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THE PLANKTON OF THE NORTH SEA IN RELATION TO ITS ENVIRONMENT

PART I.—THE HYDROLOGICAL BACKGROUND IN THE SOUTHERN NORTH SEA, 1930-37

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Introduction.

Accounts of the Continuous Plankton Recorder surveys in the Southern North Sea, 1932–37, have been given by Hardy (1939), Lucas (1940), Rae and Fraser (1941), Henderson and Marshall (1944), and Stubbings (in the press). No detailed attention was paid in these to the relations between the plankton and its environment, largely because of the absence of immediately relevant material. The data reviewed here provides a partial hydrological background against which changes in the plankton may be seen; since they are fairly extensive, it seems best to consider them first separately and then (in Part II) in relation to the plankton. This, in turn, may reflect further light on the water movements during the period and some aspects of the data will be considered further in that part.

At this late date it might seem suitable also to review the data for 1938 and 1939, but some of them are not yet available, although reference will be made to certain aspects which are known to be relevant.

In the absence of any *ad hoc* material for correlation with the plankton records, it is necessary to make such use as we can of material taken with other objects in view. The normal methods of hydrological survey are generally unsuitable for comparison with data which are essentially continuous in space, and which are taken over the same routes for much longer periods than usual. The typical hydrological cruise involves a set of stations over a particular area, stations at least twenty miles apart and extending over a period of several days. The next cruise in such an area is likely to be at least three months later, and may well be more than a year after the first. More suitable material is found in the routine samples at stations on regular steamship lines and from light-vessels. Although only one of these steamship lines coincides with a plankton recorder route, there is a set of them crossing the Southern North Sea which provides regular standards for comparison. Against the limitation that the material has been collected only at the surface, and that the observations are limited to temperatures and salinities, are set the advantages of regularity and consequent standardization. In so far as continuity in space has been a feature of the recorder work, it would be most desirable to have similar continuity in hydrological data for comparison. Unfortunately, however, the only continuous physical data, certain thermographs, are confined mainly to the Northern North Sea.[1]

The routine observations mentioned, *bateaux routiers* and *bateaux feux* of the 'Bulletins Hydrographiques,' published by the Conseil Permanent International pour l'Exploration de la Mer[2], have been selected from a number which have been maintained more or less regularly by the member nations of the Council since the last war. As a whole they provide a mass of information on salinities and temperatures *at the surface* by means of routine methods at positions along specified routes. As Lumby (1935) has pointed out, they provide the only standards whereby changes from year to year can adequately be assessed, and it is unfortunate that some of them should have been discontinued in later years, and others reduced from weekly or monthly to quarterly or less regular sampling. Apart from the relative uniformity of the methods, their value lies in their spatial and temporal standardization, and it is remarkable that, as far as one can see, so little use should hitherto have been made of them. The positions of those we have selected appear in Text-fig. 1.

We should like to express our thanks to Dr. J. N. Carruthers, Commander J. R. Lumby and Dr. L. H. N. Cooper, who have kindly read and commented on this paper whilst in proof.

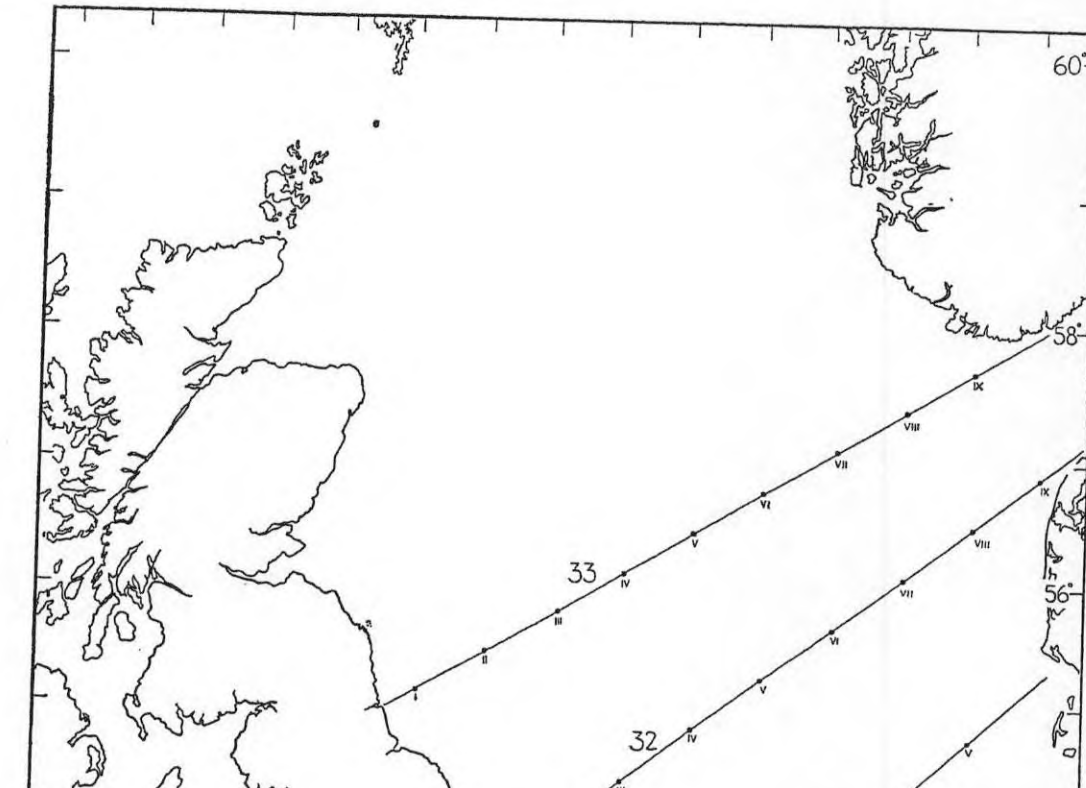
[1] The possible introduction of other continuous methods for recording physical data has been under consideration in this department.

[2] We must express here our gratitude to the Conseil Permanent for their kindness in supplying these data regularly in a form more convenient to us than that provided by the Bulletins.

Significance of the Data.

In this review the greater use will be made of salinity data, although temperature data will be used for some purposes. The methods whereby such data have been obtained were discussed by Lumby (1935). Whilst they have some defects, the evidence suggests that in the shallower waters of the North Sea and the English Channel, such surface estimates of salinity are reasonably representative of conditions in the whole water column, and more certainly of the upper part of it. In addition to providing extensive evidence of the general conditions, they should, therefore, be of value in relation to the distribution of plankton at ten metres depth. Surface estimations of temperature are more likely to deviate from those beneath them, but the evidence of trends shown by large numbers of records may be useful. For the more northerly water (*e.g.* Route 33), however, it is necessary to consider further whether the surface data are adequate to the purpose, and it is useful to have some general measure of the probable maximal deviations of surface data from, say, those of water at ten metres depth.

One measure of such differences is provided by the samples taken by Graham and Harding (1938) on a line through the English Channel, into the Southern Bight and through the "Gateway" between the Dogger Bank and the English coast in 1935–37 (their figs. 2–4). The isolines are nearly vertical through the Channel and up to the Humber region, and even in the "Gateway" region there were no great differences (*i.e.* from the biological point of view) within the superficial waters. Further evidence is provided by Graham (1938, figs. 5–12) along lines through the "Gateway" as far north as 55° N. in 1934–35. Although at times there were signs of stratification in the north-west, very rarely do the differences between the salinities at the surface and at ten metres exceed 0·1 °/₀₀, or the temperature differences exceed 2° C. To take further examples, Savage and Wimpenny (1936, figs. 25 and 26) give data for sections across the "Gateway" in 1932–35, and again there are few important differences in the upper layers. The proportion of salinity differences exceeding 0·1 °/₀₀ is under 5%, whilst seldom is a difference of as much as 1° C. recorded. Considerable temperature differences existed between the surface and bottom at times, although salinity differences were normally slight, and may have been expected to be even smaller over the shallow waters of the Dogger. Immediately to the north, and particularly to the east of the Dogger, where the water is deeper again, there is possibility of greater differences, although there is no extensive data for this region. As a measure of differences which may exist under such conditions, and probably more extreme, we have examined the abundant data more to the north of our area. These show that usually there were only large differences of salinity when the surface waters were very brackish, and that even these differences were seldom of an order such as to lead to any confusion regarding the nature of conditions at ten metres as deduced from surface samples. More precision is given by



TEXT-FIG. 1.—Showing the positions (•) of the stations on the international routes for which data have been abstracted from the 'Bulletins Hydrographiques.' The arabic numerals, 15, 22, 32, etc., are those used in the 'Bulletins' to signify the different routes, whilst the station numerals, I, II, III, etc., correspond with those used in Text-figs. 2–9. The Varne Light-vessel is denoted by the letter V. Those stations connected by a broken line have been selected to form the *ad hoc* route of Text-fig. 13.

consideration of the whole of the data for 1934 and 1937[1] at these two depths in the North Sea north of 54° N., and exceeding 24·99 °/₀₀ at the surface ('Bulletins Hydrographiques' for 1934 and 1937). Results show that when the surface waters exceeded 34·5 °/₀₀, only in 35 samples out of 502 was there a greater difference than 0·1 °/₀₀ from the waters at ten metres (and in only 8 was it greater than 0·2 °/₀₀). With lower surface salinities there were greater differences, but even with salinities between 25 °/₀₀ and 27·49 °/₀₀ the average difference was not much more than 1 °/₀₀. It is probable that the layering of the water does not seriously affect any deductions regarding the environment of the plankton at ten metres, because stratification is normally below that depth. Such a conclusion has a wide importance for the Recorder surveys since, in the extended area of 1938–39, the records were regularly taken over much deeper water than before, and it is necessary to know how far surface hydrological information may be relevant under such conditions. There is reason to believe that it will be adequate for many purposes.

Methods, etc.

The routes and stations from which hydrological data have been selected are shown in Text-fig. 1. They may be compared with the charts shown in the 'Bulletins Hydrographiques' since 1932, the same numbers being used here to denote the regular steamship observations. For simplicity the various stations on these steamship routes have been denoted by Roman numerals, both in this figure and in the figures showing graphs of the data (I denoting the stations on the English side). A number of these, *e.g.* on route 32, have apparently been made regularly in the same places (*i.e.* the longitude and the latitude for each station are given as identical on each occasion). On others, *e.g.* Route 36, these vary from time to time, whilst not always have the same number of stations been sampled. For these reasons those stations have been selected which have been sampled most often, *i.e.* truly routine ones. Their average positions have been found, and for practical purposes these have been used as if constant; random samples of the errors involved in this assumption show that rarely do they exceed five miles in any direction. Other differences from the data in the 'Bulletins Hydrographiques' concern the omission of certain stations which did not seem particularly useful for the present purpose (*e.g.* a coastal station in Route 36), whilst in one case selected stations from two routes have been combined and used as if on one route for economy and simplicity (Routes 37 and 38). For all these stations the data have been abstracted from the Bulletins as provided and used without any attempt at correction. There are good reasons for believing that some errors are present in the original data (*e.g.* the unusually low salinities in December, 1935, on Text-fig. 5), but we have decided (see also Lumby, 1935)

[1] The choice of these two years was made at random in order to provide evidence on this point. Temperature differences were also slight on the whole; for all 1937 surface values between 3° and 14° C., in only 12 cases out of 375 did the difference exceed 1° C.

that it is better to include even these unlikely data, since corrections and omissions may well lead to greater confusion and error than the original mistakes.

In order to lead up to the period of the plankton survey, we have made use of data from January, 1930, wherever possible. The following details regarding the individual routes are relevant:

Route 33. Shields–Oslo. (Text-figs. 2 and 3.) Usually weekly samples on the meridians of longitude from 1° W. to 7° E. This route is to the north of the plankton data.

Route 32. Hull–Copenhagen. (Text-figs. 4 and 5.) Usually weekly samples on the meridians of longitude from 1° E. to 8° E., with an additional station at 1° 30′ E. This route corresponds exactly with the Copenhagen line of the plankton records, the data being obtained by the same ship.

Route 31. Esbjerg–Harwich. (Text-fig. 6.) Selected sets of weekly samples on the meridians of longitude from 3° E. to 7° E. (from June, 1930, only). Whilst this route corresponds to the Esbjerg plankton line (in use from 1936), the data were often obtained from different ships on different days.

Route 36. Hull–Amsterdam. (Text-fig. 7.) Samples[1] grouped around the 5th, 15th and 25th of each month at six selected stations (for mean positions, see Text-fig. 1). There are no data for 1930 and part of 1931. Although taken at different times and by different ships, the Western part of this route lies fairly close to the corresponding part of the Rotterdam plankton line. The Eastern part of the route deviates well to the north of the plankton recorder line.

