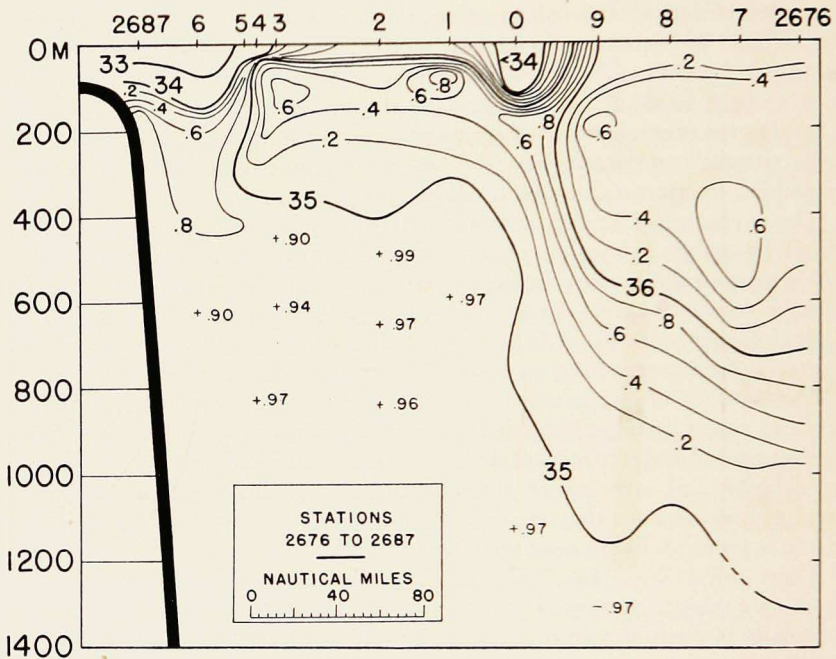


Figure 17. Salinity section, September 21-24, 1936, extending southeastward from the outer edge of Brown's Bank.

water. This they mix with Gulf Stream water and thus produce a surface layer of intermediate salinity, typical of this zone between the current and the edge of the continental shelf. This band, in which only weak permanent currents are found, is known as the slope water. The intermittent eddies can extend to considerable depths, but it is in the surface layer that the contrasting tongues of coastal and Gulf Stream water are observed. Thus tropical plankton becomes mixed with forms from our coastal shelf and both drift off slowly to the northeast, parallel to the Gulf Stream. No doubt the intermediate temperatures and salinities are unfavorable to most of these animals and in any case, the larvae of commercial fish, which happen to be

drawn into such eddies, will find themselves in deep water when the time comes to seek the bottom.

As yet no survey in the slope water area has had a sufficiently close station interval to reliably demonstrate the structure of these eddies. On several occasions, however, a single line of stations has crossed a body of almost undiluted coastal water as far off shore as the northern edge of the Gulf Stream (Figs. 17 and 18), but no direct observations are available to demonstrate whether such relatively fresh bodies of water are merely isolated pools or continuous tongues that have a connection with the waters

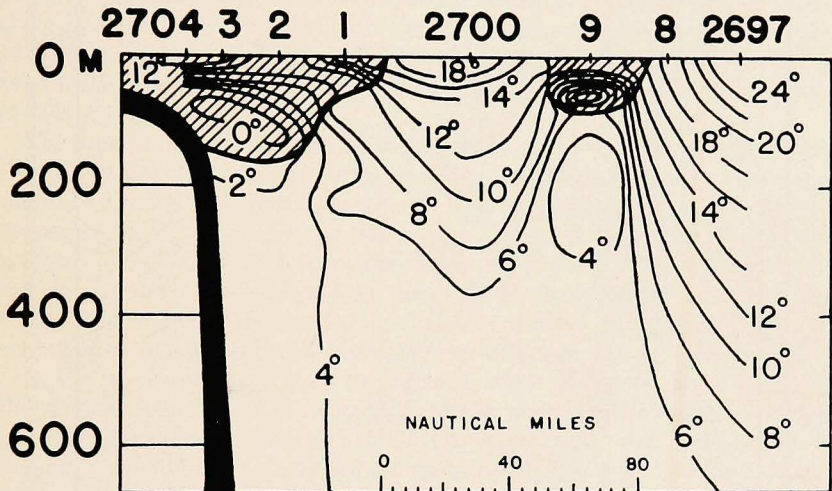


Figure 18. Temperature section, September 30–October 2, 1936, extending southwestward from the southern part of the Grand Banks. On this and subsequent sections the waters having salinities of less than 34‰ are indicated by the cross-hatched areas.

