REPORT

ON

THE SALINITY OF THE NORTH SEA.

BY

D'ARCY WENTWORTH THOMPSON.

CONTENTS.

REPORT

ON

THE SALINITY OF THE NORTH SEA.

BY

D'ARCY WENTWORTH THOMPSON.

1. In a former volume of these Reports an attempt was made to give a general account of the temperature phenomena over the greater part of the North Sea. We found it possible to prepare charts showing (1) the mean annual temperature of the surface waters, (2) the mean annual variation of temperature, (3) the mean maximal and minimal temperatures attained in the course of a year, and (4) the dates or seasons at which these maxima and minima occurred. The corresponding phenomena for various depths below the surface can be, and have in part been, described and illustrated. It is now time to attempt, in a similar fashion, to discuss the variations in salinity over the North Sea, at least in so far as we can reduce them to their mean annual values.

2. In the study of temperature we found our work greatly facilitated by making use of the assumption that the annual periodic changes of temperature at any given locality corresponded very closely to a simple sine-curve. In the case of salinities we have no right to make use of this assumption, for want of any obvious physical factor to justify it ; and, as a matter of fact, while the annual variation of salinity does often yield us a curve that closely resembles a simple curve of sines, yet on the other hand this annual periodic curve is often of a very different form ; for often a period of minimal salinity quickly follows a period of maximum and is followed in turn by a long and gradual ascent, and a south maximum and minimum within the year is also a not infrequent occurence in some regions.

The method by which our data are arrived at is a simple one. Where our observations are limited to those of the quarterly cruises we have simply taken the arithmetic mean of all the extant observations to be the mean salinity at the given station. Where our observations are more numerous, as in the Scottish area, but at somewhat irregular dates, we have drawn a continuous curve by interpolation, and have averaged the monthly values of the interpolated curve. In the next place, with varying success according to the number of observations available, we have taken mean values for corresponding dates in the successive years (1902-1907), and have connected these by interpolated curves, which are very generally sufficient to give us a first approximation to the form of the annual wave, to its amplitude or range of variation, and to the date or season of maximum and minimum salinity.

The Mean Distribution of Salinity.

3. In the annexed chart (Fig. 1.) are laid down lines, or "isohalines," which correspond to points or places of equal salinity. The main features of the map are extremely simple. By far the lowest salinities are found in the innermost parts of the Skager Rack, where we have drawn lines of gradually decreasing salinity down to the value of $25°/_{oo}$, that is to say of 25 parts by weight of salts in one thousand parts of water. From this comparatively low value we should go on rapidly decreasing, had we continued this region of the chart, until we reached the brackish, or all but fresh, waters of the inner Baltic.

In two parts of our chart we find maximal salinities, namely at the two entrances to the ocean, formed by the Straits of Dover and the Shetland Seas. In the former we find mean surface salinities of about $35{\cdot}2°/_{oo}$, but such water is in very small amount, just peeping, as it were, through the Straits into the North Sea. The Shetland Islands are bathed in water of a mean salinity of $35{\cdot}25°/_{oo}$, while immediately beyond them, through the Faeroe Channel, there runs in a narrow band a branch of the so-called Gulf Stream, with a salinity exceeding $35{\cdot}3°/_{oo}$.

Around the coasts the salinities are everywhere comparitively low, and the isohalines form a system of curves that are always convex towards the oceanic outlets. The

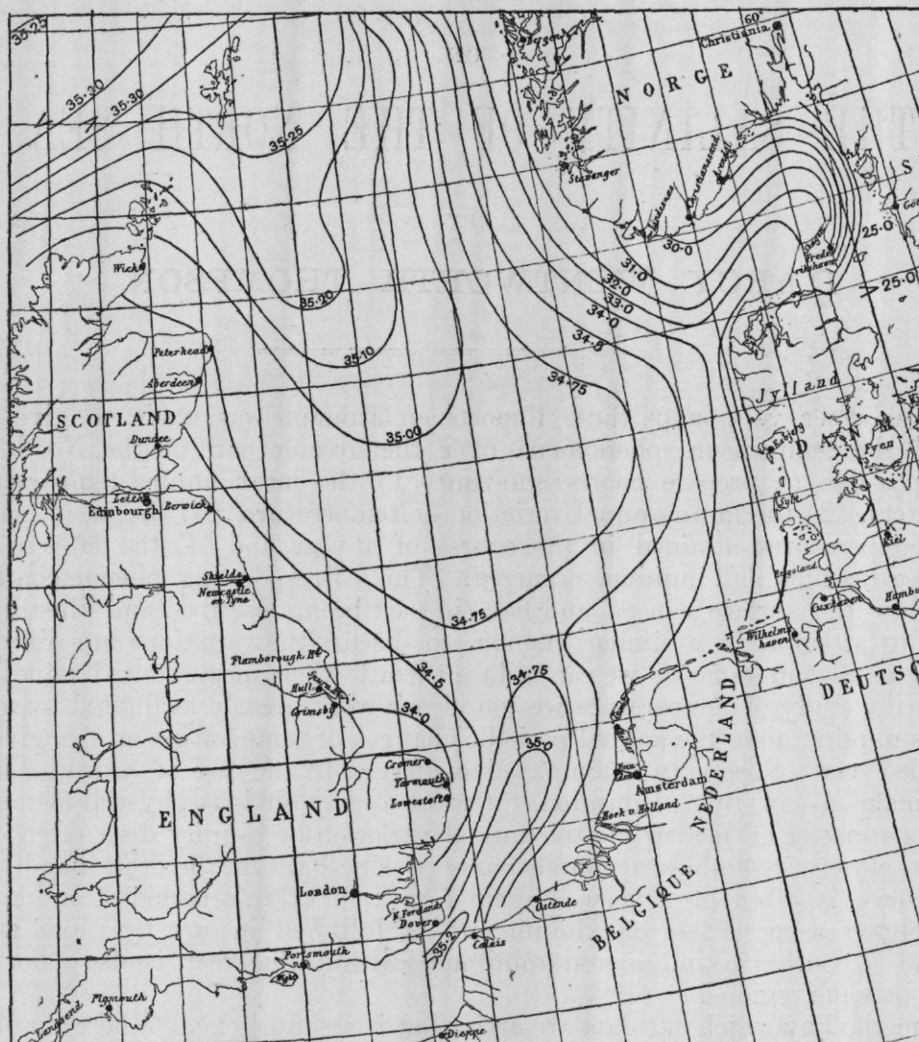

FIG. 1.—Mean surface salinity of the North Sea, 1903–7.

isohalines represented in the map do not in all cases correspond to equal increase or diminution of salt, but, as will be readily seen, are drawn at more frequent intervals in the higher values ; and, bearing this in mind, it will be seen how much more closely packed are the isohalines where they are most remote from the ocean, and how comparitively wide apart they lie where the salinity increases towards the oceanic level.

The general distribution and form of the curves of equal salinity upon the chart may be the more easily explained and understood if we think of the somewhat parallel case of the flow of heat, or of electricity, in a bar of metal, and consider the distribution of temperature, or of potential, that will arise. If we take a long bar of metal heated at one end (as in Forbes' classical experiments) and ascertain its temperature at various points when a steady flow of heat by conduction has been set up, we find that the temperature falls from one end of the bar to the other, and (since the rate of cooling is proportional to the temperature excess over the surroundings) it falls slower and slower as we pass from the heated end ; in other words, we find a falling series of isotherms, running transversely to the 'thermal axis' of the bar, and ranging themselves in a logarithmic series (corresponding, in general terms, to $\frac{dy}{y} = \lambda dx$), at increasing distances from the source of heat towards the cooler end. If, in the next place, we imagine that heat is supplied not only at one end but also at the sides or edges of the bar, then the isothermal lines, instead of being straight lines at right angles to the axis, will become curved, with their concavities turned towards the cooler end. Lastly, if we imagine our bar to be no longer narrow, but broadened out into something like a square, and the sources of heat and cold to be no longer opposite but on two adjacent sides of the square, then the thermal axis will be bent into a curve, its two extremities becoming perpendicular to one another, and the curved isotherms will be closely packed towards the concave side of the bent axis, and more widely spaced upon its convex or outer side. If now, in looking at our chart of surface salinity in the North Sea, we omit for the moment the slight complication introduced by the communication with oceanic water at the Straits of Dover, then the system of isohalines will be sure to correspond closely to the system of isotherms in a piece of metal under the last-named conditions. A bent axis may be traced from the main inlet of fresh water in the Skager Rack, passing through the middle of the North Sea, and ending in the Atlantic water to the east and north of the Shetlands; this axis is crossed by a series of isohalines, that stand more and more widely asunder as we approach the ocean; the additional influx of fresh water from the coasts bends these isohalines into curves that are in a general way concave towards the ocean, and approximately parallel to the coast lines; the isohalines are closely packed along the Norwegian coast, but are more divergent on the other side of the axis, the side of greater curvature. One further point remains: the whole system of higher isohalines, those that is to say in the neighbourhood of the oceanic outlet, is markedly shifted over towards the west, and lies much nearer to the Scottish than to the Norwegian side. This phenomenon is doubtless contributed to by more causes than one. In the first place the oblique north-easterly direction of the Gulf Stream current places the saltest water of this part of the ocean nearer to the Shetland side than to the Norwegian; secondly, the influx of fresh water from the coast is undoubtedly greater on the Norwegian than on the Scottish side; and thirdly, though this is a matter which we are not at present in a position to discuss, there would seem to be something of the nature of a south-flowing current, of low temperature and salinity, in the neighbourhood of the Norwegian coast.

From the Cattegat to the Skager Rack, around the Skaw, the axis is bent in a contrary direction to that in the North Sea; we are dealing in short with a sort of tube narrow at one end (in the Cattegat) and broad at the other (towards the ocean), and bent at the same time into a S-shaped twist. Though we have not drawn the isohalines throughout the Cattegat, yet we see that at its mouth they are closely packed in the neighbourhood of the Skaw, or on the side of the lesser curvature, and diverge as they approach the Swedish and Norwegian coasts, along, what is here, the greater curvature of the bent tube. The axis is again shifted over to one side, in this case towards the Danish one; and sufficient reason for this phenomenon may be found, not only in the greater inflow of fresh water from the Swedish and Norwegian coasts than from the Danish, but also in the natural tendency of the outgoing current from the Cattegat to incline towards the outer bank of the curved channel. The general arrangement of the curves in the Skager Rack is therefore quite comparable, on a smaller scale and with closer packing, to that which we have found in the region between Scotland and the west coast of Norway.