Routes 37 and 38. Gravesend–Hook of Holland and Harwich–Flushing. (Text-fig. 8.) Two stations from the first route have been combined with three of the second. The samples[1] were collected in a manner similar to that for Route 36, and the data have been graphed as if they were one route for convenience and economy, their mean positions being shown in Text-fig. 1.

Route 22. Southampton–Le Havre. (Text-fig. 9.) Approximately weekly samples in sets of five or four stations (usually alternate, omitting the most continental one) and approximately at intervals of 9′ longitude.

Varne Light-vessel (V, Text-fig. 1.) Average monthly values from samples taken some eight times each month. These, and Routes 22, 37 and 38 lie to the south and west of our plankton data.

In addition to the data mentioned above, which have been used and plotted more fully, others have been abstracted on similar principles for incidental reference. These are Routes 23 (Newhaven–Dieppe), 21 (Southampton–St. Malo), 16 (Plymouth–Guernsey), 15 and 10 (variously crossing the mouth of the English Channel along similar courses), together with the Sevenstones Light-vessel. Reference is also made to certain individual stations for special purposes.

A suitable graphical method was not at once apparent for the illustration of

[1] Unlike those for the other routes, the values given for these observations on each occasion represent the mean values for a number of observations made during five days prior to and five days following the "mean" date.

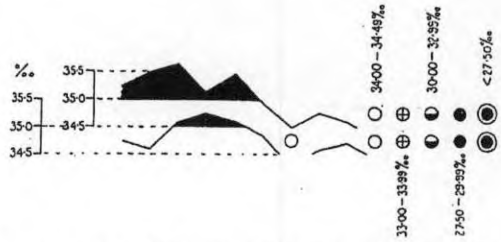
the major data. The widely varying salinity ranges make unsuitable any simple method of graphing, since a linear scale which clearly shows the total variations in salinity tends to minimize the important, but much smaller, variations within the higher ranges. Since we wish to show in one figure as many data as possible, both for comparative purposes and for economy, a simple graphical method, with a linear scale, is used for salinities above $34{\cdot}49°/_{oo}$ (the values over $34{\cdot}99°/_{oo}$ being shown in black), whilst below this value a range of symbols is used to show the different types of more or less brackish water (see scale below for Text-figs. 2–9). In this way one can distinguish at a glance the regions of most saline water (blacked-in) from those of moderate but still appreciable salinity (line), and both of these from the remaining regions, of quite different constitution, in which the varying brackishness of the water is shown by the increasing density of the circular symbols.

Reference to Text-fig. 1 shows that not all the mean positions of the stations (*e.g.* on Route 36) are equally spaced, and even where constant positions have been given (*e.g.* Route 33) it is uncertain that the true positions were in fact so regular. In view of the small variations involved, it has been thought more convenient to present the data as if all the stations on any one route had been equidistant, and so constant in position. Thus the successive sets of data for any route can readily be compared when arranged as vertical series, in time order for each year, the years appearing in consecutive columns. The method is similar to that adopted for the continuous plankton records in earlier bulletins. All data for one station in any year may be found in a vertical line under the appropriate Roman numeral, whilst lines of stations at similar times of the year may be found in horizontal line, the letters J, F, M, etc., representing the months.

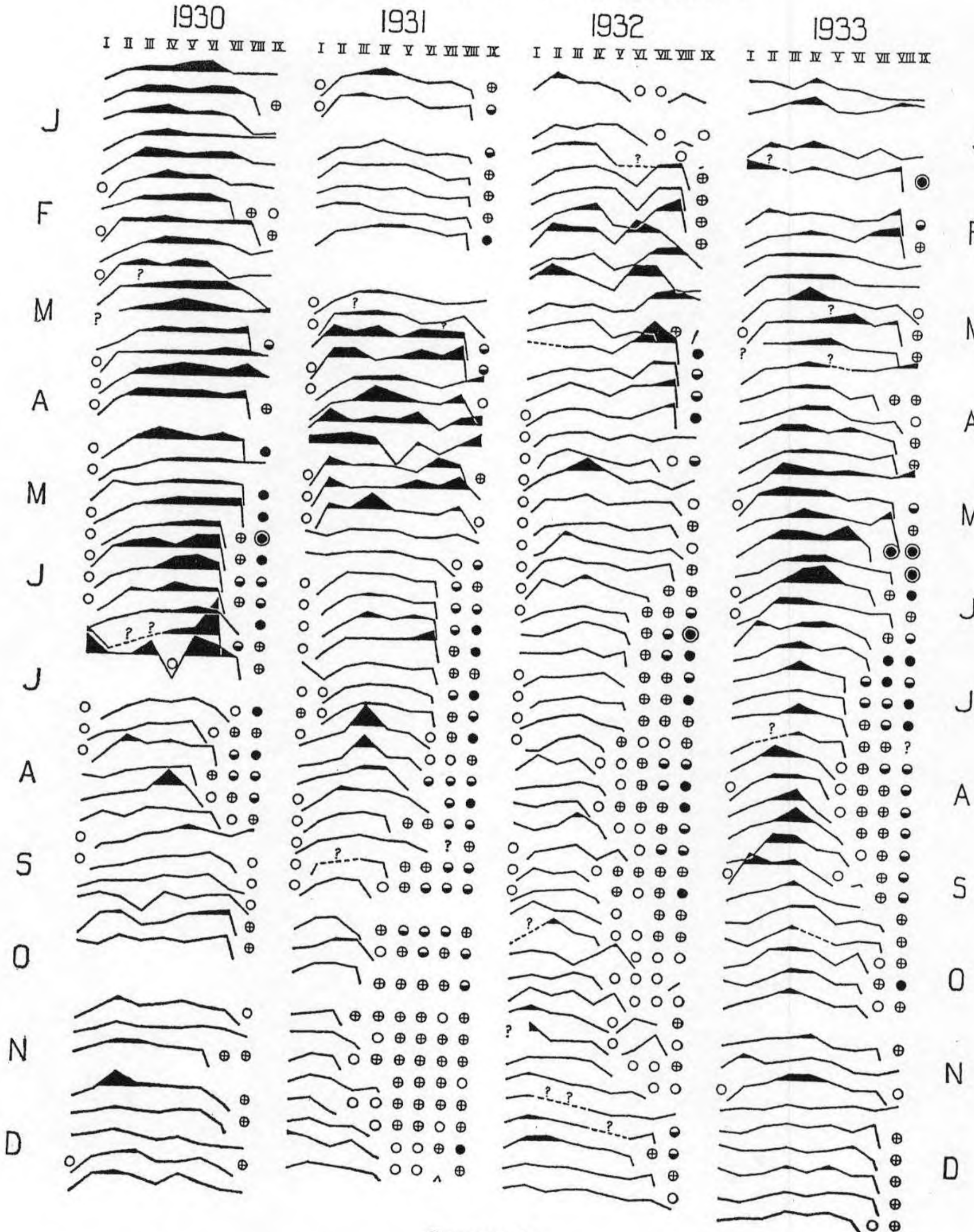
Few other symbols have been used in these graphs, but reference should be made to certain conventions. Where observations denoted by linear methods and those shown by circular symbols are adjacent, the trend between them is denoted by a line from the last "graphical" value, tending towards the position the other would have had had it been shown on the "graphical" scale, but stopping short on the $34{\cdot}5°/_{oo}$ baseline. The rate of change of salinity is thereby shown. Similarly, within the usually broad area of lower salinity values, such higher ones as appear are shown "graphically" in a similar manner. In the extreme cases these may appear on the $34{\cdot}5°/_{oo}$ line as points only.

Where odd observations have failed, the omissions have been denoted by the symbol "?" and, if in the graphical sections, the adjacent stations have been connected, where possible, by broken lines.

Three sets of abstracted data have been obtained. For the first, Text-fig. 10, it has been useful to provide a numerical measure of the annual changes on the

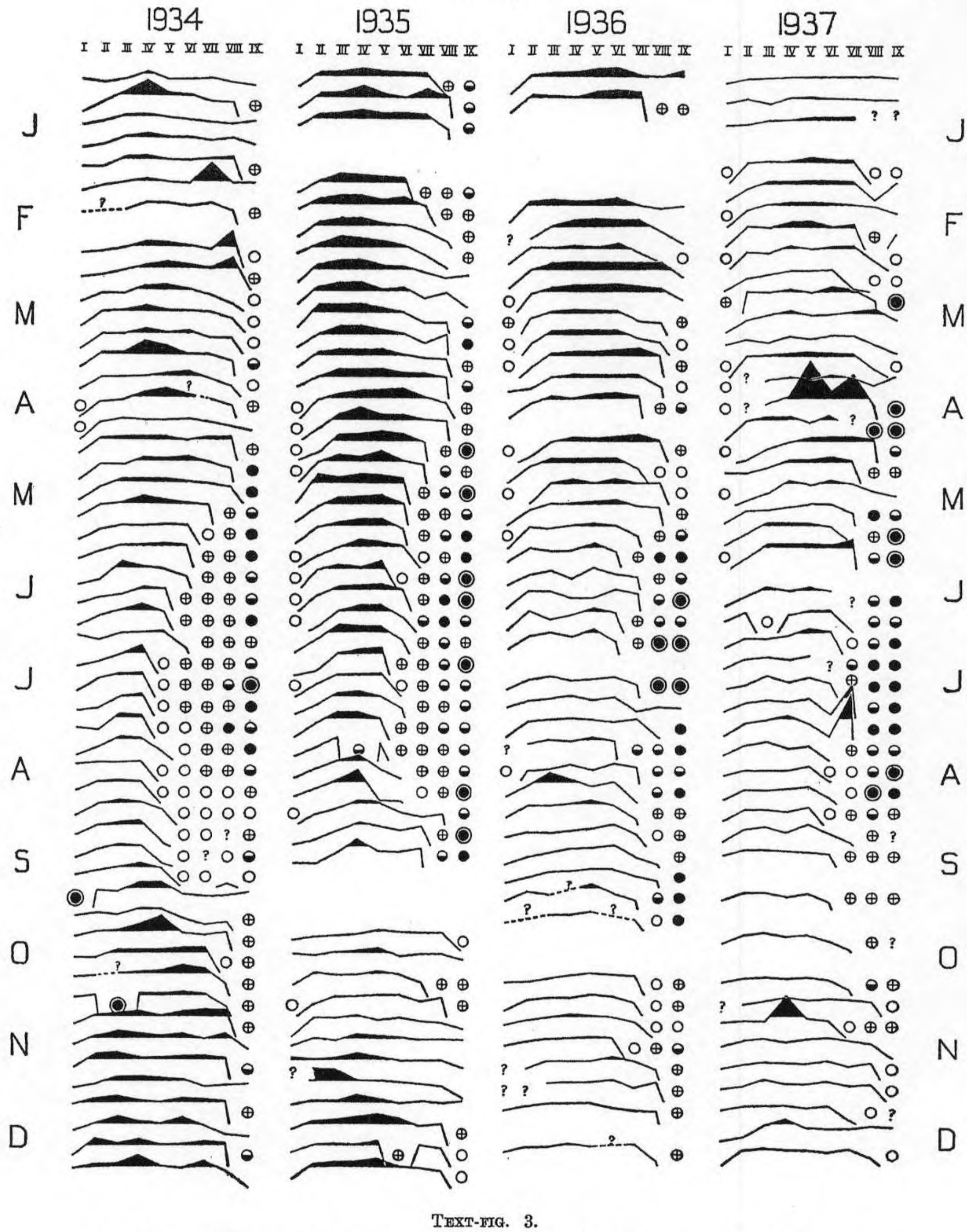


TEXT-FIG. 2*a*.—Scale of salinities for Text-figs. 2–9 and 13.



TEXT-FIG. 2.

TEXT-FIGS. 2 and 3.—Route 33 (Shields–Oslo). Showing the surface salinities at stations I–IX (Station I being that nearest to the English coast) at weekly intervals during 1930–37. For each weekly set, the linear graphs show the varying salinities above 34·49°/₀₀, the blacked-in portions being above 34·99°/₀₀; the increasing brackishness of waters below 34·49°/₀₀ is denoted



TEXT-FIG. 3.

by the increasing density of circular symbols (see scale in Text-fig. 2a on p. 7, and also text). The sets of graphs are arranged in eight vertical series, one for each year; the months, within which the weekly graphs fall, are denoted by the letters J, F, M, etc., down the sides of the vertical series, each letter indicating the middle of the corresponding month.

different routes, and we have plotted for certain of them, against time, the number of occasions in each month when salinities exceeding certain values were recorded so that, for example, one can compare the abundance of water exceeding 34·99°/₀₀ salinity in different seasons and years.[1] From these we have been able to derive (Text-fig. 12) a general impression of the trends on the different routes by the method of "moving averages"; whilst such impressions can only be most approximate, they may be as useful as can be expected from the data. For the second type of abstracted data (Text-fig. 13) we have selected certain stations from the standard routes to form a sequence representing a "route" extending from the mouth of the English Channel, through the Straits of Dover, into the North Sea (broken line in Text-fig. 1); the mean monthly salinities along this "route" are shown at monthly intervals by methods similar to those adopted in Text-figs. 2–9. In the third abstraction the data for most of these stations are shown by linear graphs in time sequence, so that the times of occurrence of particular types of water at certain positions may be readily compared (Text-fig. 14).