over the continental shelf. In Fig. 17 almost pure coastal water can be seen at Station No. 2680 on the very edge of the Gulf Stream. This section was made in September 1936 on a line extending southeastward from Brown's Bank. Further to the eastward on the same cruise other bodies of coastal water were observed (Fig. 18) well beyond the continental slope. The positions of these stations, along with those of other sections made by the "Atlantis" within a two weeks period, are shown in Fig. 19. The latter diagram also demonstrates one possible interpretation of this survey. Admittedly the network of stations is so wide that any horizontal projection can be drawn in several different ways, but if any confidence is placed in the principles of isentropic analysis (Montgomery 1938), it seems likely that from Georges Banks eastward on this occasion there were several

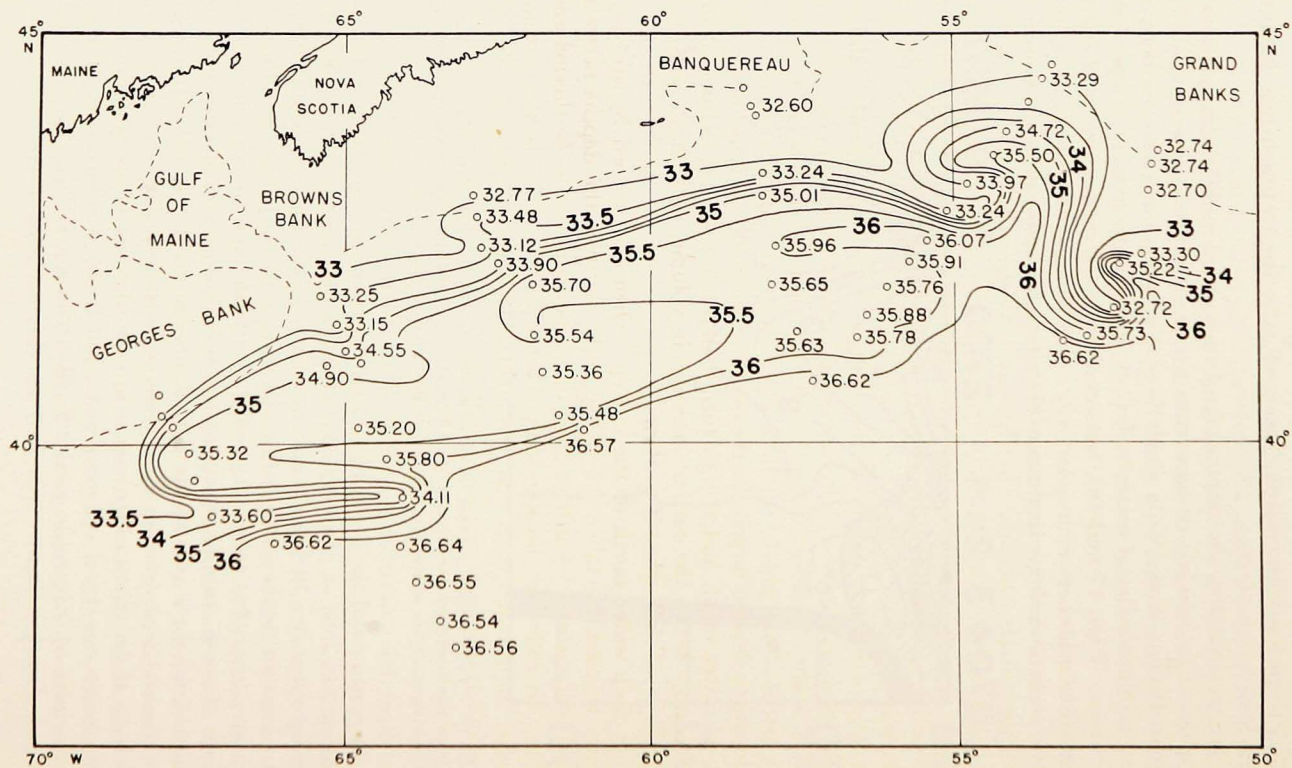


Figure 19. The distribution of salinity on the surface $\sigma_t = 26$ in the eastern slope water area, September 15–October 11, 1936.

tongues of coastal water being drawn off into the eddies in the manner indicated.

