CONTRIBUTIONS TO THE HYDROGRAPHY OF THE NORTHERN AND MIDDLE NORTH SEA AND THE FAROE-SHETLAND CHANNEL.

By

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Submitted for the Degree of Doctor of Science of the University of Edinburgh. September, 1939.



EXPLANATORY NOTES.

The following papers, either already published, or in manuscript, are presented:-

1. "The Surface Water Drift in the Northern and Middle Areas of the North Sea and in the Faroe-Shetland Channel. A Cartographical Analysis of the Results of Scottish Surface Drift-Bottle Experiments of the Year 1912; with a Discussion on some Hydrographical and Biological Implications of the Drift-Bottle Results of 1910, 1911, and 1912, including Statement of a Theory of the Upper Water Circulation of the Northern and Middle North Sea."

2. " Surface Drift-Bottle Results in Relation to Temperature, Salinity and Density Distributions in the Northern North Sea."

3." Recent High Salinity Records from the Northern North Sea."

4. " Salient Features of the Hydrography of the Northern North Sea and the Faroe-Shetland Channel in 1935."

5. " Hydrographical Significance of the Results of Surface Drift-Bottle Experiments in the Faroe-Shetland Channel."

6. " Fluctuations in the Intensity of the Oceanic Incursion into the Faroe-Shetland Channel."

The foregoing papers and the researches of which they treat are entirely and without exception the original and independent work of the subscriber, executed in pursuance of his duties as Senior Naturalist(Hydrographer) to the Fishery Board for Scotland, now the Fisheries Division of the Scottish Home Department.

The first paper is in continuation of a series, the first three numbers of which were submitted for the Degree of Doctor of Philosophy of the University of Edinburgh in December 1932. The next three papers were each, before publication, prepared for and delivered at successive annual conferences of the International Council for the Exploration of the Sea, in 1934, 1935, and 1936 respectively.

Paper 5,/

Paper 5, in manuscript, was similarly read before this Council in 1938. On account of the exigencies of a departmental office entailing much routine laboratory work and, during the past year, frequent absences of two or three weeks' duration from headquarters, there has not hitherto been adequate opportunity to present this paper for publication.

Paper 6, which includes work upon data acquired at sea during the present summer, was prepared for delivery at Washington, U.S.A., in the beginning of September 1939, at the Seventh Triennial Assembly of the International Association of Physical Oceanography. The paper is intended for publication as a Government report if circumstances now permit, or, alternatively, and subject to official approval, in the publication of a learned society.

ABERDEEN,
September, 1939.

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1937

No. I

The Surface Water Drift in the Northern and Middle Areas of the North Sea and in the Faroe-Shetland Channel

Part II, Section 3: A Cartographical Analysis of the Results of Scottish Surface Drift-Bottle Experiments of the Year 1912; with a Discussion on some Hydrographical and Biological Implications of the Drift-Bottle Results of 1910, 1911 and 1912, including Statement of a Theory of the Upper Water Circulation of the Northern and Middle North Sea.

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PREFACE

THE present paper is the fourth of a series on the surface drift of the Northern and Middle North Sea and neighbouring regions to the north and west, the three previous publications being as follows :—

(1) *Fisheries, Scotland, Sci. Invest.*, 1930, No. II (containing Figure 1, Tables I–XII).

(2) *Fisheries, Scotland, Sci. Invest.*, 1930, No. IV (containing Figures 2–17, Tables XIII–XXIII).

(3) *Fisheries, Scotland, Sci. Invest.*, 1931, No. III (containing Figures 18–35, Tables XXIV–XL).

Among the reasons for continuing these interpretations of the surface drift-bottle results of more than twenty years ago in such detail as they are given in this and the earlier reports cited, the chief are, first, that the records in question form the most continuous series of the kind that exist for such a lengthy period, until we come to more recent years, when, the value of these earlier experiments having been established, they were resumed on a similar scale ; and, second, because it has lately become evident that these earlier results, differing in important particulars from one year to the next while obviously conforming to some general underlying principle, will constitute an excellent basis for the interpretation of more recent material.

The data analysed in the following pages are included in an Appendix to (1) above, which comprises a broad summary treatment of the complete records for the years 1910 to 1914 inclusive. Papers (2) and (3) deal in greater detail, on a cartographical basis, with the results of the 1910 and 1911 experiments respectively. In the present paper the records for 1912 are similarly treated.

Details concerning the initiation, objects and limitations of these experiments are given in the earlier publications, particularly the first. Only brief mention need therefore be made of them here, since the foregoing papers contain much that is indispensable to an adequate appreciation of the 1912 analysis. Moreover, direct reference to these earlier works is frequently necessary in this report.

From the standpoint of fisheries research, the main purpose of surface drift-bottle experiments is to obtain information relative to the passive transport of plankton, including embryonic and larval forms.* The immediate object of the work may therefore be said to be the measurement of the direction and velocity of the surface drift in the region, or regions, involved. The term "surface drift," however, with special reference to drift-bottle results, as these are interpreted in this and the former papers already quoted, calls for some explanation.

It is generally recognised that there are several factors, e.g. winds, tides, density distributions, bottom and margin configurations, the rotation of the earth, etc., which influence, in greater or less degree according to time and place, the movement of surface waters. These factors are to be looked upon as in the nature of physical forces acting in and upon the fluid medium of the sea. Without entering into discussion of the extremely complicated question of what may be the relative effects

* The writer has found them to be of further and scarcely less valuable consequence in that they afford a much better appreciation of temperature and salinity distributions than can be obtained, as a rule, from the study of these quantities alone. See (**10***d*).

of these several forces in the North Sea, it suffices here to state that the quantity which drift-bottles may be taken to measure, and which has been equated to the surface drift, is the resultant horizontal effect of all forces upon a practically smooth body which is suspended as freely as circumstances allow, immediately below the sea surface. In other words, no distinction is made, meantime, between the apparent rate at which such a body, namely, a drift-bottle, passes *through* the surface waters of the sea, and the velocity of that which is referred to as the surface drift.