Returning for a moment to the salinites actually indicated on the chart, we see that in no part of the surface of the North Sea (save in the immediate neighbourhood of Shetland) does the mean salinity exceed $35{\cdot}25°/_{oo}$; that the greater part of the whole North Sea is covered by water of a salinity from $34{\cdot}75°/_{oo}$ to $35{\cdot}25°/_{oo}$; that towards the coasts the salinity falls off rapidly, and in much greater degree towards the continental than towards our insular coast; so much so that the North Sea coast of Norway, Denmark and Germany are washed by water whose mean salinity is less than $32{\cdot}0°/_{oo}$.

4. If we turn now to the chart representing the mean annual salinity at the bottom (Fig. 2) we see that, subject to certain differences, the general arrangement of the curve of equal salinity is similar to that of the surface. It must be remembered that this diagram is no longer drawn to a single plane, as was the former one, but follows the varying depth of water; it represents in a general way a plane, shelving from the shallow southern portions of the North Sea towards the deep waters of the north, and towards the deep channel that runs down the Norwegian coast and into the Skager Rack.

We notice in the first place the now well-known phenomenon that in the whole southern portion of the North Sea, from the Dogger Bank southwards, the curves of salinity at the bottom are all but identical with those of the surface; the comparative shallowness of this portion of the sea, and the extent to which it is constantly mixed up by wave-motion and tidal current, are sufficient to explain this condition. Elsewhere the differences between the surface and bottom phenomena are of a simple kind. Everywhere there is an appreciable excess of salinity at the bottom, and in the deep waters of the Skager Rack and off the Norwegian coast the discrepancy is very great. Where our chart begins in the northern part of the Cattegat, the bottom waters have already a salinity of $34°/_{oo}$, where that of the surface waters is less than $25°/_{oo}$. Along the main channel of the Skager Rack the salinity is over $35{\cdot}1°/_{oo}$, or within $\cdot2°/_{oo}$ of the saltest water with which we have to deal anywhere in our region. The axis perpendicular to the isohalines is no longer shifted over to the Danish coast in the region of the Skager Rack, nor to the same extent as before in the region between Scotland and Norway; and

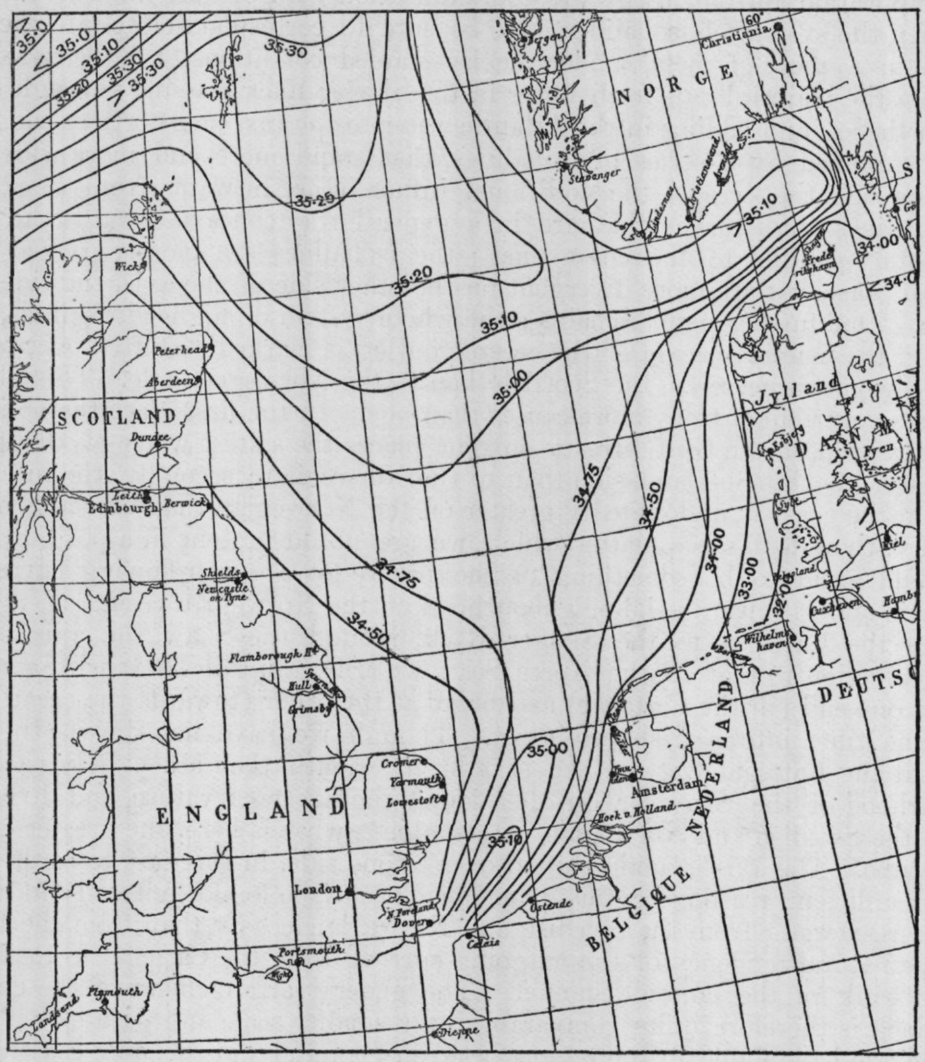

FIG. 2.—Mean salinity of the North Sea at the bottom, 1903–7.

while in the latter case its position is accounted for by the contour of the bottom, the former case reminds us that the westward shift was due to the special conditions of surface inflow, as well as to the distribution of salinity in the oceanic waters beyond.

Looking in a general way at the salinities of the bottom water, we see that over the whole of the North Sea the differences are comparatively small. Northward of the latitude of Aberdeen the bottom of the North Sea has everywhere, save in the near neighbourhood of the coast, a salinity of from $35{\cdot}1°/_{oo}$ to $35{\cdot}3°/_{oo}$. Only in the German Bight, or angle of sea between the Danish and the Frisian coasts, do we find a stretch of water that rapidly falls from $34°/_{oo}$ to about $32°/_{oo}$ of salinity.

While similar charts have been drawn for depths of 50 and 100 meters, it does not seem necessary to reproduce them here, for the reason that they bring to light no important features that cannot readily be deduced from the main charts of surface and bottom conditions.

5. It is of interest to examine, by the help of another form of diagram, the rate of change of salinity from one part of the sea to another. In Fig. 3 I have attempted to represent the varying salinity, at the surface and at the bottom, along a line drawn from the north of Shetland to Borkum, that is to say from the north to the south of the North Sea. The salinity at the bottom here falls into a very even curve, showing, as our chart did, a very slow diminution of salinity in the north, a gradually increasing one in the middle of the North Sea, and a rapid drop in the neighbourhood of the continental coast.

This curve is only diagrammatic, firstly because of the scale on which it is drawn, which has led to the crowding together of the descending portions of the curve, and secondly because, within the region of rapidly diminishing salinity, our observations are extremely few, and we really know very little about the actual rate of decrease in the neighbourhood of the shore. Nevertheless, the main facts are clear. The phenomenon with which we are dealing is not, technically speaking, one of simple diffusion, but of diffusion aided and immensely accelerated by gradual or piecemeal mixing from point to point over a large area. Molecular diffusion is as inadequate to produce the observed progressive changes in salinity throughout the waters of the sea, as is conduction of heat to produce the observed changes in temperature; but mixture, or convertion of small masses, produces in both cases a result very similar in regard to its ultimate distribution to what would have been attained under the strict laws of diffusion and conduction. In the end we have at one end the comparatively fresh coastal waters (more or less intermittently replenished), and at the other end the all but uniform dead level of oceanic salinity. Under these circumstances the gradient of salinity may be treated as infinite at the one end and zero at the other; in other words, as we have actually found, there is an extremely rapid rise in salinity from the coast outwards, and then a slower and slower increase till we reach the ocean.

In the same diagram (Fig. 3) it will be seen that the curve of salinity for the surface waters is identical with that for the bottom waters from the region of the Dogger Bank southwards, as indeed has already been shown to be the case; and again the two curves are not perceptibly different towards the extreme north of our area. Midway, however,

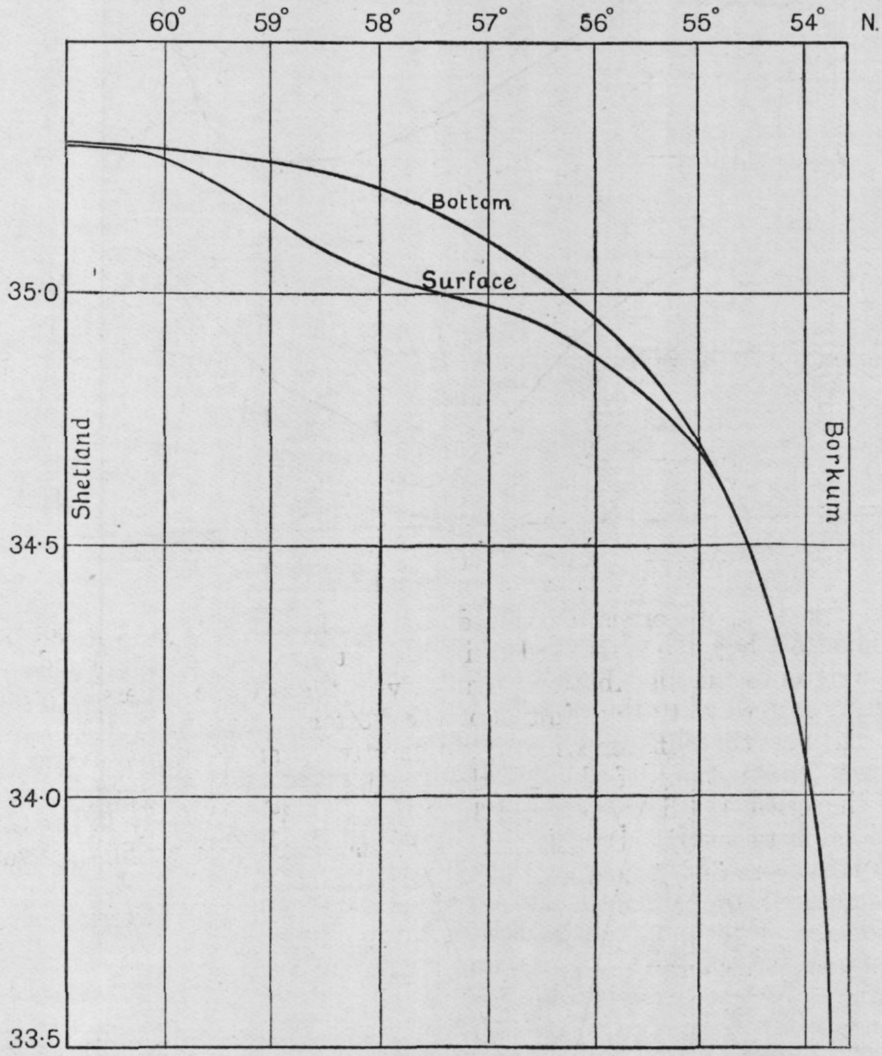

FIG. 3.—Diagram showing mean salinity, at surface and at bottom in the North Sea along a line from Shetland to Borkum.

the surface salinity is considerably lower, and its curve takes a downward bend; this difference, as we may see by reference to the charts, is due to the simple fact that the line from Shetland to Borkum cuts the deep isohalines more nearly at right angles than the surface ones, the latter having been deflected in a greater degree towards the Scottish coast.