With these matters in mind the routine data may be reviewed, first for the North Sea stations, and then for the Channel waters.

THE BASIC HYDROLOGICAL DATA.

Route 33 (Text-figs. 2 and 3) shows two chief types of surface water. The western water was mainly of higher salinity, whilst the eastern water usually provided lower values, although sections of brackish water appeared in the extreme west, just as higher salinities were at times found in the east. The symbols for the lower salinity water present a useful picture of the varying expansion of the brackish surface water off the mouth of the Baltic. Whilst there was usually a maximum spread of brackish water in the late summer months, it varied greatly from year to year. In 1930 it was only moderate in extent and was greatly exceeded in 1931, when the maximal area was recorded in the autumn. It then occurred progressively earlier up to 1935, varying in extent but generally decreasing after 1934, whilst in 1936 and 1937 it was, on the whole, rather later. In distinction from the spread of water below 34·5°/₀₀, the number of stations giving samples below 30°/₀₀ was much greater during the second half of the period (and particularly 1937) than in the first half; on the other hand, the salinities in this region were quite high at times. In association with the variation of the Baltic water, the extent of the higher salinity surface water varied, this being particularly small in the autumn of 1931 and the summers of 1932 and 1934, although in the latter year the actual salinities were quite high. On the whole the higher salinities appeared in the spring and summer, and reappeared in the autumn. After persisting for a long period in 1930, the salinities over 35°/₀₀ were much scarcer in 1931

[1] This has certain disadvantages when compared with mean salinities, but it avoids the difficulties introduced when the means of values taken in very different types of water may be quite unrepresentative of any conditions recorded.

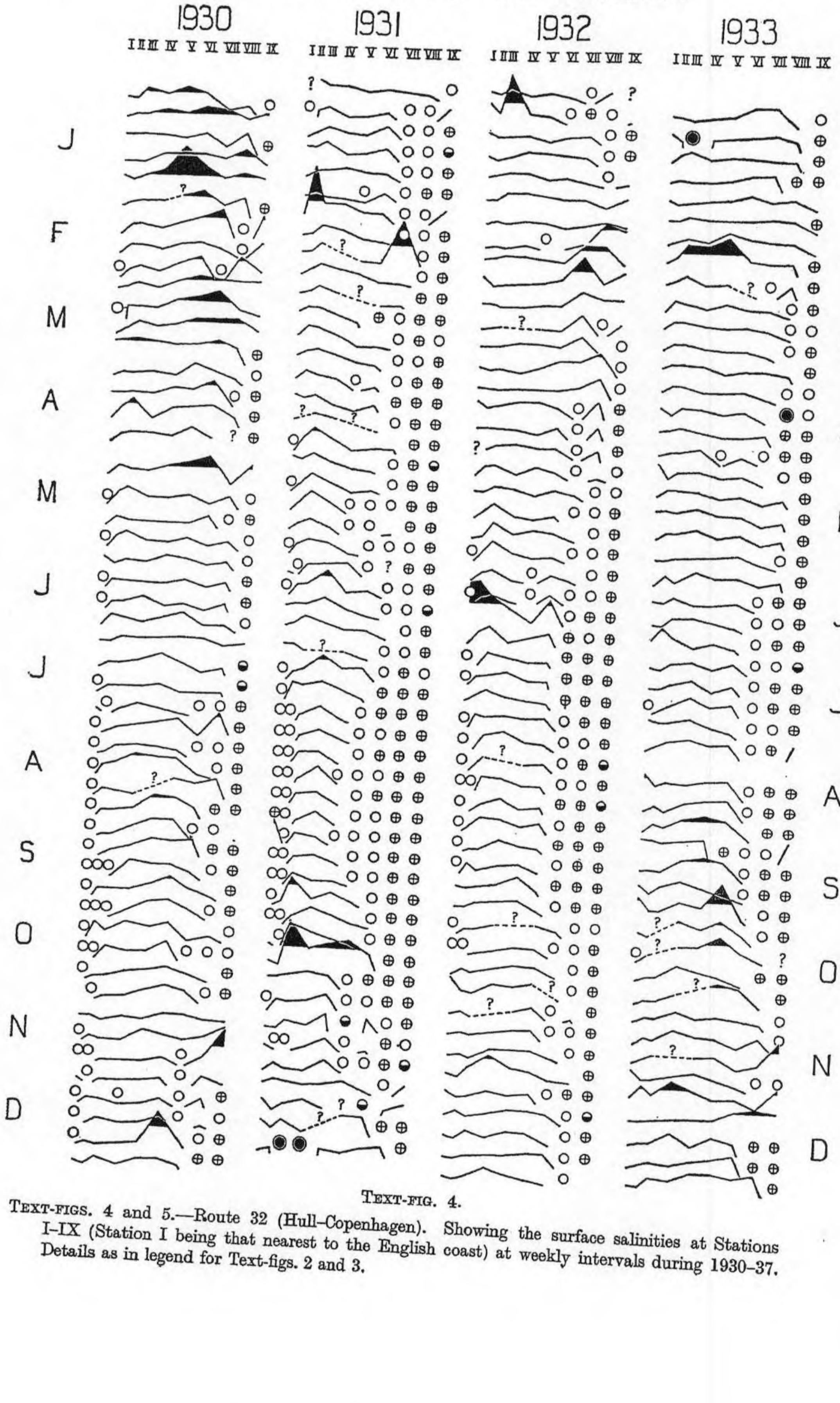
and 1932 and then steadily increased, to attain a period of consistently high values from the autumn of 1934 until the summer of 1935. They then decreased again, until in 1937 they were nearly as low as in 1932. Other points concern the spatial and temporal relationships of the different water masses (*e.g.* the shifting zones of salinity exceeding 34·99 °/∞), the persistence of particular formations (*e.g.* in the summer of 1934) and the sudden changes in time and space. In particular, the extent of the low salinity water at the western end of the line decreased from 1931 to 1934 and then increased again; whilst it is probable that individual surface samples of low salinity are likely to be unreliable indications of the conditions in the water column, yet broad annual changes such as appear here may have significance for the plankton production, and are in themselves signs of important events in the sea.

Turning now to Route 32 (Text-figs. 4 and 5) we should emphasize that on this line the water samples were taken by the same ship and, when the plankton recorder was used, at the same time as the plankton samples.[1]

The salinities were generally lower than on Route 33, but rather similarly distributed. The eastern area of low salinity was most extensive in 1931 and appeared to persist longer than on Route 33, whilst it tended to vary less and was less brackish, presumably since it does not include waters flowing from the Baltic. The areas of high salinity in the west were less saline than on Route 33, and they were least marked in 1931, increasing to 1935, and then decreasing again. On the whole they were more equably widespread on this route, but there were periods of distinctly high salinities over to the east in the winter and spring. The area of low salinity water in the west was more marked and occurred rather later than on Route 33; it was most evident at the beginning and end of the eight-year period. In general there was not the persistence of isolated patches of high salinity surface water such as occurred on the northern route, but a striking feature was the occurrence of patches of high salinity water with no obvious precedents on Route 33, in contrast with the other occurrences of such water, either following or associated with similar water on 33. Such patches were generally found in the autumn and winter, but also occurred in the summers of 1936–38.

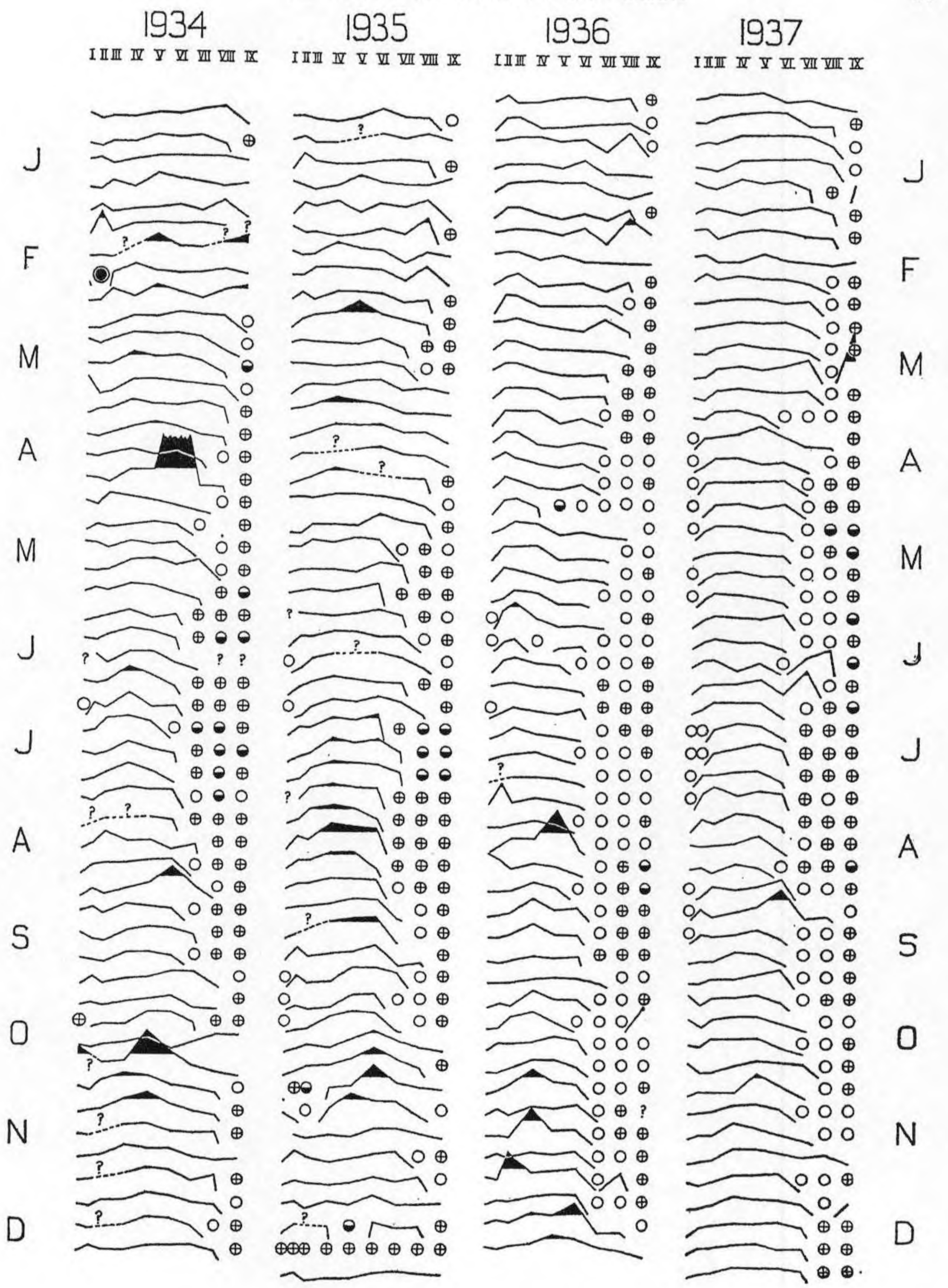
Route 31 (Text-fig. 6) coincides with the Esbjerg plankton line which was started in 1936; although the water samples were not always taken on the same ships, they were often taken on the same dates. Salinities below 34·5 °/∞ were much commoner here, although high salinities occurred in the autumns and winter records of 1934–35 and 1935–36. The lower salinities were mainly but variably restricted to the north-eastern end of the route, and it seems as if the higher salinity water was spreading northwards on certain occasions; at other times there appear to be pulses of only moderately saline water. The more saline water does not always include the first (*i.e.* the most southerly) station, but usually it does. For

[1] The temperature distributions along this route show that 1933 was undoubtedly the warmest year in this area, with 1934 and 1935 probably following, although there were great seasonal and spatial variations. In particular there were very sharp changes in the spatial relations between the warmer and colder water. The data will be used mainly in connection with plankton observations (Part II).