The experiments, of which those dealt with in the following pages are the third consecutive yearly series, were not the first of the kind to be carried out over the same regions. The generalised picture derived from earlier data, however, besides having since been shown to be misleading in important particulars, has also, and for still other reasons, been found to be inadequate in the investigation of marine biological problems, partly on account of its insufficiency in the matter of detail, but chiefly by reason of the large deviations which are liable to occur in any one year from conditions which such a generalised picture may be taken to imply are normal, or mean, annual conditions. The picture referred to is that published by Fulton in 1897 (**4**).* Similar shortcomings, from the point of view of fisheries research, are ascribable, although in lesser degree, to Böhnecke's more recent diagrams (**1**) based on salinity distributions. Hence, in the writer's view, the necessity for acquiring, first of all, detailed information relative to, and in the first instance limited to, each of a number of years. Undoubtedly, a wider purpose is served if the years in question are consecutive.

It is on this principle that the present series of drift-bottle papers is submitted, as well as for the reasons given in an earlier paragraph. As far as possible, the data are analysed on their own merits, with observance of a few simple rules governing their cartographical treatment. These rules are recapitulated in introducing this part of the present paper.

Conjointly with their work upon drift-bottle records, several investigators—notably Fulton (**4**), Gilson (**5**), Liebert (**9**) and Carruthers (**3***a*)—made a study of wind data, demonstrating certain broad relationships between wind and surface drift in the regions embraced by their experiments. Except for their citation, here and there, as of probable significance in relation to peculiarities in the routes estimated for some drifters—generally in relatively shallow, landward parts—no attempt is made in the present series of papers to establish wider or more general connexions between the prevailing winds and surface water movements.

From the nature of the experiments, such results as are obtained must obviously be held to apply, in the first instance, only to the most superficial layer of water to a depth equivalent to the length of a drift-bottle. Evidence from another source (**10***d*), however, tends to the conclusion that, in open-sea areas, and as regards direction at least, the currents deduced from surface drift-bottle interpretations may generally be taken to apply also to the richer plankton-bearing levels at some metres' depth.

Finally, the reader is referred to the writer's earlier papers for explanations regarding the conventions used throughout the text, in the tables, and on the charts contained in this paper, although most of these should be readily understood from the context.

J. B. T.

ABERDEEN, *December* 1936.

* Bracketed numbers in heavy type refer to the List of References on page 59.

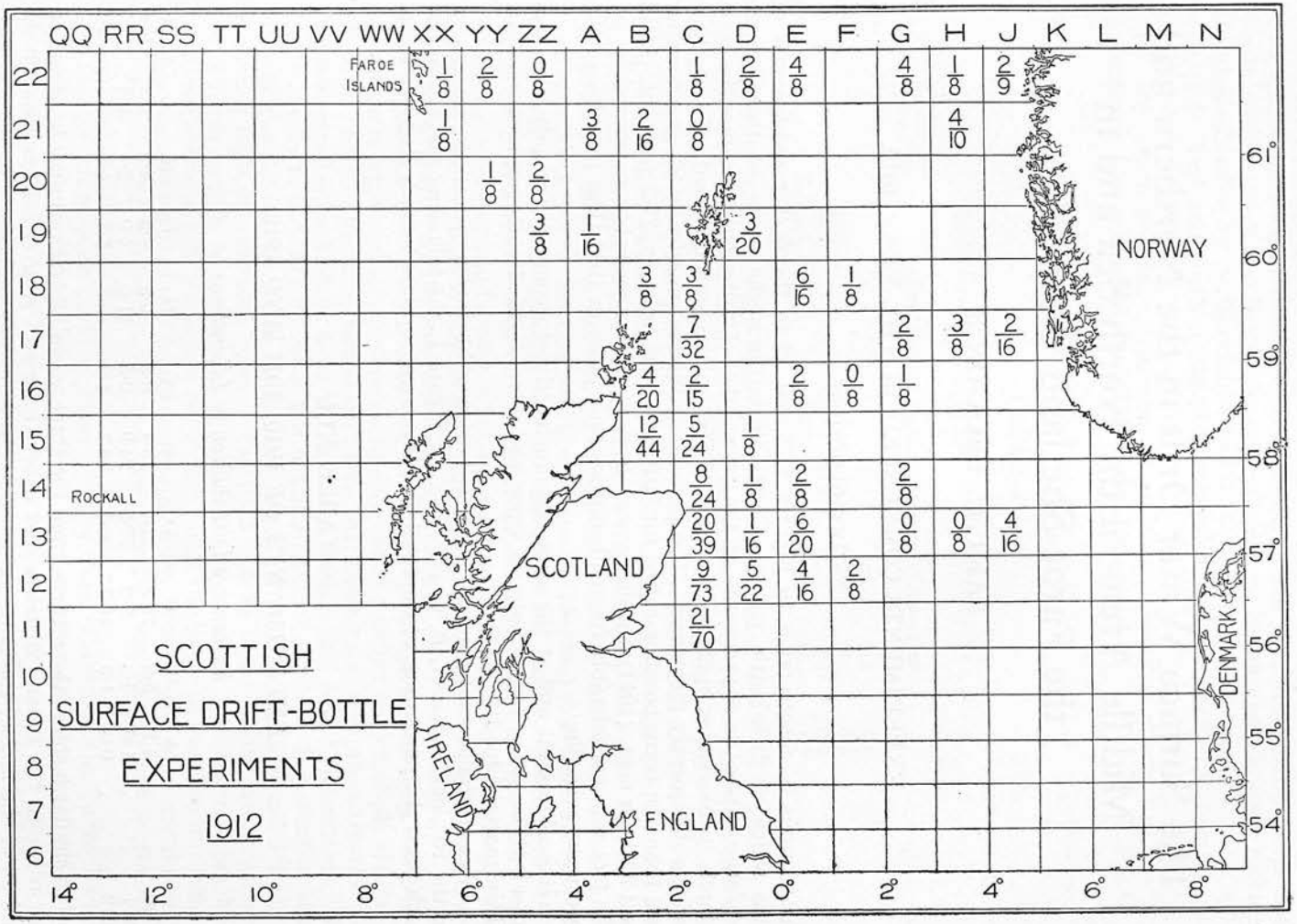

QQ RR SS TT UU VV WW XX YY ZZ A B C D E F G H J K L M N
FAROE ISLANDS
NORWAY
SCOTLAND
ROCKALL
IRELAND
ENGLAND
DENMARK
SCOTTISH
SURFACE DRIFT-BOTTLE
EXPERIMENTS
1912
61°
60°
59°
58°
57°
56°
55°
54°
14° 12° 10° 8° 6° 4° 2° 0° 2° 4° 6° 8°

FIG. 36.