THE MEAN PERIODIC VARIATION OF SALINITY.

6. When, as is usually the case, we find that the mean salinity from our quarterly and other cruises during several years furnishes us, at any one station, with a smooth

annual curve, we accept this as evidence and as the measure of a mean periodic variation. The underlying periodic variation is no doubt complicated by unperiodic variability, but the mean of five years' observations seems to be sufficient to give us a first approximation to a measure of the periodic pnenomenon. It is not sufficient to give it us with great accuracy, and especially is it inadequate (taking into account the small number of observations in each year) for the precise determination of the phase of the periodic wave, that is to say, of the mean annual epochs of maximum and minimum salinity.

The following are some examples of the mean curves that we obtain by interpolating between the observations, and by averaging the results of successive years.

In Fig. 4 we have the annual curve of salinity for stations Sc. 41*a*, 41*c*, 44 and 46, along the line from near the middle of the North Sea to the Firth of Forth.

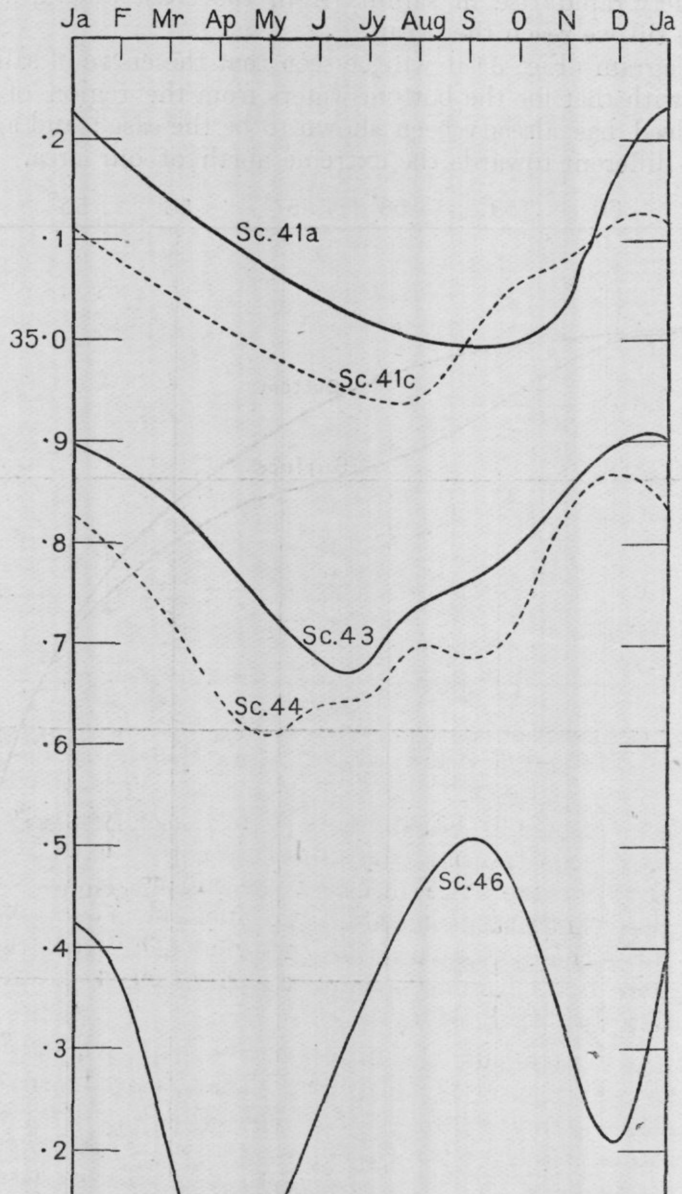

FIG. 4.—Mean annual curves of salinity (1903–7) at the surface, for five Scottish stations, from the Firth of Forth eastward.

We see here (1) that the mean salinity falls from station to station as we approach the coast, the fall being great between Sc. 44 and 46, just at the mouth of the Firth of Forth: (2) that the range of variation (or amplitude of the curve) increases as we come coastward, slowly at first, rapidly between Sc. 44 and 46: (3) that in all cases there is a maximum of salinity about the months of December or January, to which, at Sc. 46, another maximum in autumn is superadded : (4) that the date of minimum salinity shows signs of a progressive alteration in date, appearing later and later in the year as we pass from the coast seaward.

In Fig. 5 we show the corresponding curves for a group of stations (Sc. 5, 6 and 12) in the neighbourhood of Shetland, and for one station (Sc. 34), eastward of the Moray Firth.

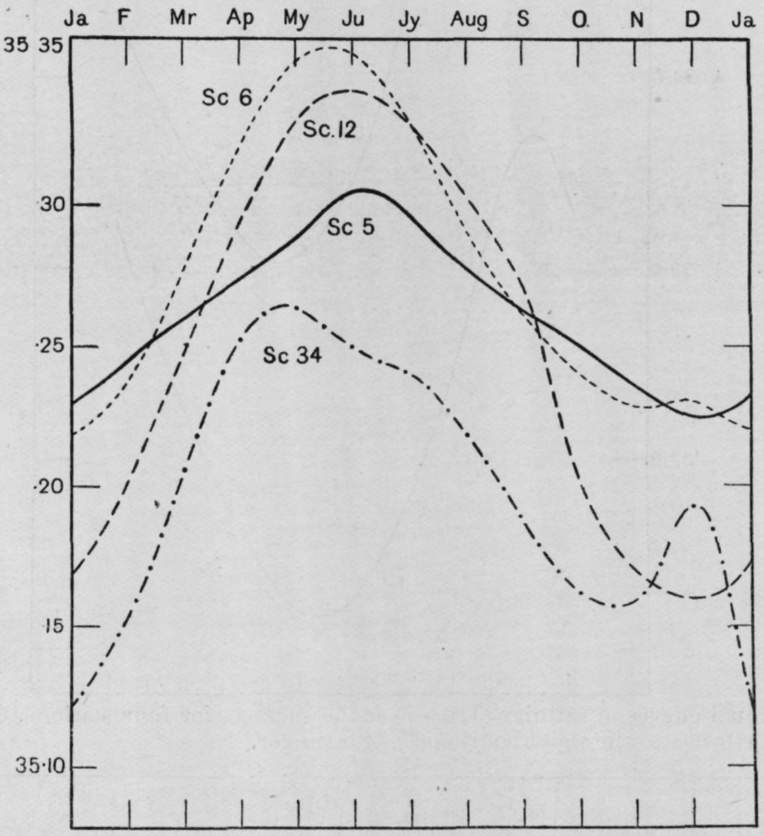

FIG. 5.—Mean annual curves of salinity, 1903–7, at the surface, for four Scottish stations in the neighbourhood of Shetland and (Sc. 34) eastward of the Moray Firth.

In all of these the period of maximum salinity is very different from the stations, in the former group, and occurs from May to June, or a little earlier in the case of Sc. 34. In the last named station there is evidence of a secondary maximum in December, which we may explain by supposing that this station is influenced to some extent by the phenomena that characterise the former, more southern, line. The smallest range is seen at Sc. 5, which lies in the Fair Isle Channel, and the highest mean at Sc. 6, which lies in the salt Atlantic water eastward of Shetland.

Passing to the eastern side of the North Sea we have in Fig. 6 the curves for a number of German stations, of which D 4 is not very far remote from our Scottish station Sc. 41A (already represented in Fig. 4), while D 6 and D 7 approach the Norwegian coast in the direction of Stavangar. Taking note of the different scale on which this figure is drawn compared with Fig. 4, we see that the range at D 4 is not very different to that at Sc 41A ; and though the season of maximum is a little later, the general features are much the same, namely a maximum in late winter and a minimum in the summer and autumn months. At Stations D 6 and D 7 the same phenomena occur in an exaggerated form. The range of variation is now comparatively enormous, and the contrast is great between the high salinities in winter and early spring and the low salinities of summer and autumn ; at D. 7, which lies nearest to the Norwegian coast, the mean salinity is markedly lower, and the phase is distinctly earlier than at D. 6. The same figure contains the curve for D. 3, which lies in the middle of the North Sea, in about 56° N. 3° E.; it is clear that we have in this case a striking likeness, though with higher mean and diminished range, to the curves for D. 6 and D. 7.

In Figs. 7 and 8 I have attempted to lay down the mean annual periodic variation in salinity at the surface and at the bottom.

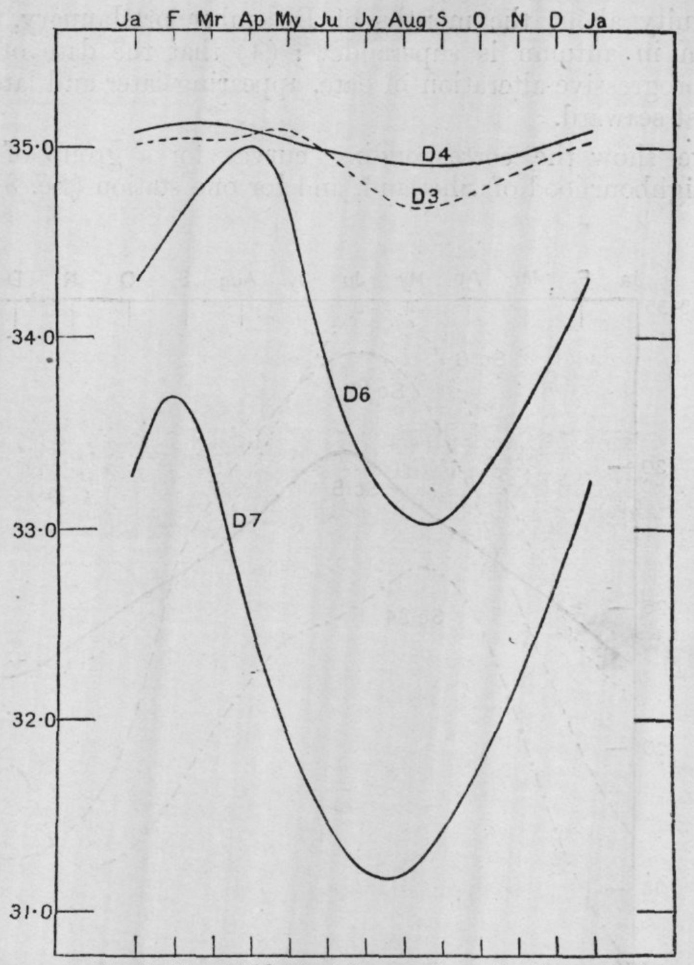

FIG. 6.—Mean annual curves of salinity (1903–7) at the surface, for four stations, from the middle of the North Sea to the neighbourhood of Stavangar.