While a satisfactory understanding of these large scale mixing processes must await more specialized observations, there is already ample evidence that from time to time (Walford 1936) and in various ways a considerable amount of bank water is carried off shore in the surface layer of the slope water band. Whatever the mechanism, such movements will be destructive to the plankton thus removed from the fishing grounds. In addition, it can be argued on theoretical grounds that such eddies will be more numerous during periods when the Gulf Stream is decreasing in strength. Thus there is some hope that the Gulf Stream studies now being made (Iselin 1938) may provide a basis by which the fisheries investigator can judge, or even foretell, the relative proportion of a given year class that will be lost in this way.

The long period fluctuations in the strength of the Gulf Stream, if indeed they do exist, will have a more direct effect on bottom temperatures and salinities both at moderate depths on the continental slope and on the deeper parts of the shelf. In both cases the exact characteristics of the bottom water depend largely on the depth of the main thermocline layer in the slope water band, and this in turn is dependent on the volume of the Gulf Stream. When the current increases in volume, bottom temperatures and salinities will fall; when it weakens, they will rise.

In the deep water north of the current, when undisturbed by an eddy, the main thermocline layer (12° - 6°) usually occupies the depths between 100 and 500 meters. South of the Gulf Stream the same isotherms and isohalines are found at the 500-1200 meter level (Fig. 17). In the extreme and most improbable case that the current should die away completely, they would continue at approximately these deeper levels right in to the continental slope. A decrease of 50% in the volume of the current would cause the slope water thermocline to deepen to intermediate depths. That only a slight fluctuation in the depth of the main thermocline layer in the off shore waters will have a marked effect on bottom conditions along the continental slope at depths between 100 and 400 meters can be seen by examining Figs. 20 and 21. These show in cross section the coastal water, and the superficial layers of the slope water and the Gulf Stream. The stations were occupied in early June, 1937 and 1938, on a line extending from Montauk Point to Bermuda. While on these two occasions bottom temperatures differed by only about 4° at depths between 150 and 200 meters, it is evident that a more marked change in the off shore currents could cause even wider fluctuations. In addition, these sections illustrate two different stages in the development of eddies. In one case (Fig. 21) the swirl was swift and contains mixed water at its center. In the other case

(Fig. 20), the slope water currents were moderate, but almost undiluted coastal water had been carried well off shore.

No doubt the long period changes in strength of the Gulf Stream are so gradual that the bottom living population is easily able to migrate up and down the continental slope and thus remain in water of suitable temperature and salinity. But it is also possible that from time to time sudden fluctuations in the off shore currents can cause rapidly changing bottom conditions that might even result in the death of the less mobile forms. It can be argued that the famous destruction of the tilefish in 1882 along the outer edge of the continental shelf between Delaware Bay and Nantucket Shoals

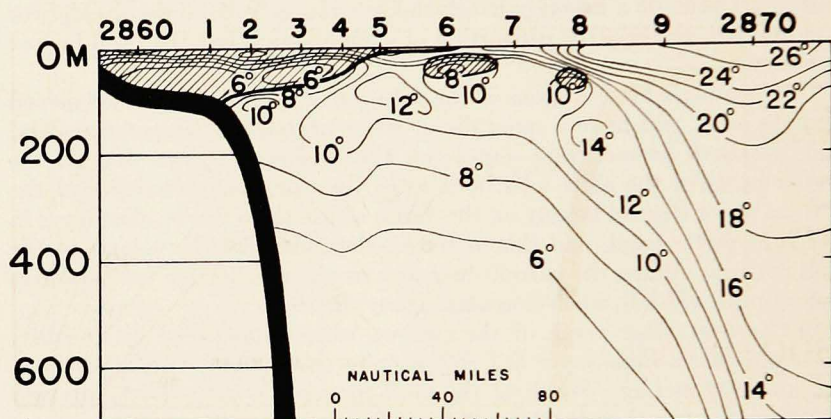


Figure 20. Temperature section, June 4-6, 1937, extending southeastward from Montauk Point, Long Island. Salinities less than 34‰ are cross-hatched.