The Surface Water Drift in the Northern and Middle Areas of the North Sea and in the Faroe-Shetland Channel

PART II, SECTION 3

EXPERIMENTS COMMENCED IN THE YEAR 1912.

INTRODUCTION.

ANALOGOUS in construction to Figures 1, 2 and 18 in the earlier publications of this series of drift-bottle papers, Figure 36 outlines the scope of the Scottish surface drift-bottle experiments of the year 1912. During the nine months from March to November inclusive, a total of 766 bottles was liberated, 176 of these being subsequently recovered. The percentage return, practically 23, is somewhat less than the corresponding ratios for 1910 and 1911, namely, 27·3 per cent. (1910) and 26·3 per cent. (1911), the differences, however, being probably accounted for by the fact that considerably fewer liberations took place in 1912 than in either of the two years preceding.

It is of interest and at the same time instructive to compare, broadly, the data for all three years, before entering upon the more detailed cartographical analysis of the material for 1912.

With reference, first of all, to the distribution of liberation operations, in relation to the Regional Areas A, B, C, . . . etc., of Figure 1, the following table gives, for each year, the percentage of the total liberations appropriate to each Regional Area.

TABLE XLI.

EXPERIMENTS OF 1910, 1911 *AND* 1912.

Percentage Distribution of Liberations.

	A	B	C	D	E	G	H	J	K	L	M
1910 . .	4·1	5·9	20·3	21·4	15·1	0·9	9·5	4·5	4·5	0·9	12·9
1911 . .	1·0	4·8	9·2	37·9	24·9	0·5	11·6	4·9	2·4	0·5	2·3
1912 . .	0·0	1·0	15·7	26·5	28·7	1·0	6·3	5·7	4·6	6·3	4·2

In similar fashion, the returns from the three years' liberations may be classified according to the coastal districts and other regions of recovery defined on pp. 13 and 14 of the first of the papers quoted in the foregoing preface. For present purposes it will be sufficient to include two or more of these sections in each of five more comprehensive groups, thus :—

R1. The Outer Hebrides (west of Scotland), the west and north coasts of the mainland of Scotland and the western shores of Orkney and Shetland (i.e. Sections 1 and 2).

R2. The east coast of Great Britain (Sections 3 to 7).

R3. Continental shores of the North Sea north to latitude 62° N., including Danish, Swedish and Norwegian shores in the Skagerak and Kattegat north of about latitude 57° N. (Sections 8 to 12).

R4. West and north coasts of Norway north of latitude 62° N. (Sections 13 and 14).

R5. Other regions, e.g. At Sea, Faroe Islands (Sections 15 and 16).

In accordance with this scheme we have Table XLII.

TABLE XLII.

EXPERIMENTS OF 1910, 1911 *AND* 1912.

Percentage Distribution of Recoveries.

	R1	R2	R3	R4	R5
1910 . .	4·6	40·3	32·8	18·2	4·3
1911 . .	2·2	25·4	44·0	27·9	0·4
1912 . .	3·4	34·1	46·0	14·8	1·7

Evidently no part of the Regional Area A was visited in 1912. Also, very little appears to have been done in Area B in the third year of these experiments, and, while the 1912 liberations in Area C bulk proportionately larger than those of 1911, but fall short of the 1910 operations in the same Area, the paucity of the 1912 material from the Faroe-Shetland Channel as a whole (see Tables III and IV) is, for several reasons, unfortunate. Chief among these is the fact that the major surface water movements in this region have an *a priori* connexion with subsequent events in the Northern North Sea. It has also been demonstrated (**10***a*) that the results of liberations in Areas A and B tend to differ characteristically from those accruing from experiments begun in Area C, indicating a distinction, as regards surface water movement, between the northern and southern halves, practically, of the Faroe-Shetland Channel region. It seems unlikely that much, if anything, will be added to existing information on this matter by the analysis of the 1912 data.

Despite the above circumstances, the R1 percentage for 1912 (Table XLII) seems quite appreciable. Reference to some of the earlier tables (Nos. III to V), however, elicits the information that this particular ratio comprises returns from experiments begun in Area D as well as from Area B and Area C liberations. The same applies to the 1911 R1 ratio, but not at all to that of 1910. In actual numbers, two of the drifters liberated in Area D in each of the years 1911 and 1912 were returned from R1 districts. One of the 1912 returns is, so far as this examination of Scottish records has gone, peculiar. Liberated on 20th September, a few miles south-eastward of Smith Bank in the Moray Firth, the bottle in question was beached within the short period of 12 days in Strathy Bay, midway along the north coast of the mainland of Scotland. This will probably be a cardinal record in the cartographical analysis to follow.

Finally, an adverse point in regard to the work of 1912 in the Faroe-Shetland Channel was the limitation of experiments there to the months of May and June—to the liberations, in fact, of a single round cruise from Shetland to Faroe and back again into the North Sea by a more southerly route. In 1910 and 1911, drifters were put out in this region in two distinct periods of the year, and a comparison of the results of the May and August liberations of both years led to the same conclusions, namely (1) that the surface current connexion between the Faroe-Shetland Channel and the Northern North Sea lay by way of the opening *between Shetland and Norway*, and (2) that the liaison was the more firmly established in the earlier

season. There is, however, despite the shortcomings of the 1912 Faroe-Shetland Channel data, at least a suggestion among certain other results for the year that the former condition again held.

With regard to liberations within the North Sea, it is evident from Table XLI that, in 1912, as in 1911, more than half of the work for the year was carried out in the Regional Areas D and E, i.e. on the western side of the North Sea. The corresponding ratio for 1910 is about one-third. Accordingly, having regard to the general cyclonic nature of the North Sea surface drift system as established by Fulton, one might expect to find relatively greater numbers of British east coast recoveries among the 1911 and 1912 records than among those for 1910. Table XLII (R2) shows that, in both cases, the contrary is true, although the anomaly is less as regards 1912 than for 1911.

Taking into account only the experiments begun in the Regional Areas D and E, the following table gives, for each of the three years under discussion, the percentage relationships of the British east coast strandings to the total return from all parts.

TABLE XLIII.

	D	E
1910 . . .	38·6	84·7
1911 . . .	27·8	59·2
1912 . . .	39·1	53·6

In 1910 and 1912, conditions in Area D would appear to have been almost equally favourable to the beaching of bottles on the British east coast. Other considerations, however, suggest that these conditions were even more favourable in the latter year than is indicated in the above table.