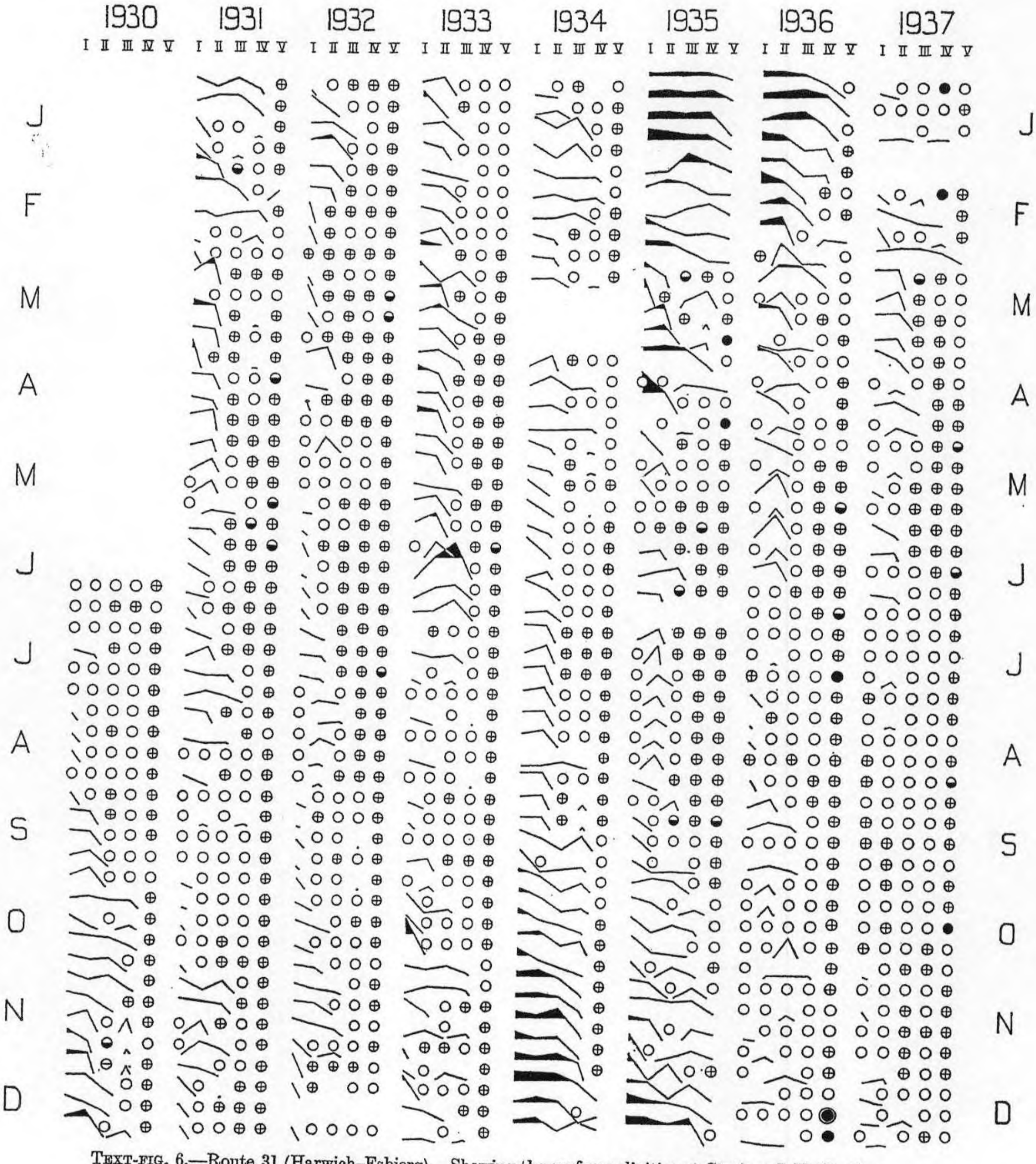


TEXT-FIG. 4.

TEXT-FIGS. 4 and 5.—Route 32 (Hull–Copenhagen). Showing the surface salinities at Stations I–IX (Station I being that nearest to the English coast) at weekly intervals during 1930–37. Details as in legend for Text-figs. 2 and 3.



TEXT-FIG. 5 (see opposite).



TEXT-FIG. 6.—Route 31 (Harwich–Esbjerg). Showing the surface salinities at Stations I–V (Station I being that nearest to the English coast) at weekly intervals during 1930–37. Details as in legend for Text-figs. 2 and 3.

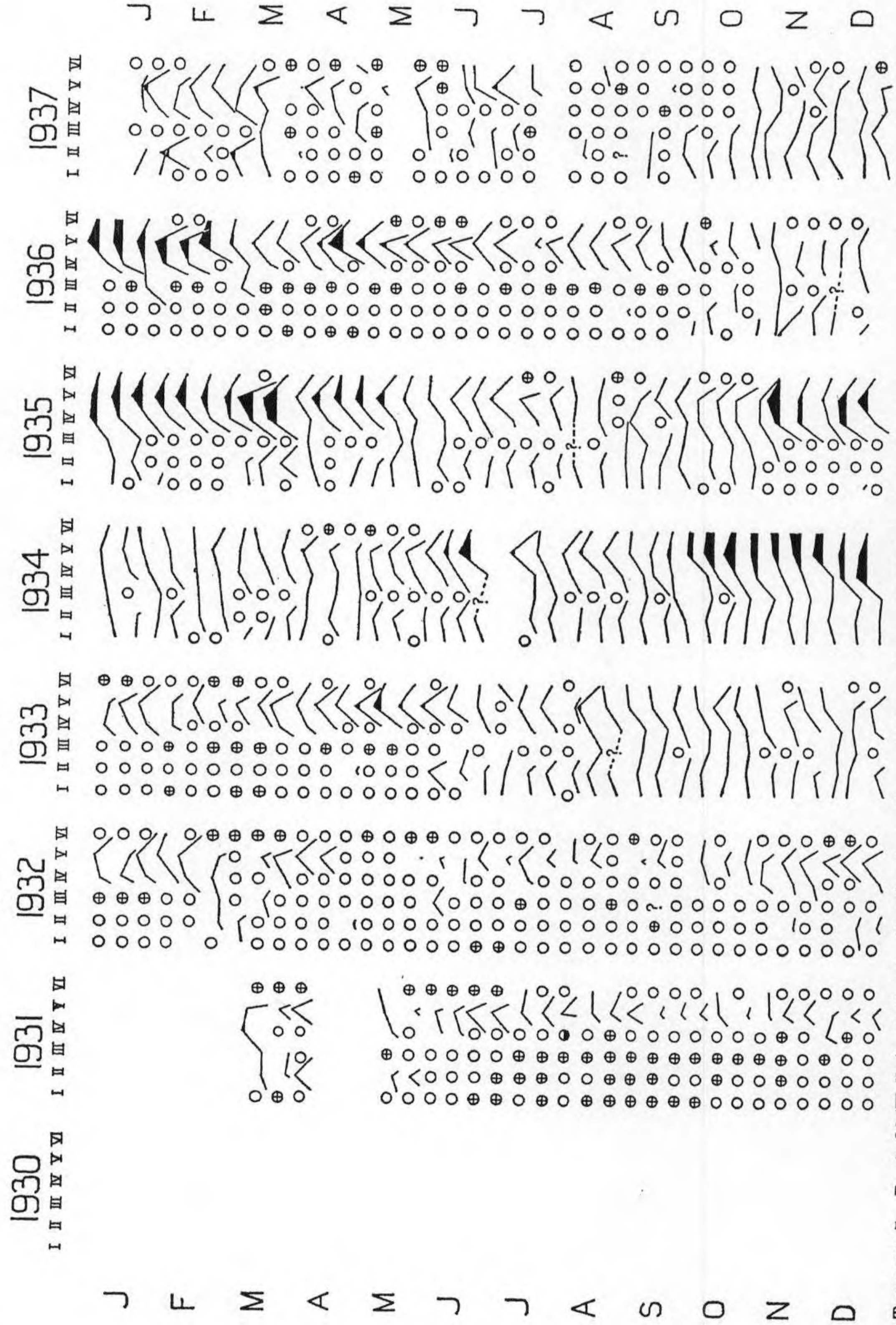
later reference should be noted the long period in 1937, when less saline water covered the whole route, sometimes with quite low salinities in the south.

Whilst there are obvious relationships between Routes 33 and 32, there appear to be no immediate ones between these and either Route 31 or 36, except in the general trend which will be mentioned later. In fact, Route 31, and to some extent Route 36, provide, by their generally lower salinity, a boundary between the more saline surface waters to the north and the south. The western three stations of Route 36 (Text-fig. 7) are close to the standard Rotterdam plankton line, but the eastern ones diverge to the north of it since the route proceeds to Amsterdam. Some of the earlier data are not available. The salinities on the whole were higher than on Route 31, but low salinities were widespread in 1931 and 1932, after which moderate values and then higher ones became general, only to return towards the earlier conditions after the beginning of 1936. Usually the highest salinities occurred on station V, although VI gave at times even higher values. In contrast the western stations were usually more brackish, but the period from July, 1933, to the end of 1934 (together with parts of 1935, 1936 and the end of 1937), when more saline water occurred there, is noteworthy. The whole distribution of the data suggests, as we might expect, that normally there was a narrow channel of more saline water on this route, which extended at times, but which sometimes, as in 1937, disappeared. Station III, perhaps because of its proximity to the coast, was usually of particularly low salinity.

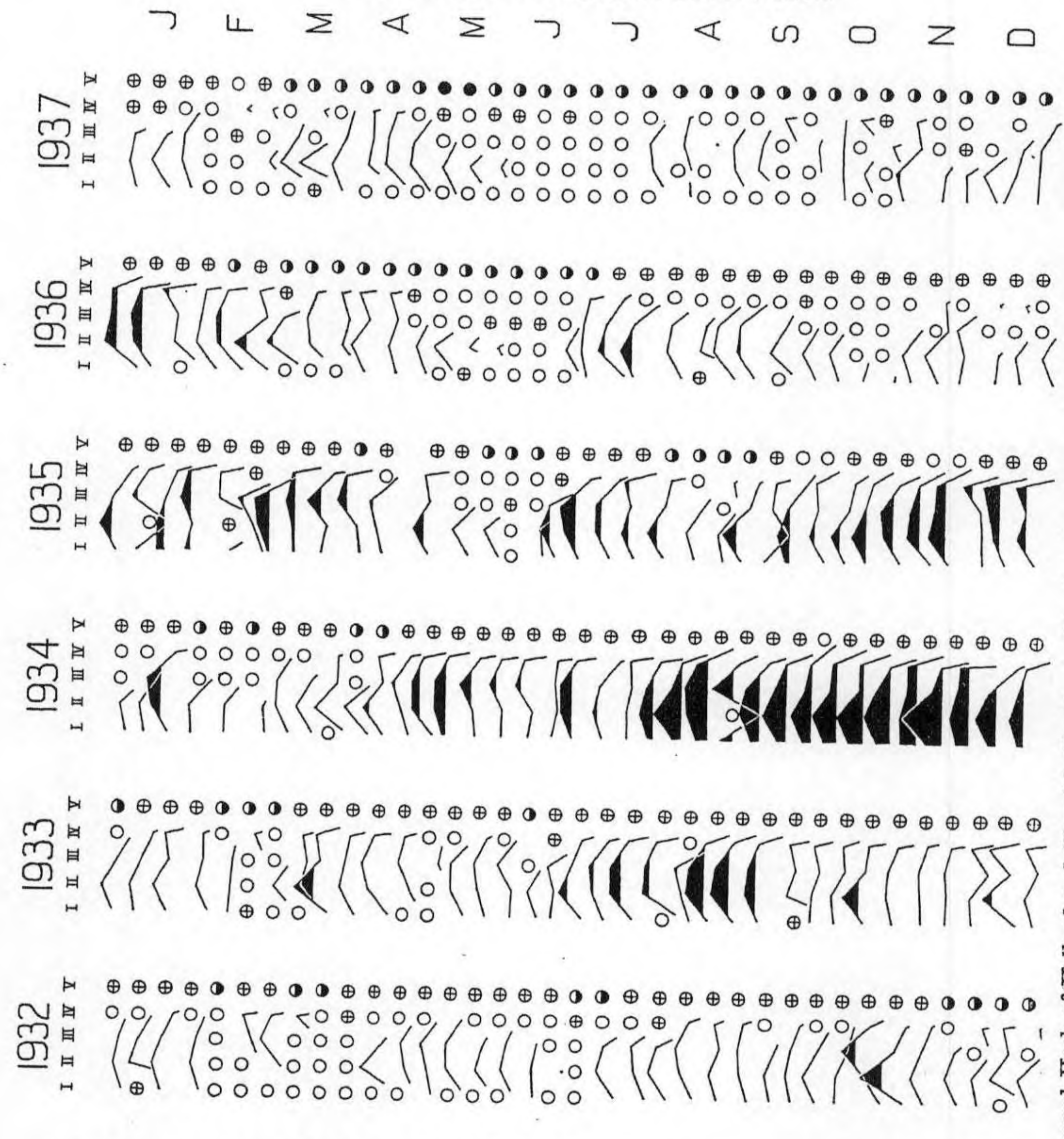
The distribution was generally similar on the combined Routes 37 and 38 (Text-fig. 8), except that the salinities were higher, the channel of higher salinity water was rather wider, and was more towards the west. Usually the samples from station II, but sometimes IV,[1] were the most saline. A complete series of data is available and, as in previous routes, the general salinity decreased after 1930, increased in 1933, and became even higher in 1934, after which it decreased once more. Salinities were particularly high in the late summer, autumn and early winters, whilst there were periods of generally low salinity, as in October, 1931, and June and July, 1937. The most easterly station was below 34·00°/oo without exception, but the western station, inside the Foreland, showed quite striking changes; only in 1934 was it very saline, and then nearly as much so as the central ones.