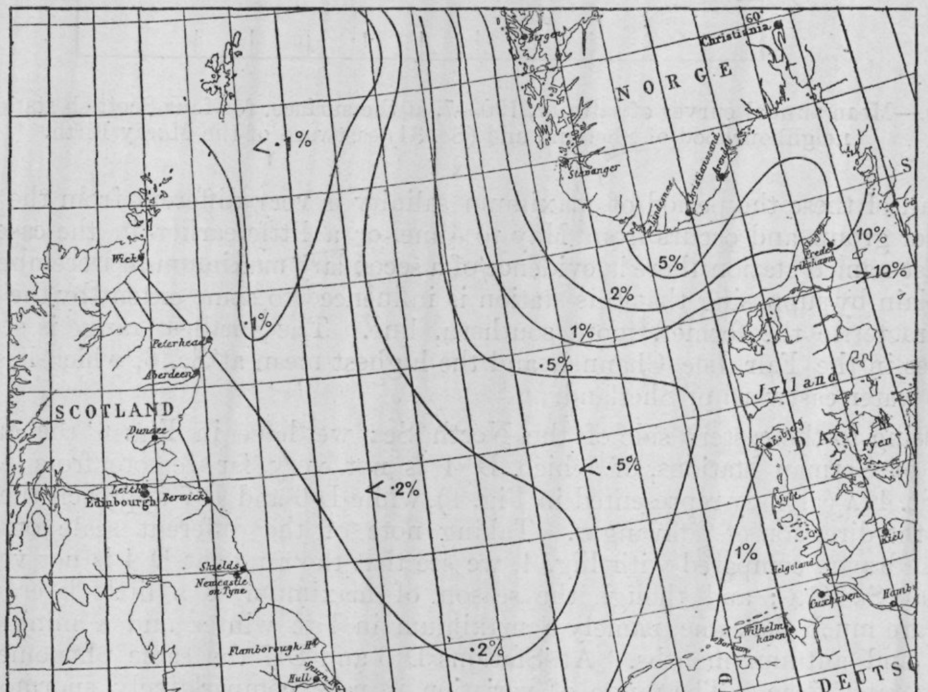

FIG. 7.—Mean annual variation of salinity (per mille) at the surface of the North Sea, 1903–7.

The general direction of these curves is on the whole similar to that of the isohalines in the former charts: for we find that where the mean salinity is highest, it is also least

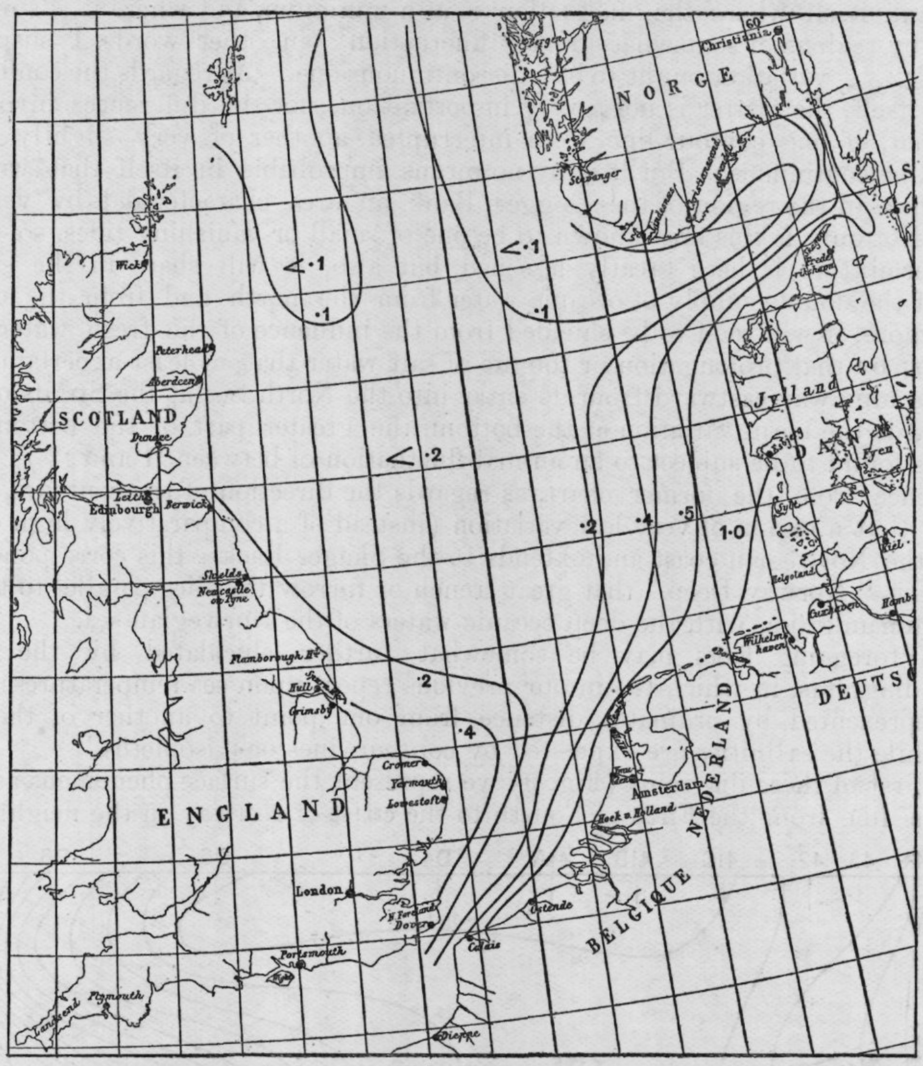

FIG. 8.—Mean annual variation of salinity (per mille) at the bottom, 1903–7.

subject to variation. This is as much as to say that such changes in salinity as take place in the neighbourhood of the ocean, and are due to the influence of the ocean, are far less in magnitude than those that take place owing to changes in the fresh-water supply; and this follows as a simple corollary from the relations diagrammatically shown in Fig. 3.

Considering the surface chart, we see that in the two regions where the North Sea communicates directly with the Atlantic, namely, at the Straits of Dover and in the neighbourhood of Shetland, the annual variation in salinity is less than ·1 gram of chlorides in one thousand grams of water, or in the 35·25 grams of chlorides that that water approximately contains. In the Straits of Dover, by the way, this region of low variability (and of high salinity) is only characteristic of the centre of the Channel; and again between Shetland and Norway the region of low variability, like that of high salinity with which it corresponds, is thrust far out from the Norwegian coast by the large and fluctuating supplies of fresh water which that coast sends down to the sea.

The salinity over the greater part of the North Sea is subject to a periodic annual fluctuation of from $\cdot 1^{\circ}/_{\circ\circ}$ to $\cdot 5^{\circ}/_{\circ\circ}$ of salinity (or ·1 to ·5 grams of chlorides per 1,000 grams of water). But this fluctuation increases rapidly towards the eastern parts of the sea as we approach the Norwegian and Danish coasts, and especially as we enter the Skager Rack. At the entrance to the Cattegat we have an annual fluctuation of about $10^{\circ}/_{\circ\circ}$ (on a mean salinity of somewhere about $25^{\circ}/_{\circ\circ}$), and sweeping round the northern part of the Skager Rack as far as the Naze we still have a region characterized by an annual fluctuation of over $5^{\circ}/_{\circ\circ}$. Along the southern side of the Skager Rack the fluctuation is much less, and falls rapidly as we approach the North Sea.

Over the Dogger Bank the range of fluctuation is certainly very small, but the quarterly observations which we have for this region are by no means sufficient for the investigation of so small a periodic change, and our stations are also few. I have provisionally drawn the curve which represents the limit of $\cdot 2^{\circ}/_{\circ\circ}$ of mean variation so as to run continuously southwards down to the Dogger Bank from an area which we are well able to define from our Scottish work ; but I rather think there are signs of a region over the bank itself where the fluctuation is at a minimum, and where it is surrounded on all sides by regions of somewhat greater fluctuation ; in other words, I suspect that the curve of ·2°/₀₀ variation ought to be a discontinuous one. As regards the configuration of the chart itself, the matter is not a very important one, for the differences involved are so slight that, if one contour-line were interrupted, another of very slightly different value would be continuous. But it is by no means improbable in itself that we should find somewhere in the region of the Dogger Bank an area characterized by very small variation. Not only is this area known to be one of small or vanishing tides, so that one cause of intermixture is here greatly lessened, but also, it will share in the steadying influences of the double supply of oceanic water from the north and from the channel ; and furthermore, it will tend to be shielded from the influence of the fresh waters of the German coast by that prolongation or tongue of salt water that, at least at certain seasons, is traceable a long way eastward from its entry into the North Sea at the Straits of Dover.

As regards the mean variation at the bottom, the greater part of the bottom of the North Sea is found to be subject to an annual fluctuation of between ·1 and ·2°/₀₀. The chief difference from the former chart, as regards the direction of the contours, is found in the fact that a region of very low variation (instead of a comparatively high one) lies adjacent to the Norwegian coast and extends to the Skager Rack ; this corresponds to the position of the " Norway Deep," that great trench or furrow that lies parallel to the coast, in direct communication with the deep oceanic waters of the Norwegian sea.

8. The foregoing facts may be somewhat further elucidated by the help of " isopleth " diagrams, in which (as in our previous report upon sea temperatures) a period of time is represented by ordinates, distance from one point to another of the sea by abscissae, while the salinities are expressed by contour lines or " isopleths."