In 1911 the great majority of the British east coast recoveries from Area D liberations were effected on the shores of the Moray Firth and resulted from liberations in the Firth itself. Farther from land, and practically throughout the whole year, the surface drift was essentially towards the east and therefore away from the British coast. At the same time, the almost continuous functioning of the anticyclonic Moray Firth Eddy produced, in effect, a more or less self-contained system in the inner reaches of the Firth, and this was responsible for the retention over considerable periods of drifters set afloat within the area, thereby enhancing the probability of their being cast up on the neighbouring coastline, as actually happened.

Similar circumstances are scarcely at all arguable in explanation of the higher Area D percentages of 1910 and 1912. In the latter year particularly, very little work was done in the Moray Firth—less than one-quarter, in fact, of that accomplished in 1910, and, numerically, the Moray Firth liberations of 1910 are to those of 1911 in the ratio of 1 to 1·6. Over the whole of Area D the liberations of 1910 and 1912 differ in the aggregate by only 34, those of 1910 being in the majority; so that one might expect the British east coast strandings from the Area D liberations of 1910 to be proportionately more numerous than those relating to 1912. In actual fact, the reverse is the case, tending to the conclusion that, in the north-western part of the North Sea, the westerly trend of the off-shore waters which was characteristic of 1910 was even more pronounced two years later. In the intervening year, as already stated, the tendency was in the opposite direction.

The position as regards Area E differs considerably from that pertaining to Area D. Its discussion, moreover, is rendered more difficult by the fact that in this region also there is a closed gyratory system of drift, but one which, besides being of greater extent laterally, is liable also to greater fluctuations in its superficial area and shape

than the Moray Firth Eddy, whose maintenance is very largely due to the configuration of adjacent coasts. The Mid-East Scottish Coast Eddy is distinctly more a part of the major North Sea circulation than is the Moray Firth system and is therefore in greater degree affected by neighbouring open-sea conditions.

In general, however, it may be accepted from Table XLIII that, of all recoveries resulting from liberations in Area E, more than half the number will take place on the British east coast. The converse apparently holds in regard to Area D. Secondly, the figures of the table suggest that, in 1912, the easterly component of the surface drift in Area E was even more effective than it was a year before, being in both years much stronger than the same influence in 1910. It has to be observed, however, that proximately coastal liberations were less frequent in 1912 than in either of the two years preceding.

The British east coast recoveries from liberations in Areas D and E together may be looked upon from another angle, namely, in relation to the total return from all experiments in each of the three years. As percentages, these relationships are, for 1910, 27·4 ; for 1911, 24·6 ; and for 1912, 27·2. It is at once evident by comparing these figures with the R2 entries in Table XLII, that it is not alone by reason of the results from Areas D and E that the 1912 percentage of British east coast returns is 6·2 less than that registered in 1910 and 8·7 greater than the 1911 ratio. In other words, the British east coast strandings emanating from these two Regional Areas do not, in any one of the three years dealt with, constitute the total return from the western North Sea seaboard. This condition was most nearly fulfilled in 1911. The question then arises as to the origin of the remainder of the east British recoveries, especially as regards the years 1910 and 1912. By way of answer to this question Table XLIV was constructed.

TABLE XLIV.

EXPERIMENTS OF 1910, 1911 *AND* 1912.

Percentage Derivation of British East Coast Recoveries with Reference to Regional Liberation Areas.

	A	B	C	D	E	G	H	J	K
1910 . .	1·6	6·6	13·1	18·0	50·0	0·0	8·2	0·0	2·5
1911 . .	0·0	1·4	1·4	36·2	60·9	0·0	0·0	0·0	0·0
1912 . .	0·0	3·3	0·0	30·0	50·0	6·7	0·0	0·0	10·0

The absence of British east coast recoveries from the 1912 liberations in Area C is a noticeable feature of Table XLIV, particularly as, by Table XLI, an appreciable amount of work was accomplished in this region in that year. From the whole of the Faroe-Shetland Channel area the entire contribution for 1912 to this class of return is confined to results from the Regional Area B, within which only 1 per cent. of the liberations for the year was carried out. Further examination of this circumstance reveals that only eight drifters were liberated in Area B during 1912, and these from a single station in the month of June. All three recoveries from this series took place among the Orkney Islands, so that, in the light of former findings relative to the peculiarity of the surface drift in the neighbourhood of Orkney, it seems that very little evidence, if any, may be forthcoming from the 1912 analysis as to the relationship between surface flow in the Faroe-Shetland Channel and that in the North-Western North Sea.

Results from Areas D and E have already been sufficiently discussed from the point of view of British recoveries, except perhaps to note that, in all three years, Area E furnished the biggest proportion—at least half—of the British east coast

returns for the year, despite the fact that liberations in Area E were in only one year (1912) more intensive than those in Area D.

Passing to the entries in columns G, H, J and K in Table XLIV, the figures there quoted afford some interesting comparisons. First of all, the year 1911 is unique in that no British east coast stranding resulted from liberations in those Areas ; evidence, again, of the strong eastward tendency already remarked upon in relation to the off-shore surface water movement on the western side of the North Sea during 1911. Secondly, the only one of the four regions which is twice represented in this class of return is the Area K, and in view of its orientation relative to the British coast this matter obviously calls for further examination.

Reference to Table IX shows that, in both of the years involved, namely, 1910 and 1912, the results in question belong to the liberations of the month of May. Eight of the nine bottles concerned were recovered on the east side of Shetland, the remaining drifter landing on Fair Isle, midway between Shetland and Orkney. Both sets of recoveries—there were three in 1910 and six in 1912—took place in the same season of the year, actually between the end of June and the end of August. These points of similarity are of some significance, suggesting not only a recurrence in 1912 of the same peculiarity in the flow of the surface waters over the northern edge of the Continental Shelf as has been demonstrated for each of the previous two years, but a repetition also, in the corresponding period of 1912, of the system of drift which apparently characterised the North-Western North Sea in the summer of 1910.