Each of these routes shows more or less marked seasonal reductions in salinity, the individual features of which will be discussed more fully later in relation to the plankton, but taken together they show a striking agreement. After a period in 1930 when salinities were fairly high, they were lower in 1931–32, only to increase again up to 1934 and/or 1935; they were regularly lower in 1936 and 1937, when in some instances unusually low values were recorded. This trend is summarized in Text-fig. 10, where the data for the extent of the higher salinity water (*i.e.* the numbers of occurrences exceeding a given value in each month) are shown graphi-

[1] It is interesting that III rarely provided the highest salinities, although it was nearer the mouth of the Channel and (one might expect) nearly in line with IV along the flow route (Text-fig. 1).



TEXT-FIG. 7.—Route 36 (Hull–Amsterdam). Showing the surface salinities at Stations I–VI (Station I being that nearest to the English coast) at intervals of ten days during 1930–37. Details as in legend for Text-figs. 2 and 3.



TEXT-FIG. 8.—Routes 37/38. (Gravesend–Hook of Holland and Harwich–Flushing.) Showing the surface salinities at Stations I–V (Station I being that nearest the English coast) at intervals of ten days during 1930–37. Details as in legend for Text-figs. 2 and 3.

cally. Although the times of the maxima vary a little—from the autumn of 1934 in the south to the spring of 1935 in the north—the whole series presents essentially the same cycle. Such an agreement is striking, and it is strengthened when we note, in the same figure, that the mean salinity (as well as the numbers of high salinity occurrences) at the Varne Light-vessel showed a similar trend.

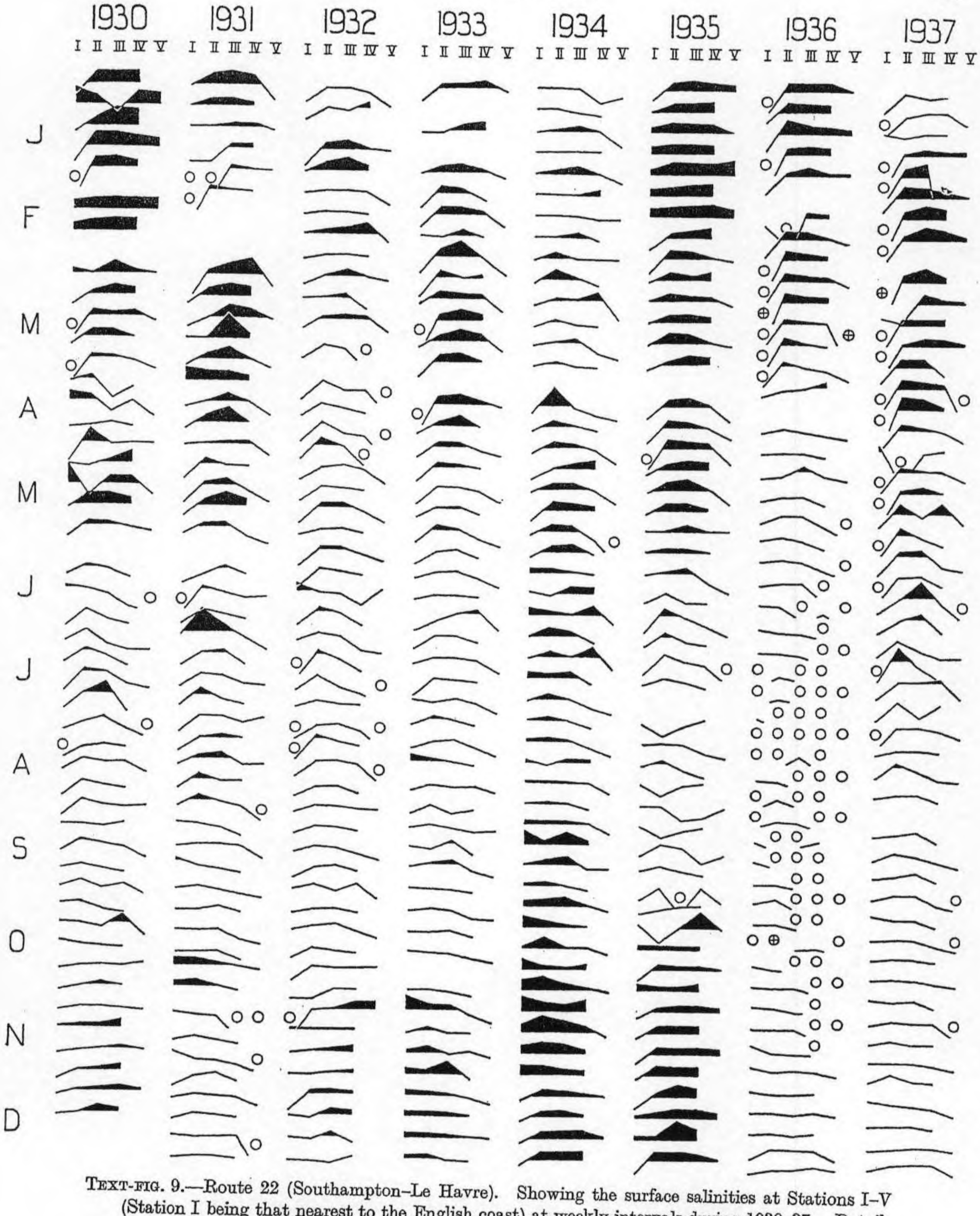
In relation to the facts just reviewed, it will be remembered that Tait (1935) reported increasing salinities in the north-western North Sea during the period 1930–34, whilst in later years (' Reports of the Fishery Board for Scotland ') these were said to have been decreasing. The observations were associated by Tait with the effects of a cycle of Atlantic influence in that area, and he considered that a maximum was probably attained in 1934 (see also Van Riel, 1936), the influence decreasing during 1935 in association with the increased polar activity which began during the summer of 1934 (Tait, 1936). Eggvin (1937) records a progressive decrease in salinity from 1935–36 ; whilst by 1937 it is reported that " the inflow of Atlantic water into the northern North Sea . . . appears to have been weaker than for at least five years " (' Scottish Fishery Board Report for 1937 '). The report for 1938 suggests this recession to have continued into that year. There thus appears to have been a similar cycle over the whole area extending from the North-western North Sea through to the Straits of Dover.

In order to see how far this trend extended we abstracted some of the English Channel data. Those for Route 22 are shown fully in Text-fig. 9. A period of high salinities in the springs of 1930 and 1931 was followed by lower ones in the springs of 1932–34 (rather higher in 1933), and then in the summer of 1934 the salinity began to increase, developing further in the autumn, to give widespread high values in the spring of 1935. It then decreased in the summer, and rose again in the autumn and winter of 1935–36, only to decrease to abnormally low values in the next summer. Although it was again higher than in some years in the spring of 1937, the net effect was of a decrease leading to low values for this route in the autumn. Broadly speaking a similar result is shown by other Channel lines which cannot be shown fully here. Data abstracted from Routes 15 and 22 are shown in Text-fig. 10, along with those for the North Sea. It will be seen that both Route 22 and Route 15 provided very low salinities in 1936.

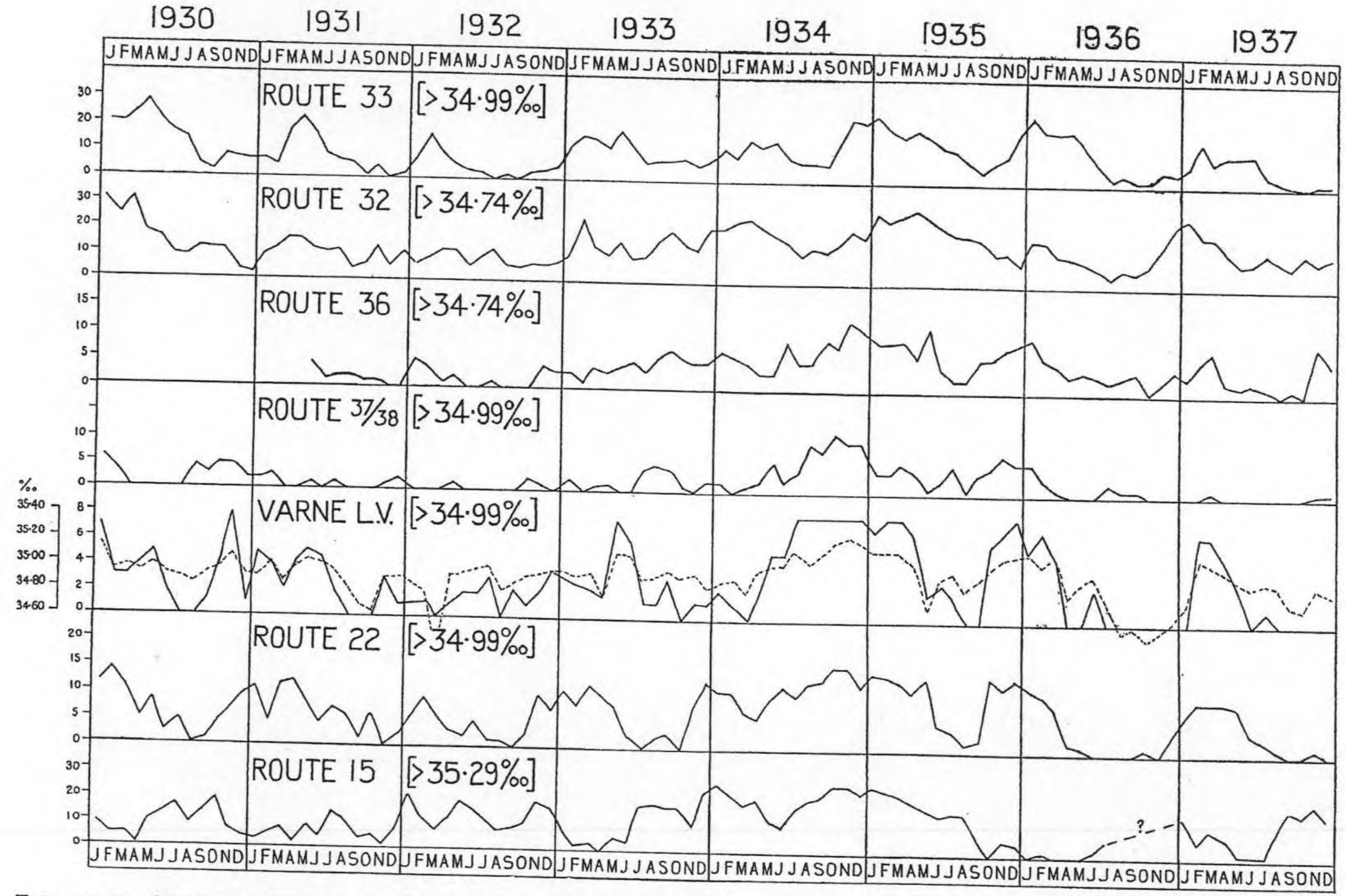
Discussion.

The Salinity Trend during 1930–37.

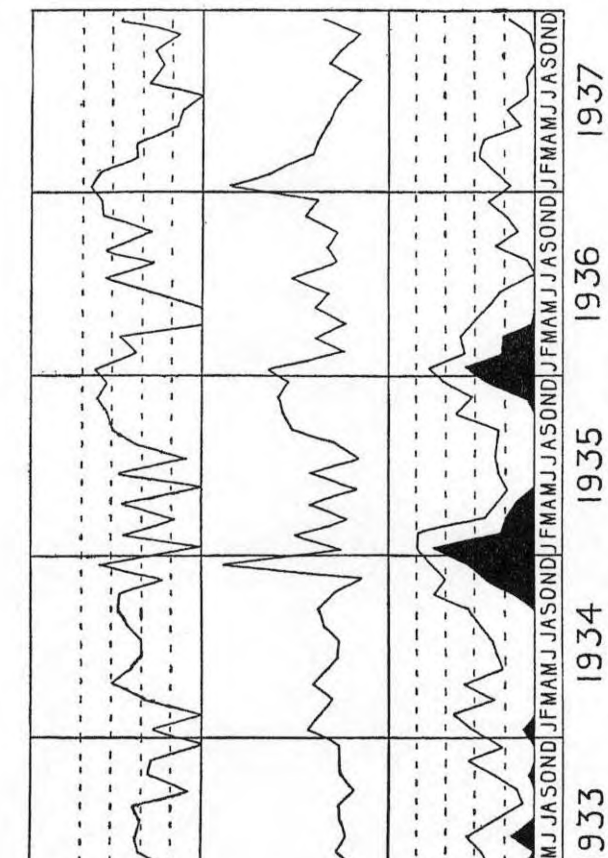
It seems necessary to conclude from all these observations that during the period of the plankton survey, 1932–37, there was an increase of salinity up to the period 1934–35, followed by an equally marked decrease, over an area which extended from the Northern North Sea right through the region of our plankton samples down to the southernmost parts of the North Sea and, in varying degrees, to the western end of the English Channel. In order to obtain a better idea of this trend, which is liable to be confused by the local and considerable seasonal



TEXT-FIG. 9.—Route 22 (Southampton–Le Havre). Showing the surface salinities at Stations I–V (Station I being that nearest to the English coast) at weekly intervals during 1930–37. Details as in legend for Text-figs. 2 and 3.