In the first of these diagrams (Fig. 9) we represent the surface phenomena as regards salinity on a line from the Firth of Fourth to the coast of Norway in the neighbourhood

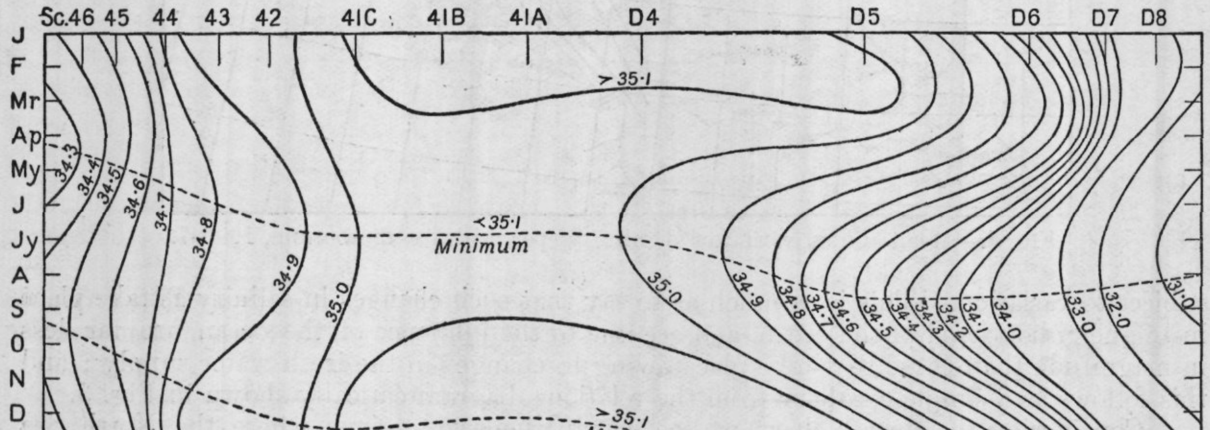

FIG. 9.—Diagram showing mean variations of surface salinity along a line from the Firth of Forth to the Naze of Norway.

of Lindesnaes. We see that towards the middle of the North Sea we cross a region of maximal salinity as well as of minimal variability, the salinity at our Scottish stations 41B and 41A only varying a little on either side of 35·1°/₀₀. As we pass westward towards the Firth of Forth, new isohalines succeed one another, but they are comparatively little bent, and though the salinity falls, the annual range does not very greatly increase. On the other hand, as we pass eastward, not only do the isohalines become extremely numerous, but they form very sinuous curves, so that a vertical line cuts them in increasing numbers ; in other words, at any given point the variability in time becomes extremely great. Thus at Station D. 7, in the neighbourhood of the Norwegian coast, the range is from about 32°/$_{oo}$ to over 34°/$_{oo}$. We can further trace upon this diagram the dates of maximal and minimal salinity, though it must always be remembered that the number of our observations and the process of interpolation by which the curves have been constructed do not permit us to accept, without the greatest caution, any but the most salient features of the diagram. We see that in the central part of the sea the minimal salinity is in summer, and the maximum in winter. The corresponding dates are undoubtedly earlier as we approach the Scottish coast, and they again advance in the neighbourhood of the coast of Norway, probably to a greater extent than our diagram actually shows.

The next diagram (Fig. 10) covers a series of stations from Sc. 4 at Fair Isle to D. 14 near the Horn Reef, on the Jutland coast. The phase is nearly identical at all parts of the diagram, showing a maximum everywhere in spring, and a minimum everywhere in

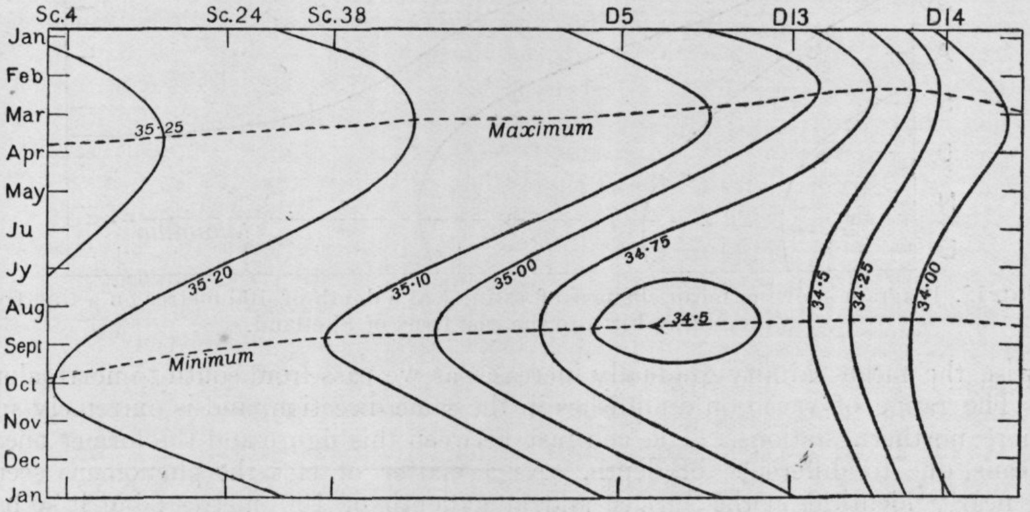

FIG. 10. Diagram showing mean changes of surface salinity along a line from Fair Isle to the Horn Reef.

autumn. The mean salinity diminishes steadily from the Shetland to the Danish end of the line. The range of variation tends to increase in the same direction, but seems to be greatest between Stations D. 5 and D. 13, which lie most nearly opposite to the mouth of the Skager Rack.

The next figure (Fig. 11) is compiled from such observations as we have from the work of the Dutch Commission (though in this part of the sea they are at best scanty),

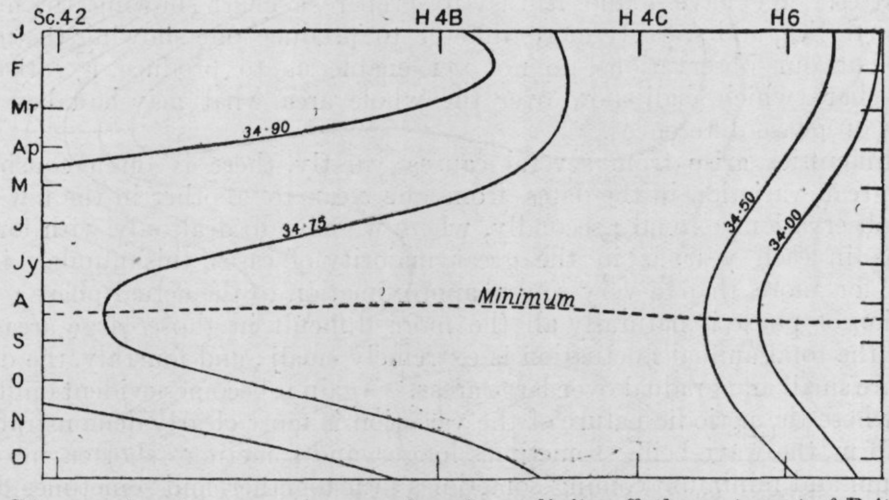

FIG. 11. Diagram showing mean changes of surface salinity off the east coast of Britain, from the latitude of the Firth of Forth to that of the Humber.

parallel to the English coast from off the Firth of Forth to the neighbourhood of the Humber. The phenomena agree in a general way with those indicated in the preceding figure.

Lastly, Fig. 12 is drawn for a depth of 100 metres on the line of stations from the mouth of the Moray Firth to the east coast of Shetland. The phases are very nearly the reverse of those seen in the preceding figures, for the maximum salinity is evidently in summer-time, and the minimum is near to midwinter. The highest salinities shown are in the neighbourhood of Stations Sc. 4 and 5, that is to say in the Fair Isle Channel, but

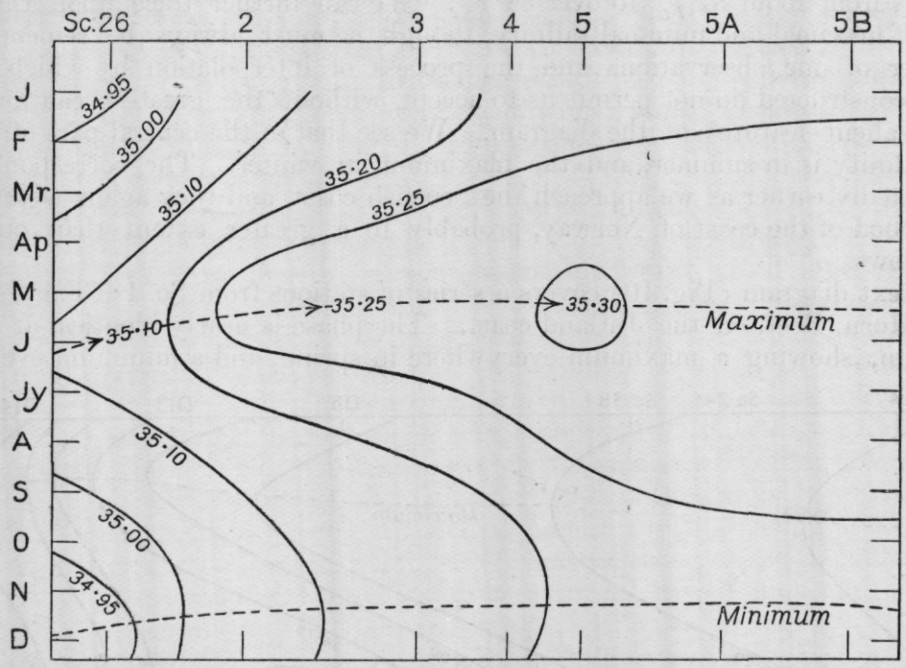

FIG. 12. Diagram showing mean changes of salinity at a depth of 100 metres on a line from the Moray Firth to the east coast of Shetland.

otherwise the mean salinity gradually increases as we pass from south to north along the line. The range of variation diminishes in the same direction, and is extremely small at the more northern stations. The contrast between this figure and the former ones is by no means due to difference of depth. As a matter of fact the phenomena seem here to be nearly identical at the surface and at a depth of 100 metres; but it so happens that the curves at this latter depth come out somewhat more simply and smoothly, being less disturbed by minor perturbations.

THE EPOCHS OF MAXIMAL AND MINIMAL SALINITY.