Support for the suggestion is forthcoming from a similar inquiry into certain other figures of Table XLIV. It is learned from the appropriate statistics of these experiments (**10***a*) that the above liberation-period and the times and places of recovery apply also to the 1912 data for Area G and to some of the 1910 data for Area H. Records pertaining to Area H which do not conform to these conditions are, however, as has in fact been demonstrated (**10***b*), closely related, in one way or another, to the remainder of the data under discussion, and although they may not be of immediate utility in the analysis of the 1912 material, it may be of interest for future reference to note that they can be classified in three groups :—

(1) Bottles set adrift in the month of May and recovered on the east side of either Orkney or Shetland, *but not until the month of December following*.

(2) Bottles liberated in May and found during the following August, or not until towards the end of the year, on the British east coast *south of Rattray Head*.

(3) *September liberations* returned from east Shetland and Orkney in December.

With regard to the first two groups, the liberations took place in Area H north of latitude 59° 30′ N. The September bottles were despatched in the same longitudinal area, but south of latitude 58° 30′ N. The fact that some bottles were returned from Orkney and others from Shetland does not constitute a real difference in the nature of these recoveries. *A posteriori*, the dynamical conditions to which the contemporaneous returns from both districts are attributable were one and the same.

A final observation which may be made in relation to the British east coast recoveries concerns the most southerly stranding-place recorded in each of the three given years. In 1910 two bottles were returned from the English coast south of latitude 54° N., the more southerly point reached being in the vicinity of Sutton-on-Sea, Lincolnshire, in latitude 53° 18′ N. Both bottles originated at a May station some 20 miles east of Buchan Ness, and were picked up in the month of July following. The corresponding return for 1911 was that of a September drifter liberated about 25 miles east of Fife Ness and found in the next month in latitude 54° 27′ N., while, in September 1912, a bottle emanating from one of the June series of liberations in the Moray Firth was returned from a point five miles south of Bridlington, Yorkshire, i.e. practically on latitude 54° N.

Attention may now be given to the Continental returns of 1912 in relation to the like records of the previous two years. Associated, apparently, with a proportionately smaller British coast return for 1911 in comparison with 1910, was an enhanced proportion of recoveries on the eastern North Sea seaboard in the former year (R3, Table XLII). For obvious reasons recoveries effected in the Skagerak and Kattegat are included in this category in the initial broad survey of the material. The corresponding percentage for 1912 is even greater than that for 1911, and in order to study its significance more closely, especially as regards the various origins of the bottles concerned, Table XLV is given.

TABLE XLV.

EXPERIMENTS OF 1910, 1911 *AND* 1912.

Percentage Derivation of Continental Recoveries with Reference to Regional Liberation Areas.

	A	B	C	D	E	H	J	K	L	M
1910 . .	0·7	2·0	1·0	10·2	2·6	2·0	4·0	0·7	0·0	9·6
1911 . .	0·0	0·4	0·7	18·0	4·4	11·8	5·1	0·7	0·0	2·9
1912 . .	0·0	0·0	0·0	11·4	13·1	5·7	6·8	2·3	4·5	2·2

Perhaps the most striking feature of this table is the indication that not a single 1912 bottle from the Faroe-Shetland Channel region beached upon Danish or Swedish shores, or on the Norwegian coast south of latitude 62° N. Taken in conjunction with the previous finding that only three bottles from the same region were recovered on western North Sea shores, and these only upon Orkney, about which conditions are, as a rule, peculiar and local, there is here a suggestion that no drifter from the Faroe-Shetland liberations of 1912 entered properly into the Northern North Sea. Until confirmed by the ensuing cartographical analysis, however, this implication of the 1912 figures must be taken with great reserve, entailing, as it does, the abrogation, even if only for one year, of an otherwise well-founded conception of permanent and direct relationship between the hydrodynamics of the Faroe-Shetland Channel and the Northern North Sea.

Practically the same return from eastern North Sea shores was registered from the Area D liberations of 1910 and 1912, in both instances less than that recorded for 1911. On the other hand, the work of 1912 in Area E resulted in a considerable increase in this class of recovery as compared with the previous two years. These circumstances are in accord with what has already been inferred from the relative proportions of western North Sea recoveries in the three years concerned, through the association which apparently exists between the two classes and which has already been cited.

Area K also shows a larger percentage of eastern North Sea recoveries in 1912 than in either of the previous two years. The fact is again remarkable, as evidence of the strong tendency for surface waters in this region so near to the Norwegian coast to flow *into* and not *away from* the Northern North Sea. How strong is this tendency may be gauged roughly from Table IX, which shows that, in two of the three years in review, Area K drifters passed to both western and eastern North Sea shores.

Little can be said, meantime, as regards the remaining Areas of Table XLV except perhaps to observe that, for the first time, Area L is represented by eastern North Sea strandings in 1912 and also that, as was the case in 1911, the following year's records for Area M appear to be meagre. The latter circumstance may have an adverse effect upon the cartographical interpretation of other records for the year.

The great majority of bottles on their long ways to the Skagerak and neighbouring shores pass through Area M, data from which are therefore useful as guides to the later histories of these generally much longer-period records.

The only other matter relative to eastern North Sea returns which need be considered at this juncture concerns the recovery of 1912 bottles in the Skagerak, especially the times of such occurrences. The corresponding results of the previous two years' experiments show "blank" periods of approximately three months each, when entry into the Skagerak seems naturally to have been barred. These periods were from October to December 1910 and from December 1911 to February 1912, all four months inclusive.

Table XLVI, then, gives the frequency of Skagerak recoveries effected during 1912 and the first quarter of 1913, with the months of origin of the drifters concerned.

TABLE XLVI.

Frequency of Skagerak Recoveries during 1912 *and first quarter of* 1913.

Liberation Month.	Month of Recovery.												
	1912. Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	1913. Jan.	Feb.	Mar.
1910 Dec.	—	—	—	—	—	—	—	—	—	—	—	—	1
1911 Feb.	4	—	—	—	—	—	—	—	1	—	—	—	—
April	—	—	1	—	—	—	1	—	—	—	—	—	—
May	1	—	—	—	—	1	—	—	—	—	—	—	—
July	—	—	—	—	—	—	—	—	1	—	—	—	—
August	—	—	—	—	—	1	—	—	—	—	—	—	1
1912 March	—	—	—	—	—	—	1	—	—	—	—	—	1
May	—	—	—	—	—	—	—	—	1	7	—	—	3
June	—	—	—	—	—	—	—	1	1	6	2	2	1
July	—	—	—	—	—	—	—	—	—	—	—	—	1
August	—	—	—	—	—	—	—	—	1	2	—	—	—
Sept.	—	—	—	—	—	—	—	—	—	2	2	—	4
Oct.	—	—	—	—	—	—	—	—	—	1	—	—	—
Totals	5	—	1	—	—	2	2	1	5	18	4	2	12

There is here no decided evidence of a winter period when bottles were prevented from entering the Skagerak. On the contrary, it appears that such recoveries were concentrated in the winter months of 1912–1913, although a five weeks' interval separates the last January 1913 recovery from the first of the two effected in February. The scarcity of Skagerak returns in the months from April to June 1912 cannot be taken as evidence of a blank or nearly blank period, since the last open North Sea liberations of the year before were carried out in the month of August and the first of the 1912 experiments only in May.