was due to this mechanism. In any case, there is a clear advantage for trawlers to obtain bottom temperatures when fishing in this critical zone.

Although much of the bottom water on top of the shelf, especially throughout the spring and summer months, is directly supplied from the upper part of the off shore, main thermocline layer, the possibility of sudden changes in its characteristics is more remote. However, the in shore bottom population, because of the relative flatness of the shelf, has much less chance of adjusting its depth to meet the rise and fall of the off shore isotherms and isohalines which must accompany the fluctuations of the Gulf Stream.

The principles which we have discussed thus far only have an important effect on life in the superficial layers near the edge of the continental shelf and on bottom forms on the outer half of the shelf or a short distance down the slope. Are there any influences which can cause significant variations

in the shallower waters nearer the coast? Obviously these must be much more under the control of the local climate and local mixing processes.

As mentioned already, throughout most of the year the waters over the continental shelf are extremely stable, both because of the off shore spread of relatively fresh water at the surface and because of the sharp, shallow thermocline layer which develops during the summer months. Under these conditions vertical turbulence is able to effect almost no transfer across the zone of maximum stability, just below the wind stirred, nearly homogeneous surface film. Thus as far as nutrients are concerned, the surface layer during the spring and summer cannot be supplied from be-

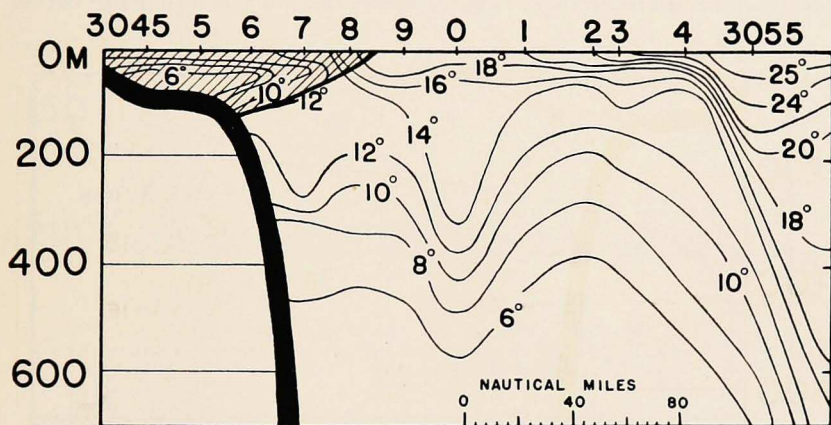


Figure 21. Temperature section, May 28-June 2, 1938, extending southeastward from Montauk Point, Long Island. Salinities less than 34‰ are cross-hatched.

neath; and even at mid-depths the vertical transfer of essential chemicals must be extremely slow.

During the last few years physical oceanographers have begun to appreciate the important role which lateral turbulence plays in the sea (Rossby 1936, Parr 1938). Under the conditions of high stability often found in coastal waters, the isopicnal transport of nutrients should prove a most fruitful study. The vital biological role that lateral turbulence plays in the open ocean has been pointed out by Redfield (1936), and more recently (1939) he has studied this process from the point of view of certain planktonic forms in the Gulf of Maine. The chemicals which are in this way pumped up from mid-depths in the Sargasso Sea are transferred isopicnally across the Gulf Stream to the edge of the continental shelf. Thus as the bottom water penetrates landward, it carries with it a good supply of nutrients. But as long as the water-column is stable these cannot easily be

transferred to the photic zone, because very few surfaces of constant density cut the surface of the in shore waters.