TEXT-FIG. 10.—Showing the frequency of surface salinities exceeding particular values along Routes 33 (exceeding 34·99°/oo), 32 (ex. 34·74°/oo), 36 (ex. 34·74°/oo, 37/38 (ex. 34·99°/oo), 22 (ex. 34·99°/oo), 15 (ex. 35·29°/oo) and the Varne Light-vessel (ex. 34·99°/oo), month by month during the years 1930–37. For comparison are shown the monthly variations in salinity at Varne (broken line).



TEXT-FIG. 11.—Showing graphically the monthly variations in direction (see inset compass scale) and speed (miles per day) of the Varne current (Carruthers, 1935, and circulated data). For comparison are shown the variations in mean monthly extension between Stations I and V along Route 31 (see Text-fig. 1 and inset chart) of surface salinities exceeding 34·49 ‰ (line) and 34·99 ‰ (blacked-in).

variations, the data for representative routes in Text-fig. 10 have been treated by the method of moving averages.[1] The resultant trends are shown in Text-fig. 12, and appear to have culminated variously between October, 1934, near the Straits of Dover and January–February, 1935, in the north and west. Particularly on Route 33 it appears that the high salinities persisted for a longer time in 1935 than the results of Tait (1936) and Van Riel (1936) suggest for the water to the north. There were signs of subsidiary maxima in 1932–33 (most marked on Route 15), and there is a suggestion that, as a whole, the cycle was somewhat earlier in the west than in the north. Although there were slight differences in phase, the similarity in the main period of maximum gives the immediate impression that over the whole area the salinity of the surface water must have increased more or less simultaneously.

Attention elsewhere does not seem to have been drawn as yet to the existence in the Channel of a cycle of salinity resembling that in the North Sea during

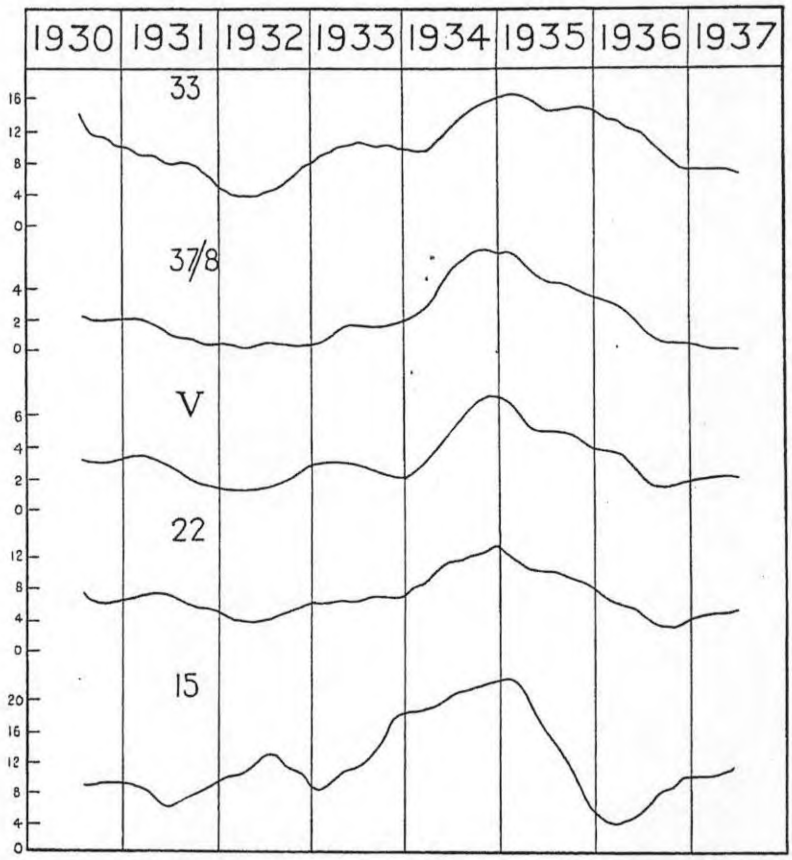
[1] This method is described, for example, by Rhodes (1933, p. 214).

these years, but we must remark here on another Channel phenomenon, *i.e.* the remarkable decrease in the quantities of phosphate available for phytoplankton production. The values off Plymouth have been much lower since 1930 than in earlier years (Cooper, 1938), whilst there have been parallel changes in the abundance of various marine animals (Kemp, 1938, reviewing various data). Within the period of low values it is of interest that the quantities of phosphate decreased rather irregularly until the winter 1934–35, when a minimum was reached, whilst in the three succeeding winters distinctly higher values were recorded, although still well below the means for the years 1922–30. It is, however, important to record that workers in this area were unable to report any clear associations between these changes and the local hydrographical data. "The plain fact is that the observations we have of salinity and temperature do not fit into the picture" (Kemp, 1938; see also Harvey, 1945, although Cooper, 1938, has suggested a connection with the Varne currents). With the exception of the signs of some parallelism in that the winter phosphate maxima became generally poorer as the salinity increased, and then rather less poor, as it decreased, we can add little to this statement, but the indications of the winter 1934–35 being the most "unusual" period may be important.

The series of data presented so far implies that we have been considering here one of those major variations such as have been thought to characterize the period 1920–22 and the early years of the century. For all three periods there have been numerous notes of unusual biological occurrences in various parts of the North Sea and the English Channel, together with records of unusually high salinities and, more or less associated, high temperatures. Evidence drawn from western central North Sea (Shields–Oslo route) and from the Sevenstones Lightvessel (together with the less complete data for the western mid-Channel region), suggest that salinities in the early twenties and the present period were of a similar order; at Varne they were appreciably higher in the earlier period. Owing to the gradual building up of the series of observations it is more difficult to obtain exactly comparable data for the early years of the century, but that reviewed by Lumby for the English Channel (1935) suggests that both near Varne and at the western end of the Channel the salinities were roughly of the same order in 1903–05 as in 1920–22; those in the North Sea do not appear to have differed greatly.[1]

[1] Whilst it might be premature to do more than point to certain similarities in these variations, it may be worth while, in relation to the latest cycle, to draw attention to the recent estimates made by Iselin (1940) regarding variations in the strength of the Gulf Stream System. Briefly, his evidence suggests that during the years 1926–31 its transport was mainly above "normal," whilst after 1931 and up to 1939 it was mainly below normal. The details of his estimates, however, make it seem reasonable to suggest a connection between the generally decreasing Gulf System transport from 1931–37, followed by an increase (Iselin, 1940, fig. 25), and the generally increasing Atlantic influence in local waters (as judged by salinity) from 1931 to 1935, followed by a decrease. Since Iselin has demonstrated that decreased transport in the central system may permit an increase in the area of the eastern North Atlantic covered by the warm and saline discharge (and *vice versa*), it may be reasonable to expect first increasing, and then decreasing, salinities in European waters during these years. It is also suggestive that Iselin's evidence provides lower values for the Gulf System transport in the early twenties than after 1925, as might be expected on the grounds of this analogy if the high

Such major cycles are of interest and must have considerable significance for the inhabitants of these waters. It will be remembered that during the period 1932–37 certain trends were found in the abundance of various plankton forms (Lucas, 1940; Rae and Fraser, 1941; Henderson and Marshall, 1944; and



TEXT-FIG. 12.—Showing for certain routes and for the Varne Light-vessel the overall trend in the frequency of salinities exceeding $34 \cdot 99°/_{oo}$, excepting in Route 15 ($35 \cdot 29°/_{oo}$), during the period 1930–37 (obtained by the method of moving averages).

Stubbings, in the press), and this biological evidence will be discussed in relation to the hydrological in Part II. The present data, however, may be analysed further, and it is important to discover, if possible, the manner in which so large an area, subdivided by the narrow Straits of Dover, became flooded with high salinity water at the surface (and presumably beneath it).

salinities for the early twenties in local waters truly resembled those of the present period in their derivation. There is at least some evidence, in fact, for what might otherwise have merely been guessed, *i.e.* that such changes as we are considering are likely to have originated in variations of the Gulf Stream System.

Origin of the Salinity Increases.

The normal, or rather, the mean, annual sequence of events in surface local waters is presented in the 'Atlas de temperature et Salinité,' published by the Conseil Permanent (1933) and in Lumby's more detailed review of events in the English Channel (1935). In contrast, the data shown in figs. 2–9 present details of certain events for a particular set of years, apparently comprising part of a cycle. The 'Atlas' shows that the chief annual changes are in relation to influences from (1) the north-west, whereby high salinity water attains a mean maximum extension in the north-western North Sea in the early spring, and (2) the west, whereby high salinity water entering through the English Channel has its mean maximum spread in the south-eastern North Sea, *via* the Straits of Dover, at the end of the year. (3) In association can be seen the Baltic influence producing a mean maximum spread of low salinity water in the summer, as well as the influences of other sources of fresh water. Long term changes over a period of years may be expected to arise rather similarly and, in the case of increasing salinities, we may look for either variably increased penetration from the north towards the Southern North Sea, or higher Channel salinities leading to the flow of more saline water through the Straits of Dover. In view of the relative sizes of the northern and southern openings to the North Sea and the effects exerted through them (see discussion by Carruthers, 1935), it may seem that the former would be the controlling influence in the area at any time, and this receives support for the present period in the evidence of Tait (1935) that there were unusual increases in this influence during the period 1930–34, followed by a decline. There can be little doubt that this influence extended well beyond the mean annual limits, and almost certainly it would increase the salinities along Routes 33 and 32 at least. Further south in the North Sea the nature of the effects are less certain. There have been no accounts of major changes in the English Channel data during the period (other than phosphate), but the evidence provided here for such changes, together with the known annual variations and the not dissimilar changes in 1920–23 and 1903–05, demands that the possible effects of influences from this quarter should also be considered. In association we should review the changes known to occur in the speed and direction of the current at the Varne Light-vessel in the Straits of Dover, since it is commonly held that the water movements in this region reflect, as a buffer, the relative influences exerted from the north and west (Carruthers, 1935).