For several reasons, chiefly concerned with the distances between the liberation-points and stranding-places of the drifters involved, and with the intervening complexities doubtless encountered by these bottles while they were at sea, the remaining ratios of Tables XLII, i.e. the R4 and R5 entries, are not amenable to discussion in this introduction. It may be observed, however, relative to the suggestion that no bottle from the Faroe-Shetland Channel entered the Northern North Sea during 1912, that the R4 percentage for that year appears to be somewhat low, although the proportionately greater R3 value in comparison with those for 1910

and 1911 may in a measure account for the apparent discrepancy. The cartographical analysis to follow will doubtless provide the desired explanation.

CARTOGRAPHICAL ANALYSIS OF THE 1912 RECORDS.

Introductory.

In these reports the cartographical analysis of surface drift-bottle records pertaining to the Northern North Sea and adjacent waters primarily depends upon those relatively short-period returns from which directions and velocities may be deduced. Such records form the basis for the interpretation of the longer-period recoveries associated with them, either in point of date or place of liberation, or of date or place of recovery.

Because of the complexity of the surface water movements in the above regions, however, not every short-period return at once affords a reasonably true estimate of direction or velocity, for an approximately straight course cannot always be accepted in respect of even the quickest return. Most of them, however, are of service in so far as they yield minimum average values for the speed of the drift during certain intervals. Directions are of lesser moment to start with.

Collectively, the longer-period recoveries, in course of their cartographical treatment, generally yield the desired information as to directions and may lead therefrom to successive partial adjustments of the mean velocities upon which their analysis is based. These steps are attained by adherence to the fundamental principle of consistency with which, undoubtedly, contemporary drifters in the same region must be held to comply, as regards both direction and velocity.

Directional consistency is achieved by observing the following rules in the cartographical reconstruction of bottle-histories :—

First, the individuals of a group of bottles set away simultaneously at a given point are to be looked upon as having moved off from that point more or less in close company, and, similarly, drifters found within a few days and miles of one another must, in the absence of evidence to the contrary, be supposed to have approached their stranding-places from the same general direction. Implicit in this latter statement is the assumption of coincidence between the dates of recovery and those of the actual stranding of the bottles concerned. This must obviously be fallacious in many instances, but from the results already obtained it is evident that the problematical times spent by some drifters on the beach before they are discovered are, in the majority, such small fractions of the entire periods between the dates of liberation and recovery that they do not come within the limits of precision attainable in these analyses. They are accordingly neglected, at any rate in the first instance.

Again, when there is no doubt that, at some stage in their open-sea careers, the several bottles of a group have drifted apart, it is held that, under most circumstances, separation can have taken place only gradually, and, as a corollary to this, any approach to rectangular intersection of contemporaneous routes in open-sea areas is not admitted, as this would entail the untenable hypothesis of simultaneous cross drifts in the self-same waters.

Consistency as regards velocity is not so simply determined and, in practice, is not wholly evident until most of the results for a year are worked out. If then, however, on the basis of two assumptions, the mean velocities deduced and utilised throughout the analysis conform to a smooth time-velocity curve of the type shown on Figures 45, 46 and 47, consistency, it is claimed, has been achieved. The assumptions are as follows :—

(1) The mean velocity estimated for the interval embraced by a drift-period, i.e. the number of days between the dates of liberation and recovery, is assumed to be

equivalent to the actual speed obtaining on the mid-date of that interval. At certain times of the year, notably about the periods of maximum and minimum velocity, this assumption, except for very short intervals, tends to be the less valid. On the whole, however, since practically every portion of the final curve is " covered " by several results derived in similar fashion, the over-all validity of the assumption is thereby removed of all reasonable doubt.

(2) The values obtained in the above manner, in respect of more or less limited regions, are taken as being representative of open-sea conditions over the whole of the Northern and Middle North Sea. This, again, is an assumption which can be only approximately true, but the fact is that it has been found to subserve in remarkable degree the interpretation of Scottish drift-bottle records, showing, for the years 1910 and 1911 (see Figures 45 and 46), a definitely regular fluctuation in the velocity of the surface drift in those areas, underlying the irregular and for the most part temporary variations, brought about by such sporadic influences as sudden changes in wind direction or force.

As pointed out, then, these analyses of North Sea surface drift-bottle records depend initially upon the shortest-period returns. Such results, however, to serve the purpose for which they are required, may not be found to be sufficiently numerous or disperse among the records for a year. In these circumstances it seems warrantable, after the 1910 and 1911 analyses, to apply the principle of analogy, for the essential similarity between the surface drift conditions of these two years, as demonstrated in previous reports, bespeaks the probable applicability of these conditions, in their main features at least, to other years. The principle, however, must be applied with reserve, for, notwithstanding the argument of broad similarity between the conditions of one year and those of another, there can be no doubt that more or less radical differences do sometimes arise as between the corresponding periods of different years. As will be seen, the latter part of 1912 is a case in point, when compared with the final quarters of the previous two years.

Among the drift-bottle records for 1912, the few short-period results available proved insufficient to establish at once a time-velocity curve to which the remainder of the data would conform, in obedience to the conditions laid down to govern these analyses. Numerous adjustments to the provisional curve so obtained, as well as to the charted routes of the drifters, were necessary in order to achieve satisfactory co-ordination among all the records for the year. It is, of course, quite impracticable in this report to set down all the various steps in detail, but they can be summarised briefly as follows :—

The March liberations, which were the first for the year, yielded two recoveries which are capable of interpretation by analogy with former results of a similar kind. From these, the points **A** and **B** on Figure 47 are derived.