It has been pointed out by Parr (1936) that in layers where the stability is high, the lateral turbulence is increased. This principle should not be overlooked by planktonologists. It suggests that over the continental shelf the lateral spread of plankton will be particularly marked in the transition layer between the relatively light surface water and the heavier bottom water.

The resistance which the extreme stability of our coastal water offers to vertical turbulence was nicely illustrated by the recent New England hurricane of September 1938. Fig. 22 shows the temperature-depth curves

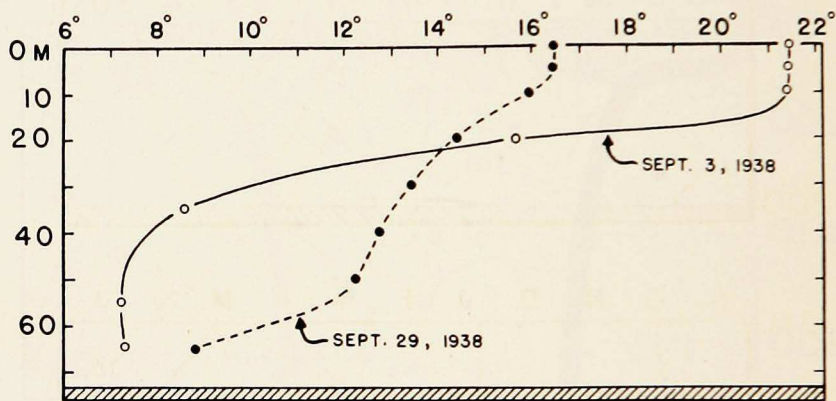


Figure 22. Temperature depth curves from a station about 20 miles southeast of Montauk Point, Long Island, before and after the New England hurricane of September 21, 1938.

from a station about 20 miles south of Montauk Point, Long Island, occupied on September 3 and again on September 29, 8 days after the gale. Although the center of the hurricane passed only a few miles west of this station, wind stirring was not able to break down the thermocline. However, turbulence did somewhat reduce the initial extreme temperature difference between surface and bottom.

The vital role which the breakdown of stability during the winter months plays in the fertility of the surface layer has often been emphasized, but it is less frequently mentioned that quite wide variations are possible from year to year in the effectiveness of the mid-winter stirring. Fig. 23 illustrates the cycle of temperature and salinity at a station in the western basin of the Gulf of Maine. At the surface the maximum cooling in this particular year (1934) came early in March. Although by mid-January the water was practically homogeneous down to 100 meters, a slight freshening

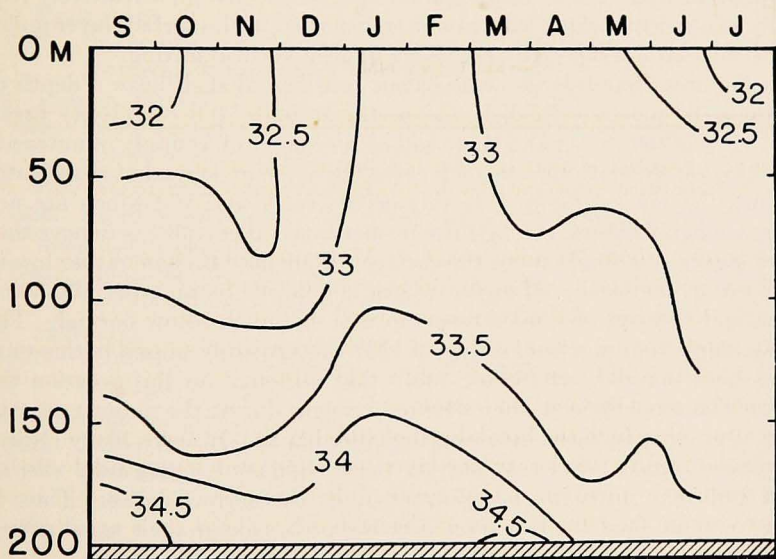
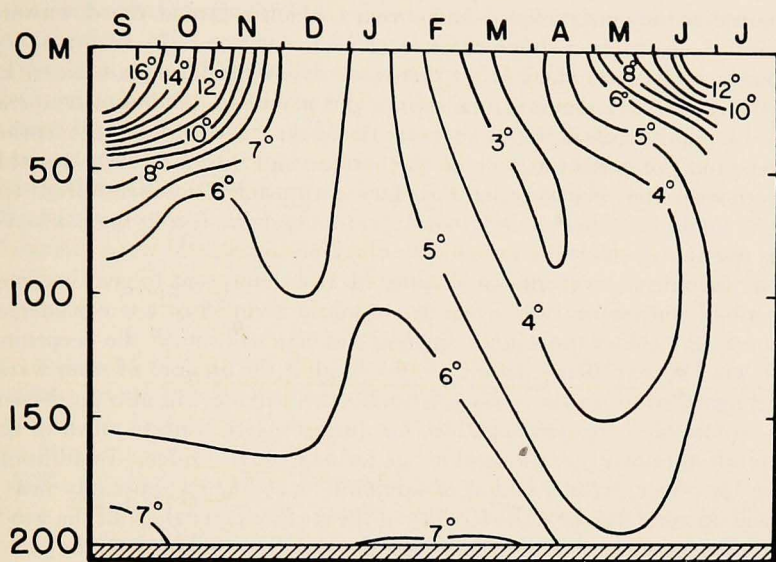