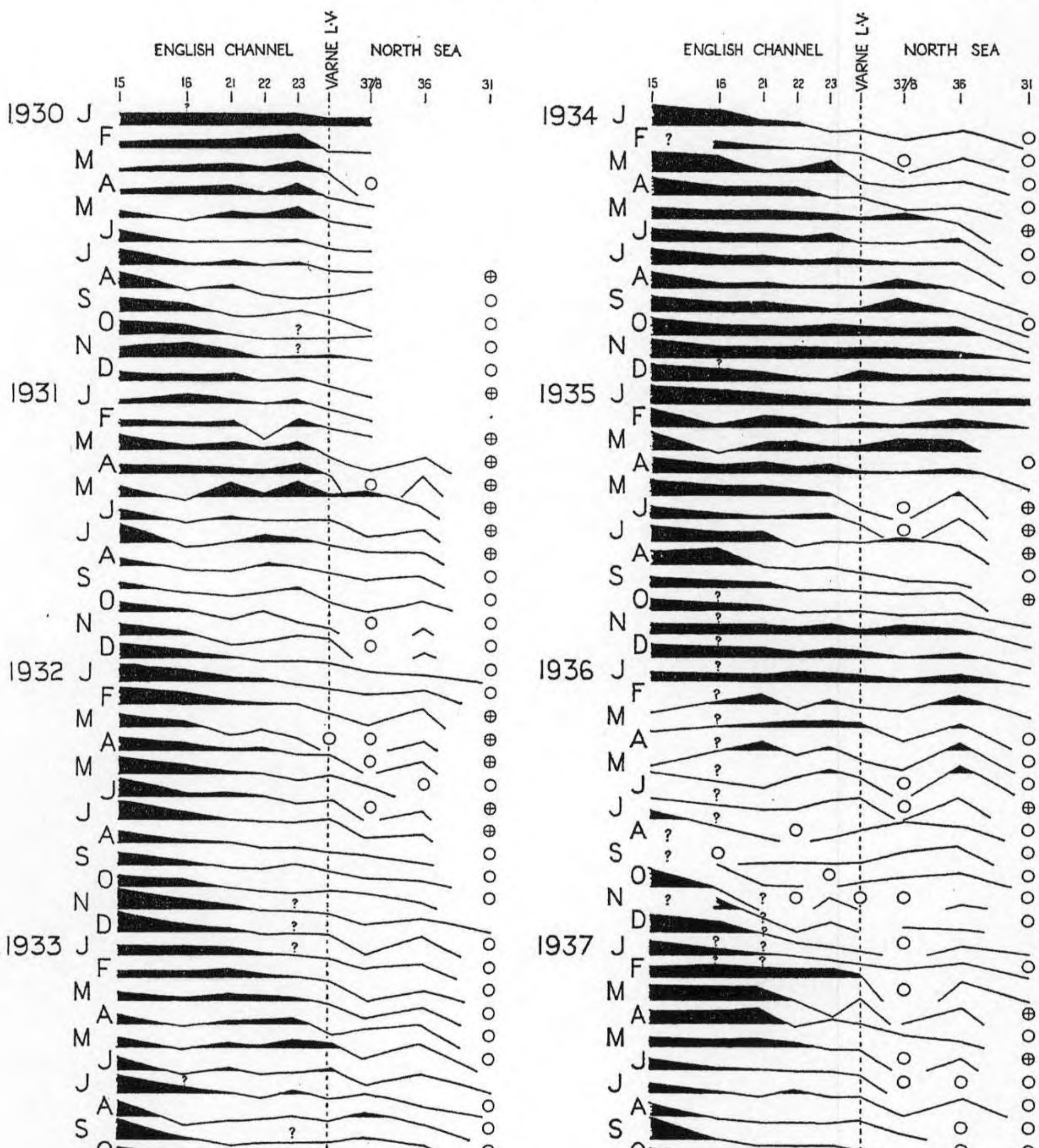
The current observations at Varne have been made continuously since 1926, the earlier ones being published in full (Carruthers, 1935), and later ones being circulated to various laboratories (see references in Carruthers, 1935, 1938 and 1939) in a most convenient summarized form. We are greatly indebted to Dr. Carruthers for the provision of these data up to the outbreak of war. The data for the years under review are shown here in Text-fig. 11 in the form of monthly records of speed and direction, for comparison with the salinity data, etc. In the years prior to 1930 the directions of the current at Varne were largely east of north, and they remained so until mid-1931. Thereafter there was a variable but considerable westerly component in them until the end of 1937, so that the major periods of current consistently east of north were the autumn and winter of 1932–33, the spring and summer of 1934, the autumn and winter of 1935–36, and the winter of 1936–37. In 1938 and 1939, however, conditions were such that the current was almost continuously well to the east of north, so that there appears to have been an irregular cycle of current variation. Carruthers (1935) has shown that from 1926 until the middle of 1931 there were usually currents flowing directly, with variable speed, into the North Sea for the greater part of each year ; it appears that the same must have applied to 1938 and 1939. Whilst it is probable that for the short periods mentioned above there were also such currents flowing from the Channel, in between them were recorded periods of very different flow, which Carruthers suggests can be interpreted as including periods of "hold-up" or "reversal": among his examples are February and June, 1932. There remain long periods in which the currents were between these extremes and which are more difficult to interpret, since at Varne they were directed towards the English coast and must subsequently have turned differently. However these may have been, the resultant flows within the North Sea must have been different from those following currents with a strong easterly component.

The changes in the direction of the Varne current led Carruthers to consider whether at times the "normal" flow from the Channel might be reversed, and water move into the Channel from the North Sea, presumably with important effects on the local flora and fauna. In particular, he has considered whether the relatively high English Channel salinities of 1922, in relation to those of 1923, may not have been "controlled by Atlantic influences exerted *via* the North Sea," since the mean current at Varne in 1922 was 4·8 miles per day but only N. 25° W., whilst that for 1923 was more "usual" at 3·4 miles N. 23° E. In agreement with the view expressed by Le Danois, he reached the opinion that such North Sea influences can occur, and that they must have been the explanation of the occurrences in 1922. On the other hand, Lumby (1925*a*) could find no contemporary evidence of such a towards-Channel flow of high salinity water in 1920–23 and (1925*b*) opposed Le Danois' opinions. As Carruthers fully realized, Lumby's evidence was "a real stumbling block," and one would expect that the usual effect of any flow from the North Sea would be a reduction in the salinity of the eastern Channel water. The present period presents several similar aspects: again we have years of high Channel (and Southern North Sea) salinity associated with relatively western Varne flows, preceded and followed by years of less salt water associated with easterly flows. Just as he believes happened in 1922, Carruthers also suggests the possibility of such northern control in 1933 (and probably later, by implication), ascribing the unduly westerly flow "to the existence of an extra strong southward thrust of water through the North Sea consequent upon extra strength on the part of the parent Atlantic stream north-west of Scotland" in 1933. In view of the very long period of westerly deviation in the Varne flow, it is necessary to decide here how far the high salinities in the Southern Bight and eastern Channel may have been largely the result of such northern influences.

Again there appears to be the immediate objection to this hypothesis that in general the salinities recorded at the surface decreased from Route 33 to Route 32 and then to Routes 31 and 36 (except during the period autumn, 1934, to spring, 1936, in which higher salinities were found on these lines than were usually to be found on Route 32). The combined Routes 37 and 38 show yet higher salinities, usually of the order of those found in the eastern Channel, whilst the salinities further west in the Channel were usually higher still. It would thus appear that at the surface there was no continuity of high salinity water through the series of Routes 33, 32, 31 and 36 to 37–38 (*i.e.* moving further south in the North Sea). There would, however, appear to be general continuity through the series starting at the western end of the Channel and moving through the Dover Straits to Routes 37–38, 36 and 31. This is shown more clearly by consideration of Text-fig. 13, showing the mean monthly salinities for a series of selected stations starting at the western end of the Channel and moving towards Varne and then into the Southern North Sea (see p. 10 and Text-fig. 1). Whilst there are occasional breakdowns in continuity (*e.g.* on the station from Route 16, doubtless due to local production of brackish surface water), there appears to be a fairly continuous high salinity stream, directed towards the North Sea, of a very varying extent. Salinities exceeding 35‰ extended only for a short distance up Channel, for example, in the autumn of 1931, whilst in the winter of 1934–35 there was a more or less continuous region of water well above 35‰ extending right through the Dover Straits and partly along Route 31.[1] Between these more or less continuous stretches of salter water and the high salinities of Route 33 there were, as far as our data go, always appreciable regions of lower salinity water at the surface. To this extent it would appear as though the high salinity water of the Southern Bight originated from the Channel rather than from the north-west, and this would apply even more to the waters of the eastern Channel.

Such a suggestion is open to the immediate objection that the surface values may not be fairly indicative of the waters in the various regions, despite the general evidence reviewed above (p. 3) that they do not "normally" show great differences from the rest of the water column (particularly in the autumn and winter when there were very high salinity values). There are reasons for thinking that this period is not a "normal" one, and we must examine such evidence as there is regarding the possibility that the higher salinity waters of the Southern Bight (and eastern Channel) may have originated in the *deeper* water to the north. If we omit the unlikely possibility that high salinity water may have come to Routes 31 and 36–38 from the sub-surface waters of the eastern side of the North Sea (for which there is no evidence), we are left with the western waters of the

[1] The great extent of the from-Channel water exceeding 35‰ in January, 1935, has already been demonstrated by Kunne (1935) and Kalle (1937).



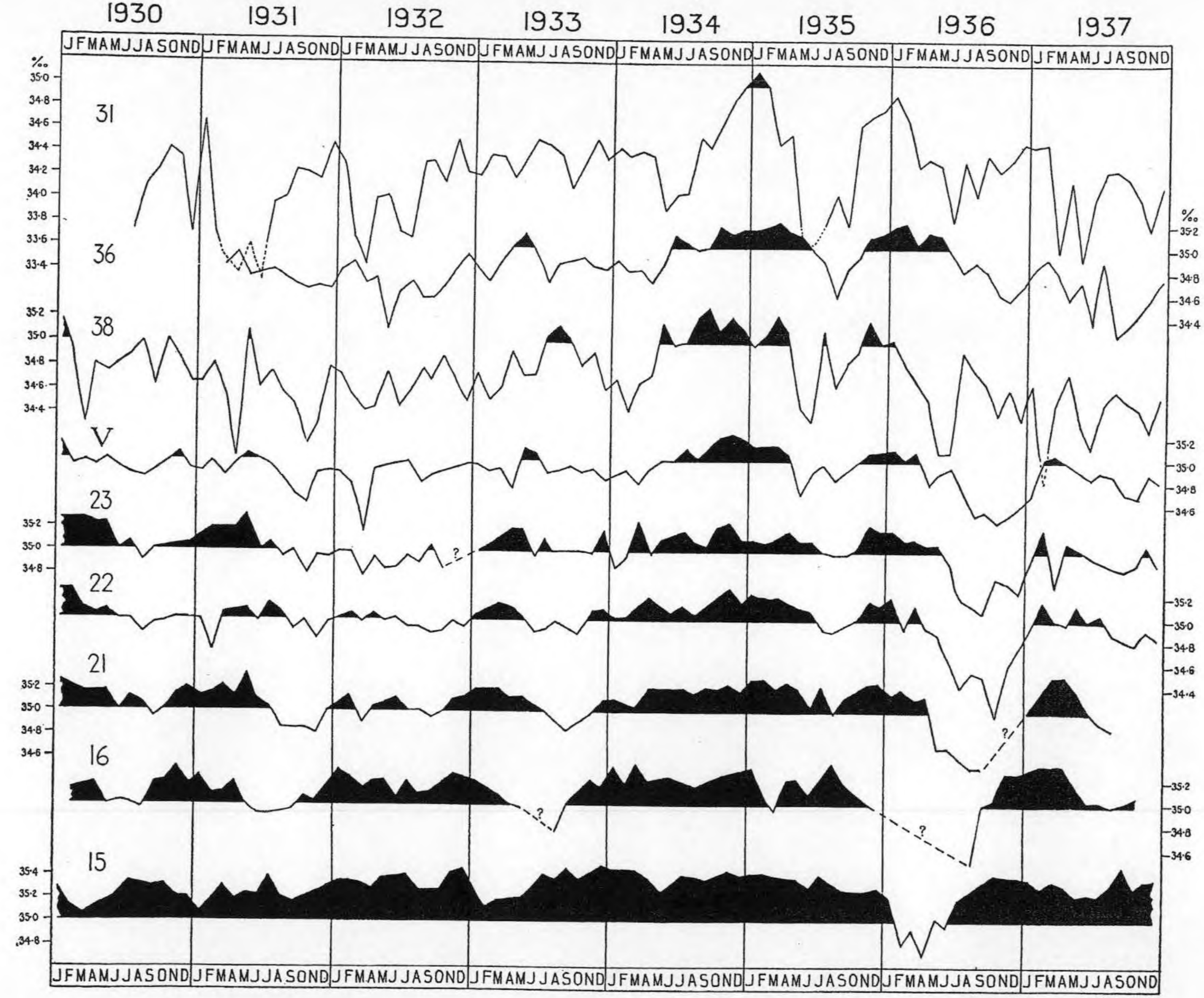
TEXT-FIG. 13.—Showing for the years 1930–37 the mean monthly salinities along a series of the standard stations approximating to the route taken by water flowing along the English Channel, through the Straits of Dover, and into the North Sea (see Text-fig. 1). The Route numbers are given above whilst graphs and symbols are used as in Text-figs. 2–9.

" Gateway " between the Dogger and the English coast, which are necessarily the more likely. Fortunately, there is direct evidence regarding these from the series of stations off Flamborough Head investigated in 1933 and 1934 by Savage and Wimpenny (1936), and also along a line through the " Gateway " in 1934 and 1935 sampled by Graham (1936) and Graham and Harding (1938). These strongly suggest that rarely, if ever, in those years was water to have been found in the " Gateway " of sufficiently high salinity to account for the high values recorded regularly on the routes of the Southern Bight. When taken with the evidence that regularly, and approximately at the same times, there were suitable salinities to be found in continuity to the south and west of these routes, we are forced to the conclusion that not only the high salinities of the eastern Channel water, but usually those of the Southern Bight as well, must have originated from the west, *via* the Straits of Dover.[1] This is confirmed by the alternative presentation of the data from Text-fig. 13 in Text-fig. 14, where undoubted trends towards the North Sea of both high and low salinity water can be seen much more clearly than in the reverse direction. There still remains every reason to believe that the relatively high salinities of Route 33, probably most of those along Route 32, and possibly some recorded at the western ends of Route 36 (p. 15) did, in fact, derive from further north in the North Sea. So far, however, from the more southerly of these having contributed towards the increasing salinities in the Southern Bight in 1933–36, they were more likely, owing to their lower salinity, to cause dilution of the more southern waters if mixing occurred.