9. Though we have introduced the subject of phase, that is to say the question of mean date of minimum and maximum salinity at the various points, in the immediately preceding description of our isopleth diagrams, yet the more comprehensive study of phase in regard to variation of salinity over the North Sea as a whole proves to be a very difficult matter. We have found it easy to prepare a chart showing the mean salinity over the North Sea, and scarcely more difficult to produce one showing the mean annual variation; but our observations do not yet enable us to produce a satisfactory and convincing chart, which shall show over the whole area what may be taken as a normal distribution of phase differences.

Our difficulties arise from several causes; firstly, there is often considerable, and sometimes great, variation in the dates from one year to another in the few years over which our observations extend; secondly, where we have to deal only with four quarterly observations in each year, as in the great majority of cases, this number is evidently insufficient for more than a very rough approximation to the actual phase; thirdly, the determination of phase is naturally all the more difficult in those large areas of the sea over which the total annual fluctuation is extremely small; and fourthly, the differences of phase also are small and gradual over large areas. Again it becomes evident on investigation that, even where the periodic nature of the variation is most clearly demonstrable, it varies greatly in form, the wave being sometimes longer, and sometimes shorter, in other words, the maximum and minimum coming sometimes near together, and sometimes dividing the year into approximately equal intervals. Once again, there are certain regions of the sea, as within the limits of the Skager Rack, and again off the east coast of Scotland, where the phase appears to alter very suddenly within short distances, and our observations are neither near enough in point of distance, nor frequent enough in point of time, to enable us to trace the boundaries and other conditions of these diverse phenomena.

Lastly, over and above all these more or less obvious sources of difficulty, there lies the essential fact that the surface salinity varies in response to several distinct causes, and that the phenomena of phase are for this reason essentially complex. Firstly, it is now well-known that surface temperature is an important factor in the case, for the fresher waters that, if present, float freely on the surface in summer-time, may in winter-time be so far cooled below the temperature of the under-lying salter layers as to equal, or even exceed, them in density, and will then tend to sink and mix readily with them ; there will, accordingly, be a tendency to a seasonal change, due directly to temperature, giving rise to lower surface salinities in summer than in winter-time. We have, in the next place, the varying meteorological phenomena of rain-fall, and of the freezing-up of the streams and rivers in winter and their more or less sudden liberation in spring; and these phenomena will act in different ways and with very different intensities in different regions ; their general tendency will be to increase the outflow of fresh waters into the sea in winter-time in regions where no long-continued frost occurs, and in early spring in regions where severe winter cold binds the rivers until they are released by thaw. Winds and currents no doubt complicate the matter, in ways and in directions that we as yet very imperfectly understand. The direct phenomena of evaporation will also play a part in the case, and will have a tendency to increase the surface salinity in summer-time as compared with winter ; and this factor will tend to run counter to that more indirect consequence of temperature-change which we first described. Lastly, there remains the fluctuating supply of oceanic water penetrating into the North Sea, due to fluctuations in the great Atlantic currents, which fluctuations we now know to be more or less regularly annually periodic, but to be at the same time subject to variations of longer or less regular period. It has been shown that the so-called Gulf Stream current, which flows on its north-easterly course through the Faroe Channel off the north-west of Scotland, is reinforced, as it were, by an annual pulse in summer-time, and weakens in winter. We shall expect to find from this cause an increase of salinity in summer-time, at least in those portions of the North Sea that by proximity to the ocean are most exposed to its direct influence. It would be of the highest interest for the solution of all the difficulties that these complicated factors confront us with if we could form an approximate estimate of the actual quantity of salt present at various epochs within the basin of the whole North Sea, and could discover whether that whole amount be a variable one, and whether it be subject to periodic variation. I have made laborious attempts to attack this problem, but I believe that it is not yet ripe for even approximate solution ; there are too many areas of the North Sea for which we have practically no information at all, and too many others in which our observations are inadequate for such a process of integration.

10. It follows that while at first sight it might seem no very difficult matter to trace by contour lines upon the chart the mean epochs of maximum and minimum salinity from month to month, yet in the present state of our knowledge the task proves to be beyond our powers.

We can, however, lay down certain statements with considerable confidence, finding confirmation of them in various ways ; but we must restrict ourselves to stations where the periods in the several years of investigation are not greatly divergent. In order to do this we have tabulated from the interpolated curves for each station the apparent dates of maximum and minimum salinity in each year, and have tried to strike a balance for each station between the results shown, discarding at the same time those stations where the results were discordant and irregular. The general result has been to show that we have too little ground on which to base the determination of an annual period (1) in nearly the whole of that northern area where the mean salinity exceeds $35{\cdot}20°/_{00}$, in other words, in the salt water to the east of Shetland and southwards to the neighbourhood of our station Sc. 38 in lat. 58° 34′ N., long. 0° 47′ E. This corresponds on the whole to the region where the mean annual variation is less than $\cdot 1°/_{00}$. Again we find difficulty along the Danish coast, where, on the one hand, observations out to sea are few, and where, on the other hand, observations at the lightships are greatly complicated by tidal phenomena ; we have similar difficulties off the east coast of England, and lastly, in the region of the Dogger Bank and generally over the middle of the North Sea, where the variation is again comparatively small, the determination of phase is very uncertain.

11. At the whole of our stations in the northern Cattegat and in the Skager Rack a period of maximum salinity at the surface is indicated in winter-time, somewhere about the month of January and February ; and over the whole of the same region, with the exception of a strip entering the North Sea off the north coast of Denmark, we find very clear indication of an epoch of minimal salinity about the month of May. Within the strip already alluded to off the Danish coast (which includes Stations S. 5 and S. 6, D. 11 and D. 12, the period of minimal salinity occurs about August, or later ; while at the

Swedish stations nearer to the Norwegian coasts of the Skager Rack, there would appear to be (so far as the quarterly observations permit us to judge) a tendency to a subordinate maximum of salinity in summer-time, about the month of August.

In the German Bight, in the region influenced by the Elbe and the Weser, and also off the mouth of the Rhine, there is again a winter maximum of salinity, but apparently a little earlier than in the Skager Rack, viz., in December–January, rather than in January–February. Again in the German Bight the minimum salinity appears to occur about May, but off the Dutch coast it would seem to be somewhat later, about July.

On the line of Scotch stations, running in an easterly direction from the Firth of Forth, there is a distinct evidence of periodic variation, the maximum salinity appearing in all cases about December or January, and the minimum about June or July. Within the Firth of Forth itself, and in its immediate neighbourhood, both dates appear to be a month or two earlier.

The few stations that we have to the northward of the North Sea, and in the neighbourhood of the Norwegian coast (Sc. 7, 8 and 9) appear to indicate a maximum in winter and a minimum in summer, but the observations are scanty. The same is true of the German Stations D. 6, 7 and 8 off the south-west coast of Norway, where the maximum appears about February to April, and the minimum from June to August, both dates on the whole corresponding, but with a certain retardation, to the phenomena found within the Skager Rack.

Over all the rest of the North Sea the various dates of maximum lie on the whole in spring, from about February or March to May, and the dates of minimum in summer or autumn, from about August to October ; and these periods, as far as I can judge, would appear to be most retarded over the region of the Dogger Bank.

The line of stations running from the Moray Firth to the east side of Shetland are characterised by a very different period, for in them, without exception, we find evidence of a period of minimum salinity about November–December, and of a period of maximum in spring or early summer, usually about the month of April, and extending to June.

In the region of the Atlantic inflow at the Straits of Dover, and immediately to the eastward thereof, there appear to be somewhat phenomena ; and, unless I am greatly mistaken, there is a large and gradual retardation of phase from north to south, along the line of Belgium stations, from the Essex coast to Ostend. I do not propose to discuss further the conditions existing in this region.

The above preliminary and approximate results may be epitomised in the following table :—

Approximate Dates of Maximal and Minimal Salinity in the Surface Waters.

	Maximum.	Minimum.
German Bight	December, January	May.
Eastward of Firth of Forth	„ „	June, July.
Skager Rack	January, February	May.
„ (north coast of Denmark)	„ „	August.
East coast of England	February	August.
South-west coast of Norway ...	February, April	June, August.
Dutch coast	„ „	July.
Rest of North Sea	February, May	August, October.
Moray Firth to Shetland	April, June	November, December.

12. While I have hesitated, for want of sufficient evidence, to put upon a chart what appear to be the annual epochs of maximal and minimal salinity I give two charts showing, as far as evidence permits, the mean surface salinities over the North Sea for the months of February (Fig. 13) and August (Fig. 14).

It will be observed (1) that somewhat greater salinities are represented in the neighbourhood of the Channel, and somewhat less to the north of Shetland, in the February chart than in that for August ; but, on the other hand, the extension of moderately salt water, down to $34 \cdot 75 ^{\circ}/_{oo}$, is very much greater in February than in August, both from the direction of the Channel and from the North. In the Skager Rack the salinities are much greater in February ; the isohaline of $31 \cdot 0 ^{\circ}/_{oo}$ lies well within the Skager Rack in February ; but passes outwards in the direction of Stavanger in August, though in both cases its lower or southern end is in the neighbourhood of the Skaw. The $34 \cdot 0 ^{\circ}/_{oo}$ isohalines sends in February a long tongue eastward into the Skager Rack, but in August not only it, but also the $33 ^{\circ}/_{oo}$ and $32 ^{\circ}/_{oo}$ isohalines, lie more or less out in the North Sea, and do not enter the Skager Rack at all.