Figure 23. The changes in temperature and salinity, September 1933–July 1934, at a station in the western basin of the Gulf of Maine.

of the surface layer developed in February which retarded the downward transfer of minimum temperatures later in the winter. In addition, the temperature diagram shows that, because of the stability maintained by the vertical salinity gradient, turbulence did not bring minimum temperatures to depths below 100 meters until May. Meanwhile, the spring freshets and the early warming of the surface had begun to form a stable layer above. It is evident that the upward transfer of nutrients from the bottom would have been much more effective had the spring been delayed a few weeks.

That the winter overturn can be quite variable from year to year becomes clear when the factors which control vertical turbulence are considered. Obviously the colder the winter, the less stability will retard the deepening of the wind stirred surface layer. In addition, if the amount of river water spreading off shore at the surface is small, the stirring will also go deeper. Both factors tend to work together, for during severe winters much of the precipitation remains on the land in the form of snow and ice. In addition, during the short, critical period of minimum stability an especially heavy gale will do more to renew the fertility of the surface layer than all the winds of the other seasons. Finally, the longer the stability remains low, the better the chance of the mixing going to the bottom on the deeper parts of the continental shelf. These deeper gullies and basins contain a relatively rich supply of nutrients which will only be transported to the surface layer under conditions that are especially favorable to deep vertical mixing.

On the other hand, large areas of our continental shelf have a depth of less than 100 meters. In such regions the stability will completely break down early in the winter and there will be no chance of a supply of nutrients remaining on the bottom. In such cases the off shore spread of river water becomes the critical factor. If this occurs early and the winds are not strong enough to break through the fresher layer, then there is danger that before spring is well advanced the surface waters may become rather low in the essential chemicals. If such a winter is followed by an especially warm spring and summer, the plankton crop may be much below normal. The spectacularly poor mackerel season of 1937 was probably caused in this way. It has been pointed out (Settee 1937) that although on this occasion the stock of fish was sufficient, they were only caught during the summer months either very close to the shore, or on the outer banks. It seems likely (North American Council 1937) that only in these regions of strong tidal stirring could sufficient nutrients be maintained in the surface layer. Thus in order to secure food the mackerel were forced to change their usual migration route.

It is of course only natural that biological investigators should be interested in finding purely biological factors to explain the fluctuations in the fisheries. In such areas as Georges Banks, where, because of tidal stirring,

the water-column remains homogeneous throughout the year, the annual variations in temperature, salinity and fertility are indeed very small. In fact, this is probably one of the main reasons for the tremendous fertility of Georges Banks. The chemicals are continually being returned to the surface layer. However, as has already been explained, because this bank is near the edge of the continent, it is in a vulnerable position from the standpoint of the slope water eddies. It remains to be seen whether or not this purely physical mechanism is sufficiently variable from year to year to explain a significant part of the variations in the catch.

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