Thus the evidence for spatial continuity of high salinity water (and, it will be seen, of low salinity water) points, even for this exceptional period, towards the conventional picture of the relations between the western and the north-western influences (p. 24). The question then arises of how, during years in which the northern pressure increased and the Varne current deviated so much to the west that Carruthers was led to postulate hold-up or reversal, surface water of unusually high salinity came to flow from the Channel in quantities sufficiently large to produce increases in salt content over the Southern Bight which were sometimes higher than contemporary values as far north as Route 33. Such an apparent disagreement makes it necessary to consider in more detail the relationships between the Varne current and the movements and salinity of adjacent waters. How, in fact, are the indications of current *direction* at Varne to be interpreted ?

This point will be considered in more detail in relation to our plankton data, but it may be well to indicate now the type of problem raised here. In Text-fig. 11 there is shown the average degree of penetration of the salter water along Route 31 (*i.e.*, from the more southerly station I to the more northerly station V, see inset chart), in relation to the varying Varne flow as recorded by Carruthers. As we have seen above, there was no agreement between the general degree of easting and westing of the current, and the general extent of higher salinity water. On the

[1] Here, in fact, appears to be the origin of the high salinities recorded in 1934 by Savage and Wimpenny (1936, p. 22).



TEXT-FIG. 14.—Showing for each of the stations used in Text-fig. 13 the mean monthly salinity variations during 1930–37. The scales used for the stations are indicated alternately at the sides of the graphs, salinities exceeding 34·99°/₀₀ being blacked-in.

other hand there was still a surprising degree of similarity in *phase* between *changes* in the two factors (just as Carruthers has shown similarity in phase between the *changes* in speed and direction, see also Text-fig. 11). *Relative easting* tended to associate with or to be followed by apparent movement *along* the route of relatively (but not always actually) higher salinities, and *vice versa*. This type of relationship is seen over a wider field if we consider the data of Text-fig. 13, together with the current directions shown in Text-fig. 11. Again the spread of salter water was usually associated with *relative* easting (*i.e.*, veering currents), although similar amounts of easting were seldom associated with similar salinity distributions. On the other hand, what appeared to be steadily developed tongues of salter water at the surface were, often suddenly over a wide area, diminished in extent and saltness after times of *relative* westing. The significant feature again appears to be the *relative* nature of the changes at any time (*i.e.*, veering or backing). In connection with this, it is significant that, when comparing Varne currents at the normal depth of $6\frac{1}{2}$ fathoms with some recorded specially at $12\frac{1}{2}$ fathoms, Carruthers found a mean directional difference of 21° E. at the greater depth, the deeper current being more easterly for eleven occasions out of fifteen. If these interpretations are correct, then the significance of the less easterly and the westerly currents may require very careful interpretation. By no means always and possibly seldom are they indicative of a reversal of flow, although they would certainly appear to indicate important changes in the local conditions.

One other instance may be given of the uncertain nature of their interpretation on their own evidence—one concerning the arrival of water of unusually low salinity in the region of the Varne Light-vessel (Text-figs. 10, 13 and 14).

Text-fig. 10 shows that salinities exceeding 35·29°/₀₀ decreased on Route 15 during the second half of 1935 and remained very low well into 1936. Similarly there was a period of low salinity on Route 22 in 1936, and further " troughs " in the salinity curves can be seen in turn on Route 23 and then at the Varne. These are seen in Text-fig. 13, and in Text-fig. 14 showing the same data plotted against time on the horizontal scale. Unduly low salinities appeared near the centre of Route 15 in February, 1936, and on Route 21 in May. On Route 22 they first appeared in June, and on 23 in July, whilst at Varne the first remarkably low sample was found in August. Unfortunately certain samples are missing from the mid-stations of Routes 16 and 21, so that the arrival at the first and the disappearance from the second position is not clear in Text-fig. 14 : there seems every reason to suppose that they were intermediate in both instances between the preceding and the following routes. We see, then, the appearance and disappearance of this unusually brackish water route by route, and it must have progressed steadily up Channel, persisting some six or seven months at each of the stations up to and including Varne. The first appearance of truly low salinity water on Route 15 coincided with backing of the flow at Varne, followed in April and May by very westerly currents, and then moderate but variable ones from June to October. By May this water had arrived on Route 21, and by June on Route 23, at least; by July it was apparently at Varne. Good estimates of the extent of this " patch " can be seen in the relevant figures, and it seems to have spread from side to side of the Channel at times, and to have extended for well over 100 miles on the surface.

This is presumably the patch recorded by Dr. Harvey in 1936 (see Kemp, 1938). In spite of the frequent westerly current directions at Varne, it moved at a fairly steady pace up Channel, covering the first half of the journey in roughly the same time as the second. On the other hand, of course, the arrival of such water at the eastern end of the Channel, and its apparent passage through the Straits, completely displaced the previously continuous stream of higher salinity water apparently stretching as far as Route 36. The important thing, however, appears to be that not only was there a from-Channel flow, for example, in the winter of 1935–36, in association with quite easterly currents, but that even whilst the current was moving back as far as 32° and 45° west of north (April and May, 1936), the Channel was first receiving, and then conveying, a readily detectable body of water, some of which was to reach (and possibly pass) Varne before the onset of the more easterly flows of the autumn. During this time there were only two months of flow to the east of north at Varne (although the speeds in 1936 were relatively high). The passage of other low salinity patches can be seen in Text-figs. 13 and 14.

It would appear as if with all but the extreme westerly currents there was still a from-Channel surface flow which, at times when the Varne current was tending more towards the west, was " hugging " the English coast rather than the continental one.

Summary.

1. In order to provide a hydrological background for the continuous plankton records of 1932–37, the regular International Council surface salinity observations over a series of routes in the central and southern North Sea have been reviewed for 1930–37, together with some from the English Channel.

2. Each route shows its individual features and seasonal variations, but all are agreed in showing a salinity cycle, with maximal salinities during the winter of 1934–35. Others have also reported a similar cycle for the Northern North Sea in association with waxing and waning Atlantic influence. Representative trends of the decreasing and increasing proportions of salter water suggest a fair uniformity in this cycle over the whole area, and it may be compared with similar changes during the periods 1920–22 and 1903–8. A possible connection with variations of the transport of the Gulf Stream system is mentioned.

3. The possible origin of such a salinity increase is discussed, and the evidence suggests that while increases in the central North Sea must have derived largely from the north, the major increases in the Southern Bight and the Eastern English Channel must have arrived from the western end of the Channel in association

with streams of unusually salt water which frequently penetrated well into the Southern North Sea.

4. The question is then raised of how, at times of increased northern penetration and unusually westerly Varne flow, such salt water passed up the Channel. It is known that deeper currents may be more easterly than those at the depths normally measured at Varne, and the present evidence, including that for the steady passage up Channel of a large patch of less saline water, suggests that only the most extreme westerly Varne currents may indicate hold-up or reversal.

5. The data will be discussed further in relation to the plankton records in Part II.

References.

CARRUTHERS, J. N. 1935. The Flow of Water through the Straits of Dover. Part II. Min. of Agric. and Fish., Fish. Invest., Ser. II, XIV, No. 4.

—— 1938. Continuous Current Measuring from Light-vessels—Review of Progress, with Results for a Third Winter—1937-38. Rapp. et Proc. Verb. Cons. Int. Explor. Mer., CVII, 3 Part., pp. 16–20.

—— 1939. First Annual Report on Vertical Log Observations in the Southern North Sea and Eastern English Channel. Rapp. et Proc. Verb. Cons. Int. Explor. Mer., CIX. 3 Part., pp. 37–45.

Conseil Permanent International pour l'Exploration de la Mer. Atlas de Temperature et Salinité de l'Eau de Surface de la Mer du Nord et de la Manche. Copenhagen, 1933.

—— Bulletins Hydrographiques pour l'Années 1930–37. Copenhagen, 1931–38.

COOPER, L. H. N. 1938. Phosphate in the English Channel, 1933–38, with a comparison with earlier years, 1916 and 1923–32. Journ. Mar. Biol. Assoc., XXIII, pp. 181–195.

EGGVIN, J. 1937. New Oceanographic Investigations in the Northern North Sea. Rapp et Proc. Verb. Cons. Int. Explor. Mer., CV, 3 Part., pp. 56–62.

GRAHAM, M. 1938. Phytoplankton and the Herring. Part III. Distribution of Phosphate in 1934–36. Min. of Agric. and Fish., Fish. Invest., Ser. II, XVI, No. 3.

—— and HARDING, J. P. 1938. Some Observations of the Hydrology and Plankton of the North Sea and English Channel. Journ. Mar. Biol. Assoc., XXIII, pp. 201–206.

HARDY, A. C. 1939. Ecological Investigations with the Continuous Plankton Recorder: Object, Plan and Methods. Hull Bull. Mar. Ecol., No. 1, pp. 1–57.

HARVEY, H. W. 1945. Recent Advances in the Chemistry and Biology of Sea Water. London, 1945.

HENDERSON, G. T. D., and MARSHALL, N. B. 1945. Continuous Plankton Records: The Zooplankton (other than Copepoda and Young Fish) in the Southern North Sea, 1932–37. Hull Bull. Mar. Ecol., No. 6, pp. 255–275.

ISELIN, C. O'D. 1940. Preliminary Report on Long-period Variations in the Transport of the Gulf Stream System. Papers in Physical Oceanography and Meteorology, VIII, No. 1. Cambridge and Woods Hole, Mass., 1940.

KALLE, K. 1937. Nährstoff-Untersuchungen als hydrographisches Hilfsmittel zur Unterscheidung von Wasserkörpern. Ann. d. Hydrog. u. Mar. Met., 1937, Heft. I, pp. 1–18.

KEMP, S. 1938. Oceanography and the Fluctuations in the Abundance of Marine Animals. Rep. Brit. Assoc. Adv. Sci., 1938, pp. 85–101.

KÜNNE, C. 1937. Über die Verbreitung der Leitformen des Grossplanktons in der südlichen Nordsee im Winter. Ber. Deutsch. Wiss. Komm. f. Meeresf., N.F., VIII, pp. 131–64.

LUCAS, C. E. 1940. Ecological Investigations with the Continuous Plankton Recorder: The Phytoplankton in the Southern North Sea, 1932–37. Hull Bull. Mar. Ecol., No. 3, pp. 73–170.

LUMBY, J. R. 1925*a*. The Salinity and Water Movements in the English Channel and Southern Bight during the period 1920–23. Min. of Agric. and Fish., Fish. Inves., Ser. II, VII, No. 7.

—— 1925*b*. A Note on the Water Movements in the English Channel and Neighbouring Seas, Considered on the Basis of Salinity Distribution. Journ. Mar. Biol. Assoc., XIII, pp. 670–672.

—— 1935. Salinity and Temperature of the English Channel. Min. of Agric. and Fish., Fish. Invest., Ser. II, XIV, No. 3.

RAE, K. M., and FRASER, J. H. 1941. Ecological Investigations with the Continuous Plankton Recorder: The Copepoda of the Southern North Sea, 1932–37. Hull Bull. Mar. Ecol., No. 4, pp. 171–238.

RHODES, C. 1933. Elementary Statistical Methods. London.

RUSSELL, F. S. 1938. Hydrographical and Biological Conditions in the North Sea as Indicated by Plankton Organisms. Journ. Cons. Int. Explor. Mer., XIV, pp. 171–192.

SAVAGE, R. E., and WIMPENNY, R. S. 1936. Phytoplankton and the Herring. Part II. 1933 and 1934. Min. of Agric. and Fish., Fish. Invest., Ser. II, XV, No. 1.

Scotland, Annual Reports of the Fishery Board, being for the years 1931–38. H.M. Stationery Office, Edinburgh, 1932–39.

STUBBINGS, H. G. (In press.) Continuous Plankton Records: The Fish Eggs and Young Fish in the North Sea, 1932–39. Hull. Bull. Mar. Ecol., No. 13.

TAIT, J. B. 1935. Recent High Salinity Records from the Northern North Sea. Rapp. et Proc. Verb. Cons. Int. Explor. Mer., XCIV, 3 Part., pp. 60–65.

—— 1936. Salient Features of the Hydrography of the Northern North Sea and the Faroe-Shetland Channel in 1935. Journ. Cons. Int. Explor. Mer., XI, pp. 164–68.

VAN RIEL, P. M. 1936. Variations in Temperature and Salinity in the Northern North Sea. Journ. Cons. Int. Explor. Mer., XI, pp. 169–82.