All the isohalines from $31{\cdot}75^{\circ}/_{\circ\circ}$ upwards, which come looping down into the North Sea from the Shetland region, are more or less shrunken in August as compared with

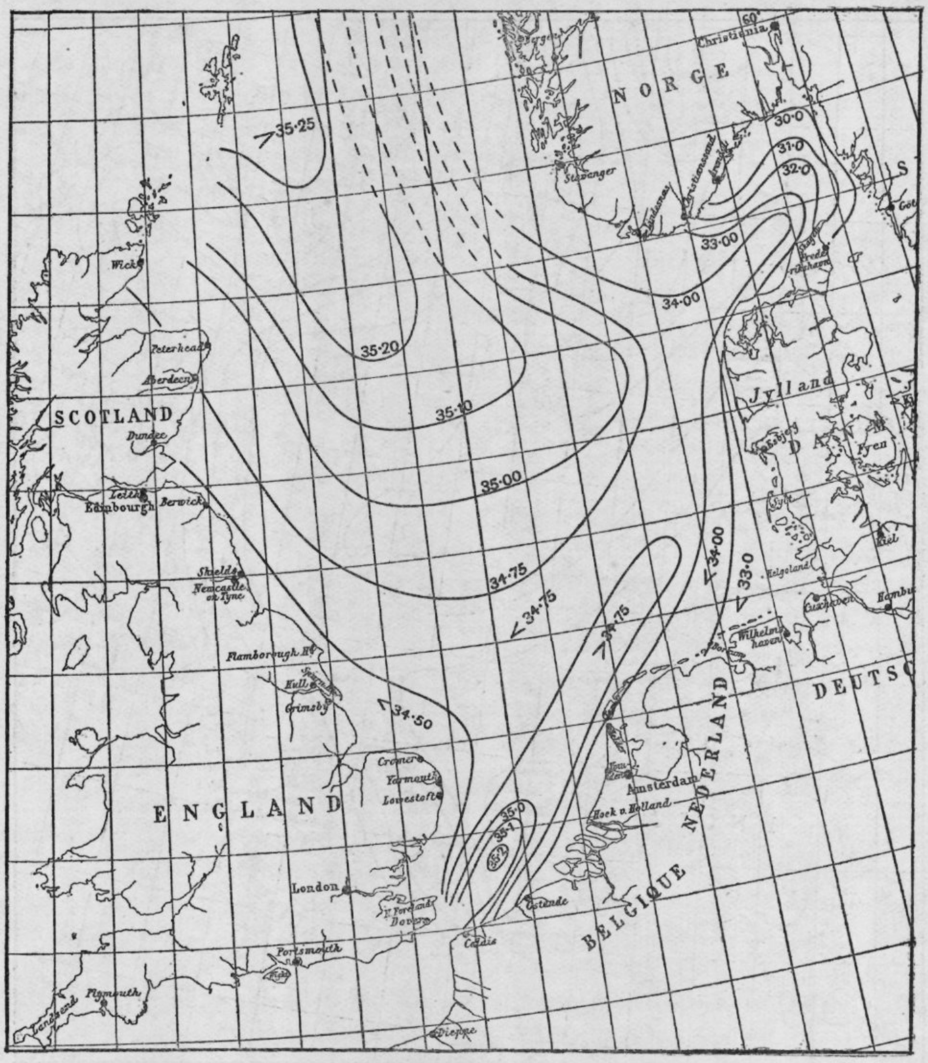

FIG. 13.—Mean surface salinity of the North Sea for the month of February, 1903–7.

February, and while their elongation in a north and south direction is somewhat diminished, it is a still more conspicuous feature that their eastern extensions are pushed towards the west. This is the result, and the representation, of that great extension of comparatively fresh waters in summer-time over the North Sea from the direction of the Skager Rack and the Norwegian coast, which we have now learnt to look for as a regular periodic occurrence.

13. The fluctuations in regard to salinity over any particular area or line of stations may, after all, be most safely studied by inspection of the sections drawn for each cruise, for in these the risk of error arising from interpolation is at a minimum ; but the method is laborious, owing to the number of such sections, and the multiplicity of detail that is represented in each. We may, however, draw simplified sections, inserting in them only the main features, and doing so within the limits of a single diagram, for several successive dates. Fig. 15 represents a section from station Sc. 26 to Sc. 5A, that is to say, from the mouth of the Moray Firth to the east side of Shetland. On the whole the salinity tends to increase pretty regularly from the former to the latter end of the section. We have represented on this diagram two isohalines only, namely those for $35^{\circ}/_{\circ\circ}$ and $35{\cdot}25^{\circ}/_{\circ\circ}$, and we have repeated these isohalines for each of the four cruises made in 1907. To the southward of the $35^{\circ}/_{\circ\circ}$ line the salinity is all below $35^{\circ}/_{\circ\circ}$, to the northward of the $35{\cdot}25^{\circ}/_{\circ\circ}$ isohaline it is all above $35{\cdot}25^{\circ}/_{\circ\circ}$. It will at once be seen, as regards the $35^{\circ}/_{\circ\circ}$ isohaline that this is shifted in August close to the southern end of the diagram, and that then it embraces only the upper layers of water ; in other words, nearly the whole of the diagram is filled by water over $35^{\circ}/_{\circ\circ}$ salinity. In February, on the other hand, a considerable space, from top to bottom, is filled with water below $35^{\circ}/_{\circ\circ}$, and the same is the case, though over a somewhat less area, in the month of November. As for the $35{\cdot}25^{\circ}/_{\circ\circ}$ isohaline, no such line appears in the diagram for the month of November, while of the other months represented, this isohaline has its most northerly position in

February. In May and August the main 35·25°/₀₀ isohalines appear between stations Sc. 3 and Sc. 5, the former being to the southward of the latter ; but in August there is

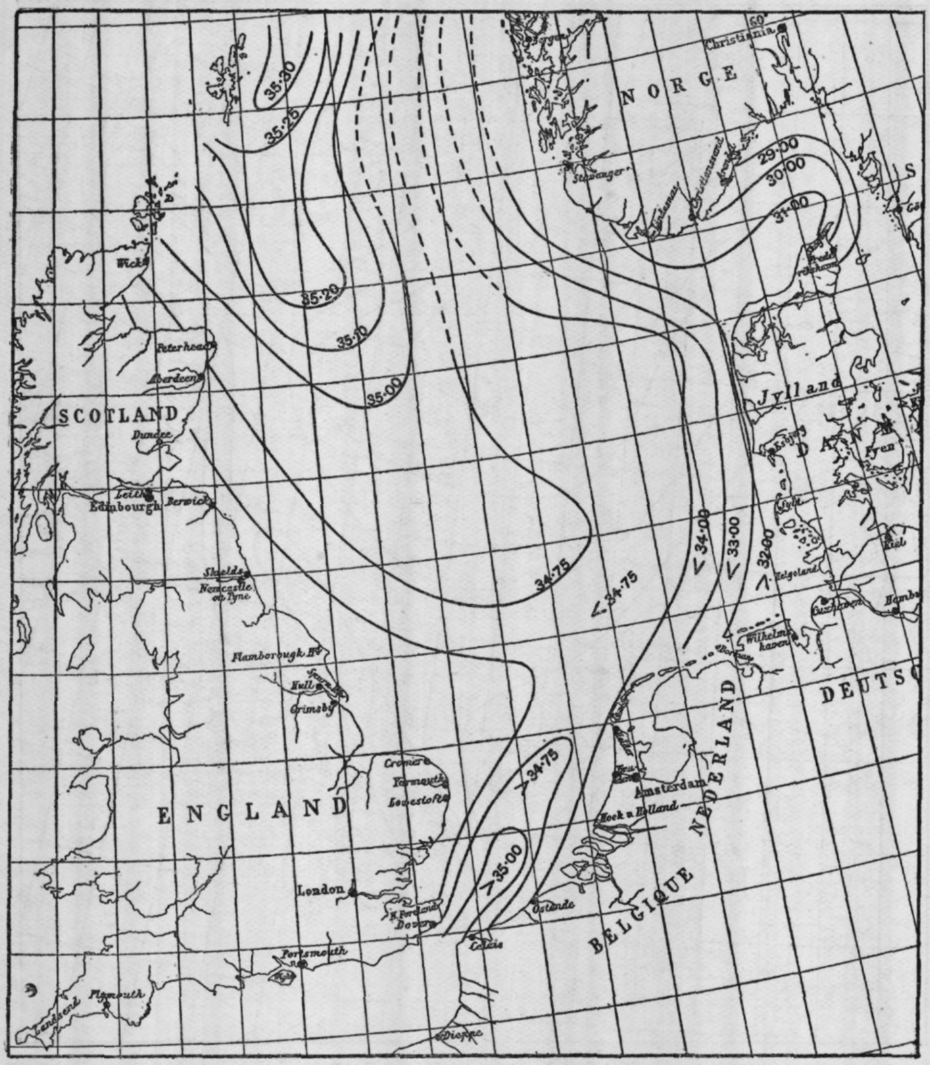

FIG. 14.—Mean surface salinity of the North Sea for the month of August, 1903–7.

another 35·25°/₀₀ isohaline, marking off a layer of salt water at the bottom in the southern part of our section. The two series of isohalines, accordingly, do not run parallel or equidistant, to one another ; but it is clear on the whole that, of the months represented, it is November in which the salinity along this line of stations is least, and August

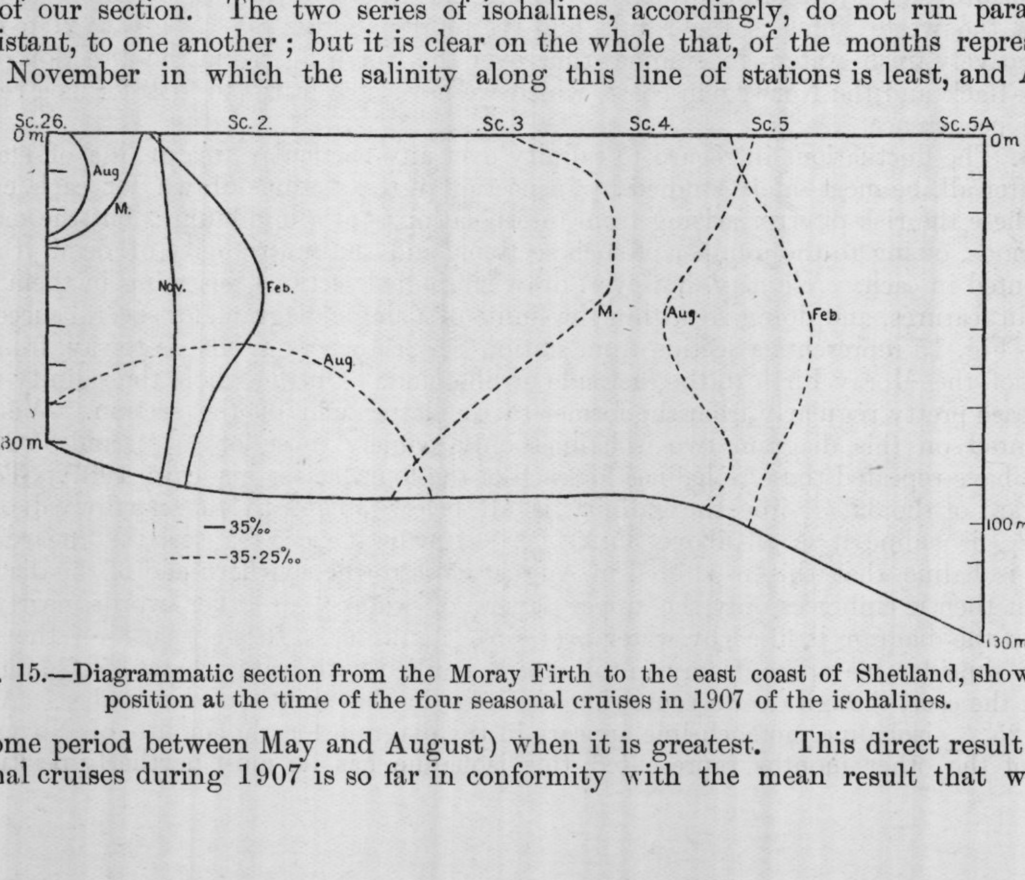

FIG. 15.—Diagrammatic section from the Moray Firth to the east coast of Shetland, showing the position at the time of the four seasonal cruises in 1907 of the isohalines.