The results of the April experiments give practically no indication of the rate of the drift in that or in the following month, and although, as in the previous two years, the liberations of May 1912 were carried out on an extensive scale, none of the resulting 56 recoveries affords, within sufficiently narrow limits, the necessary information upon which to base the analysis of the remainder.

The June experiments provide the next result from which an apparently reliable estimate of the speed of the drift can be obtained. From the 9_8 recovery on South Ronaldshay, Orkney—a straight-line course being assumed—a minimum average velocity of just over 8·3 miles per day is deduced as being applicable to the 6th–7th June, giving the point **D′** on Figure 47.

The next short-period record of apparent significance occurs only among the September records. As anticipated in the Introduction to the present report, the 12_8 recovery, involving a minimum drift-speed of 6·3 miles per day, is a cardinal record among the year's results, enabling the point **E′** to be entered on the velocity-diagram.

In the same way **F′** is derived from the 53_1 October result, and **G′** from the November record, 46_1.

In all cases save the last, and leaving the March records out of account meanwhile, fairly direct routes in respect of the bottles concerned are not improbable. For the 46-day November bottle, however, a direct passage from west to east across the Northern North Sea, from the Moray Firth to the neighbourhood of Bergen, cannot be accepted as even a near approximation to the truth, the less so because a second November record, although it embraces to some extent *extra*-North Sea waters, where the speed of the drift may be somewhat in excess of that in the Northern North Sea, entails a minimum average velocity of 9·15 miles per day, centred on the date, 5th January 1913. The point **H′** on Figure 47 is thus derived.

There is sufficient reason to accept, at least tentatively, the relative positions of **D′**, **E′**, **F′** and **H′** on Figure 47, and a smooth curve passing through these four points was employed in a first attempt to analyse the year's results. As already indicated, however, it was not until, by numerous adjustments, the curve was finally brought into the position and form in which it appears on Figure 47, passing through the corresponding points **D**, **E**, **F** and **H**, that satisfactory co-ordination was obtained throughout.

The fact of repeated revision of the whole analysis, which was rendered necessary by the above-indicated procedure, should be borne in mind by the reader, particularly where reasons in support of deductions or assumptions made may seem slender or almost lacking. Moreover, on account of the interdependence of many of the results, involving, it may be, the liberations of several months, it is practically impossible to give a coherent rendering of the actual process by which the complete analysis was evolved. Thus, although in the main the 1912 results are here examined in the chronological order of the liberations to which they refer, they were by no means thus worked out. Indeed, following the analysis of the leading March results, real progress was maintained only when the November records were treated next, then the October results, and so, on the whole, backwards as it were to those of May and April. By constant reference, however, to Figure 47, it is possible to give the following more orderly account of the year's results.

* * * * * * *

March Liberations.

Experiments in 1912 commenced on 7th and 8th March with the liberation of 58 drifters in the mid-east Scottish area. Six bottles were subsequently recovered; three in the Skagerak region after no less than six months—in one case after more than a year—and three at different places on the Aberdeenshire coast of Scotland, on 22nd March, 2nd April and 12th September respectively.

The Scottish records, particularly the two shorter-period returns, at once suggest the Mid-East Scottish Coast Eddy, which, on Figure 37, is given the position and the elliptical form determined for it from certain 1910 experiments in the area. This form of the Eddy appears generally to be associated with recoveries on the Scottish east coast to the north of the region of liberation, while the circular system of 1911 (see Figure 21), situated more to the southward, seems to favour rather the stranding of drifters to the south of Tay estuary and especially on the north-eastern English coastline.

By the route laid down to scale on Figure 37, the 15-day Station 5 drifter to Peterhead is estimated to have accomplished 165 miles at the mean rate of 11 miles per day. The 26-day drifter from the same station presumably covered about 305 miles as indicated, the appropriate curve entering the eddy proper on its south-eastern periphery and emerging from it again on its northern boundary, thereafter following the path of the 15-day bottle to Peterhead, thence to Rattray Head. The mean rate of drift in this instance is 11·7 miles per day.

By the assumption which the writer has adopted to govern the construction of time-velocity curves from drift-bottle data, the points **A** and **B** on Figure 47 are derived from the foregoing records, i.e. 11 miles per day is regarded as having been the *actual* drift-velocity on 14th–15th March 1912—the mid-date of the drift-period concerned—and the average figure of 11·7 miles per day as immediately applicable to the 20th of the same month. By the second fundamental conception expressed at the beginning in regard to these curves, the inference may be made from the above results that, during March 1912, the velocity of the surface drift, not only in the mid-east Scottish area, but in the Northern and Middle North Sea as a whole, was accelerating, no doubt towards a maximum.

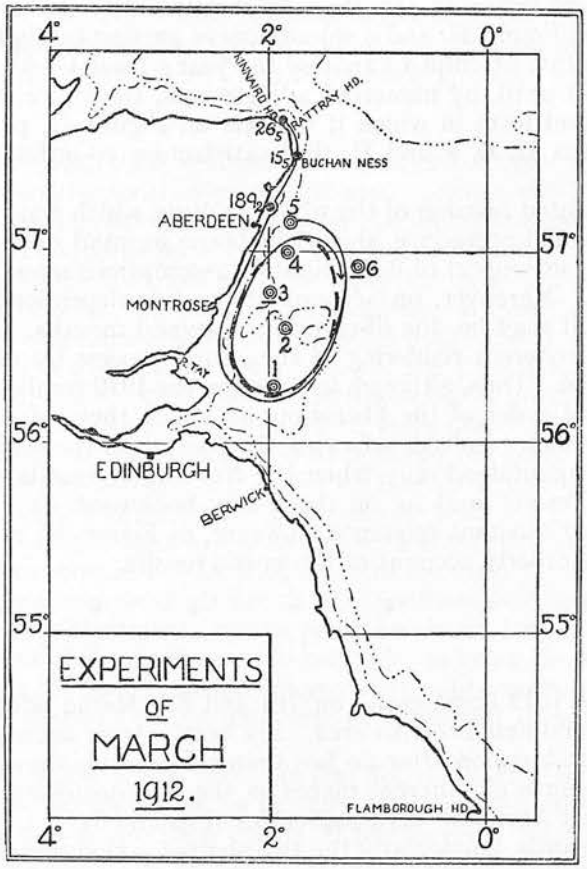


FIG 37.