(or some period between May and August) when it is greatest. This direct result of our seasonal cruises during 1907 is so far in conformity with the mean result that we have obtained in other ways, namely, that the period of maximum salinity for this region is in summer, probably about June or July, and the period of minimal salinity in winter, about November or December.

The next diagram (Fig. 16) illustrates our line of section running eastward from the Firth of Forth, the least saline water being at the western end of the line within the Firth itself, and the general tendency being for it to grow salter as we proceed seaward.

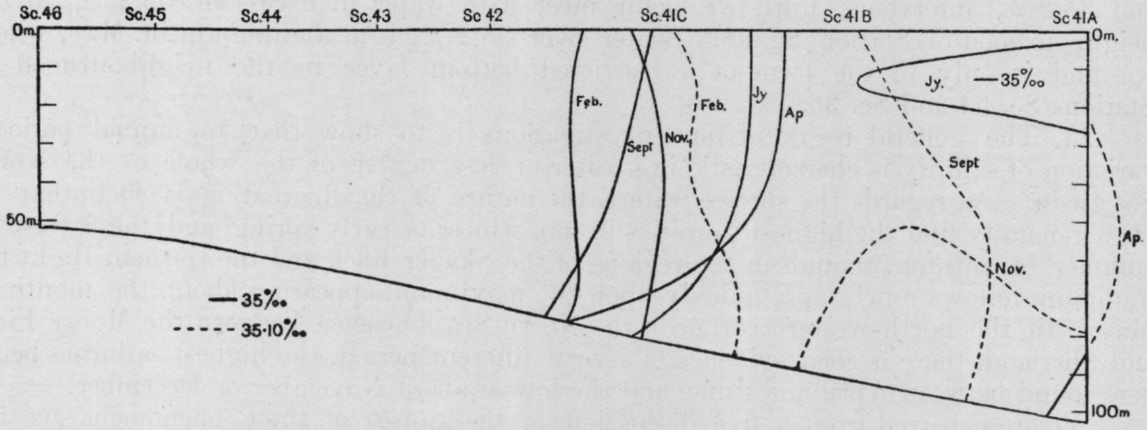

FIG. 16.—Diagrammatic section from the Firth of Forth eastward, showing the position of the isohalines corresponding to salinities of 35·00 and 35·10 per mille at various seasons during the year.

In this case the isohalines presented are those for 35°/$_{oo}$ and 35·10°/$_{oo}$. It will be seen that (of the month represented) February is distinctly that one which shows the highest salinities ; for, not only is the 35°/$_{oo}$ isohaline furthest to the westward in this month, but so also, and in greater degree, is the isohaline of 35·1°/$_{oo}$; the space included between these two isohalines is only a narrow strip, and water, whose salinity exceeds 35·1°/$_{oo}$, occupies nearly the eastern half of the whole section at all depths. On the other hand, in the month of July no water with a salinity so great as 35·1°/$_{oo}$ appears in any part of the diagram, but a tongue of fresh water, even below 35°/$_{oo}$ salinity, is seen entering the section from the east and near to the surface. By September we find a considerable invasion of water over 35·1°/$_{oo}$ at the eastern end of the section, but in November (at least in this particular year) such water had not increased in quantity, but has rather diminished, being found only in the deeper layers. On the whole it is clear that the period of maximal salinity is here a winter one, and that of minimal salinity a summer one. Figure 17 is a somewhat more complicated diagram for the line of stations from

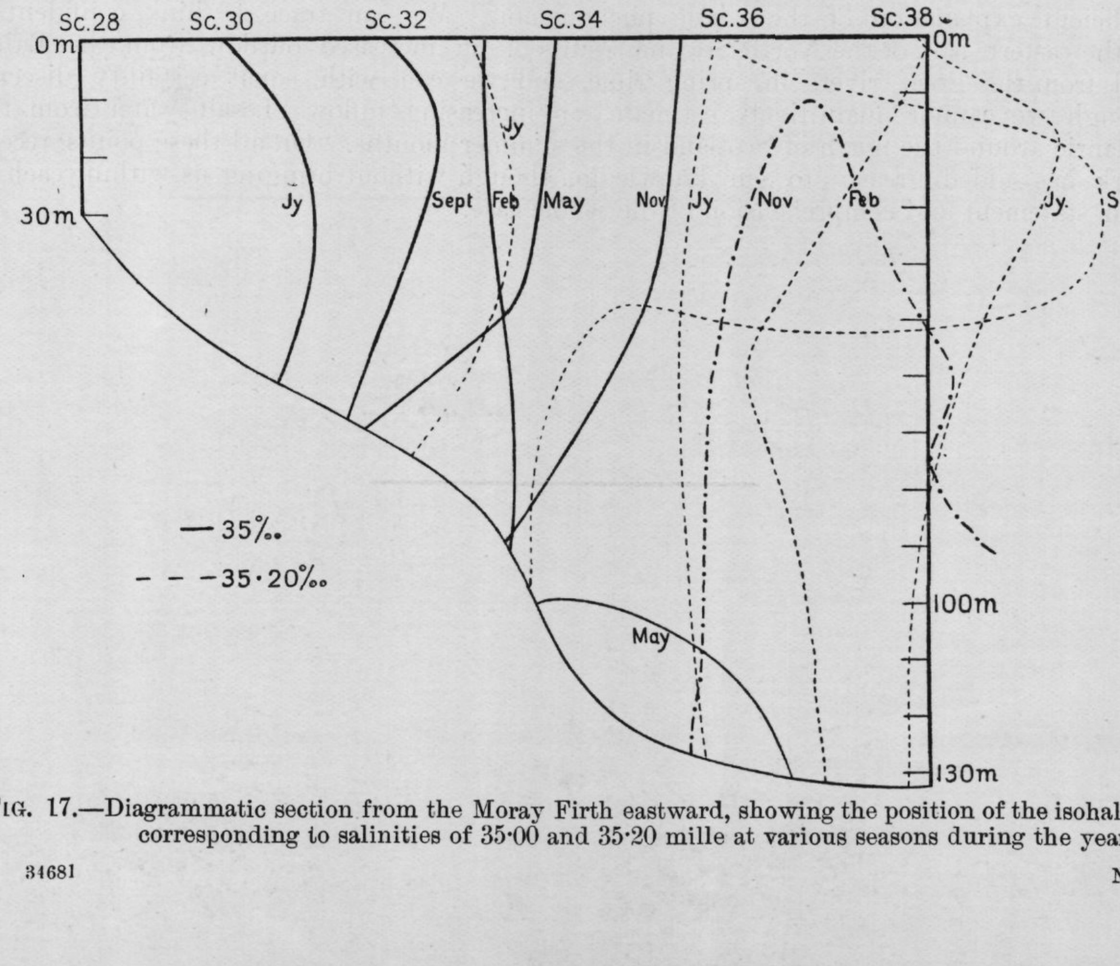

FIG. 17.—Diagrammatic section from the Moray Firth eastward, showing the position of the isohaline corresponding to salinities of 35·00 and 35·20 mille at various seasons during the year.

the Moray Firth eastward. As regards the 35°/₀₀ isohaline, it is clearly furthest to the westward in July, and most distant from the shore in November; the former season is that in which comparatively fresh water below that density is at a minimum. But the distribution of water over 35·20°/₀₀ is rather more complicated. It is in July that such water comes furthest westward, or shoreward, but it is in the form of a comparatively narrow band in the neighbourhood of Station Sc. 4, after which a region between 35°/₀₀ and 35·2°/₀₀ intervenes, until we again meet with water in excess of 35·2°/₀₀ in the neighbourhood of Station Sc. 38. Water over 35·2°/₀₀ is at a minimum in May, where we find it only in the form of a restricted bottom layer in the neighbourhood of Stations Sc. 34 and Sc. 36.

14. The general result of our investigations is to show that an annual periodic variation of salinity is characteristic in greater or less degree of the whole of the North Sea basin. As regards the surface waters, the nature of the fluctuation is such that we very generally find the highest salinities in late winter or early spring, and the lowest in summer or autumn, though in the regions of the Skager Rack and the German Bight the minimum follows much more quickly upon the maximum, appearing about the month of May. In the north-western corner of the North Sea, however, between the Moray Firth and Shetland, there is clear evidence of a very different period, the highest salinities being here found between April and June, and the lowest about November or December.

We are debarred from a free discussion of the causes of these phenomena by the insufficient details of our knowledge regarding the periodic phenomena at the surfaces and still more by the fact that we have made no adequate investigation, even of the available facts, in regard to the periodic variation in the deeper waters. The last diagrams (Figs. 15 to 17) in this paper are sufficient to remind us that the phenomena of periodic variation are far from being limited to the surface, and the same fact can be readily seen from the work already done by other investigators, for example, in the region of the Skager Rack. I venture to say, though I have not yet furnished the necessary proof, that so far as I have worked at the conditions of the deeper waters, I believe that the mean salinity at all depths will be found to follow much the same rule as the salinity at the surface, namely, to show a general increase in winter, and a general decrease in summer time.

While the frequent approximate coincidence of maximal and minimal surface salinities with the epochs of maximal and minimal temperature of the surface waters would lead us to attribute the seasonal difference in surface salinity to the varying temperature conditions, I feel convinced that such an explanation is only partially valid. It no doubt facilitates the extension westward from the neighbourhood of the Skager Rack of a surface layer of comparatively fresh water in summer-time, but it is far from being a sufficient explanation of the whole phenomenon. We can trace, I think, confidently, in the eastern part of the North Sea the results of an increased outflow from the Baltic and from the great rivers in spring time, and we can with equal certainty discern, though we cannot quantitively estimate, an increasing inflow of salt water from the Atlantic around the north of Scotland in the summer months. On all these points recent work has added greatly to our knowledge, though without bringing us within reach of clear statement and comprehension of the whole case.