In regard to the 189_2 drifter, the question is whether the Mid-East Scottish Eddy was solely responsible for its long sea career, neglecting the possibility of its having lain undiscovered for some considerable time. In addition to the probability that Station $March_{12}2$ was situated in the centre, practically, of the gyratory movement—from which may be argued a lengthy interval spent by the drifter in question under the dominant influence of the swirl—there is direct evidence from subsequent drift-bottle records for the year that the circulation persisted without interruption throughout the six months involved. Hence it is likely that the 189_2 bottle was, in fact, retained in the mid-east Scottish area from 7th March to 12th September 1912, the Eddy, as will be seen later, changing its form in the interval from the elliptical to the circular and again to the elliptical.

Nothing is gained by an attempt to analyse the Continental returns from the March liberations.

* * * * * * *

April Liberations.

A single series of liberations was made in April 1912. On the 24th ten bottles were put out at the same position as Station March$_{12}$1, but whereas the earlier experiment resulted in two Scandinavian recoveries and none on the British coast, two of the April bottles, constituting the total return from the series, stranded on 4th and 5th June on the coasts of Northumberland and Durham respectively. The drift-periods of these recoveries again suggest the Mid-East Scottish Coast Eddy,

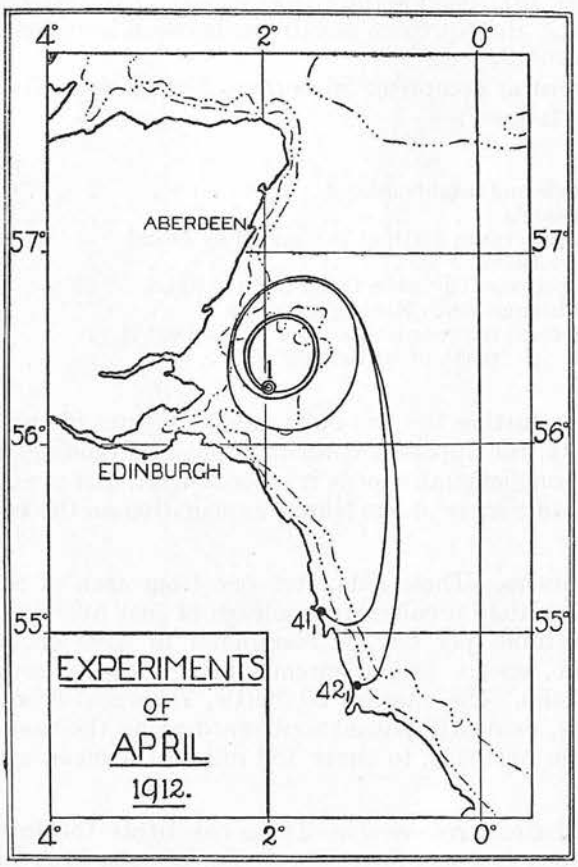


FIG. 38.

but, by the inference that certain classes of recoveries are associated with particular forms of this system, it would appear that, during the month of April 1912, a change took place in its superficial form as represented on Figure 37. Other reasons favour the assumption of the circular Eddy during the interval when the above April bottles were within its region of influence.

From the analysis of the leading March results it was inferred that the surface-drift velocity during that month was accelerating towards a maximum. At the mid-dates (14th–15th and 15th May) of the drift-periods of the two April records, it is reasonably certain that, as is shown by the velocity-curve, maximum velocity had been attained and passed. The cartographical analysis of the April records, as given on Figure 38, is the final result of a number of adjustments rendered necessary in order

to maintain consistency throughout the whole year's interpretations. The 42-day drifter is reckoned to have run a course of about 485 miles, as shown, at the mean rate of 11·5 miles per day, and the 41-day bottle just over 470 miles at about the same average speed.

The significant point on Figure 47, from these records, is the point **C**.

* * * * * * *

May Liberations.

The regions embraced by the 30 stations from which a total of 245 drifters was liberated during May 1912 include the Faroe-Shetland Channel, the southern reaches of the Norwegian Sea, the Northern North Sea between latitudes 58° N. and 60° N., and the mid-east Scottish area.

The record of returns comprises 56 bottles, distributed, with reference to their stranding-places, as follows :—

	No. of Recoveries.
Faroe Islands and neighbourhood	2
Shetland Islands	12
British coast between Firth of Tay and Holy Island	9
Schleswig-Holstein	2
Denmark, between Thyboron Canal and the Skaw	5
West Swedish and south Norwegian coasts	11
Norwegian coast between latitudes 60° N. and 62° N.	4
,, ,, north of latitude 62° N.	11

Before examining further the two outstanding features of the above distribution of recoveries, namely, the apparent concentrations of strandings (1) upon the Shetland Islands and (2) on Skagerak shores, it is convenient, first of all, to deal with those results which admit of a more or less simple explanation on the basis of the velocity-curve.

The Faroe Recoveries.—These emanated one from each of Stations 29 and 30. The 12_{29} drifter, to satisfy a calculated mileage of just over 122 overtaken at the rate of about 10·2 miles per day, is considered to have encircled the island of Suderö once, before, on its second circuit, being beached near Kvalbö on the east side of the island. The Station 30 bottle, recovered from the sea 15 miles north of Myggenaes, evidently passed southward along the east side of Faroe and northward along the west side, to cover 132 miles at a mean speed of about 10·15 miles per day.

The British East Coast Recoveries.—These constitute the total return from the liberations at Stations 1, 2 and 3, which, as can be seen from Figure 39, were not all three situated in the same region. Mid-East Scottish Coast Eddy influence is evident in the case of the sole recovery pertaining to Station 1, the bottle having, it is estimated, accomplished nearly 213 miles at an average daily rate of 11·2 miles. The course presumably taken is represented on Figure 39.

Clearly, also, in view of their stranding-places, the Mid-East Scottish Coast Eddy affected to some extent the eight drifters recovered as a result of liberations at Stations 2 and 3, and although Station 2 was situated in the area normally occupied by the Moray Firth Eddy, the correspondence among the drift-periods of both stations' recoveries—coupled with the entire lack of Moray Firth strandings, especially from Station 2—strongly suggests that the Mid-East Scottish Eddy was, in fact, the main cause of the larger differences to be observed among the recorded drift-periods. The courses estimated for the drifters concerned can be followed from the chart. Details of their estimation are given in Table XLVII.

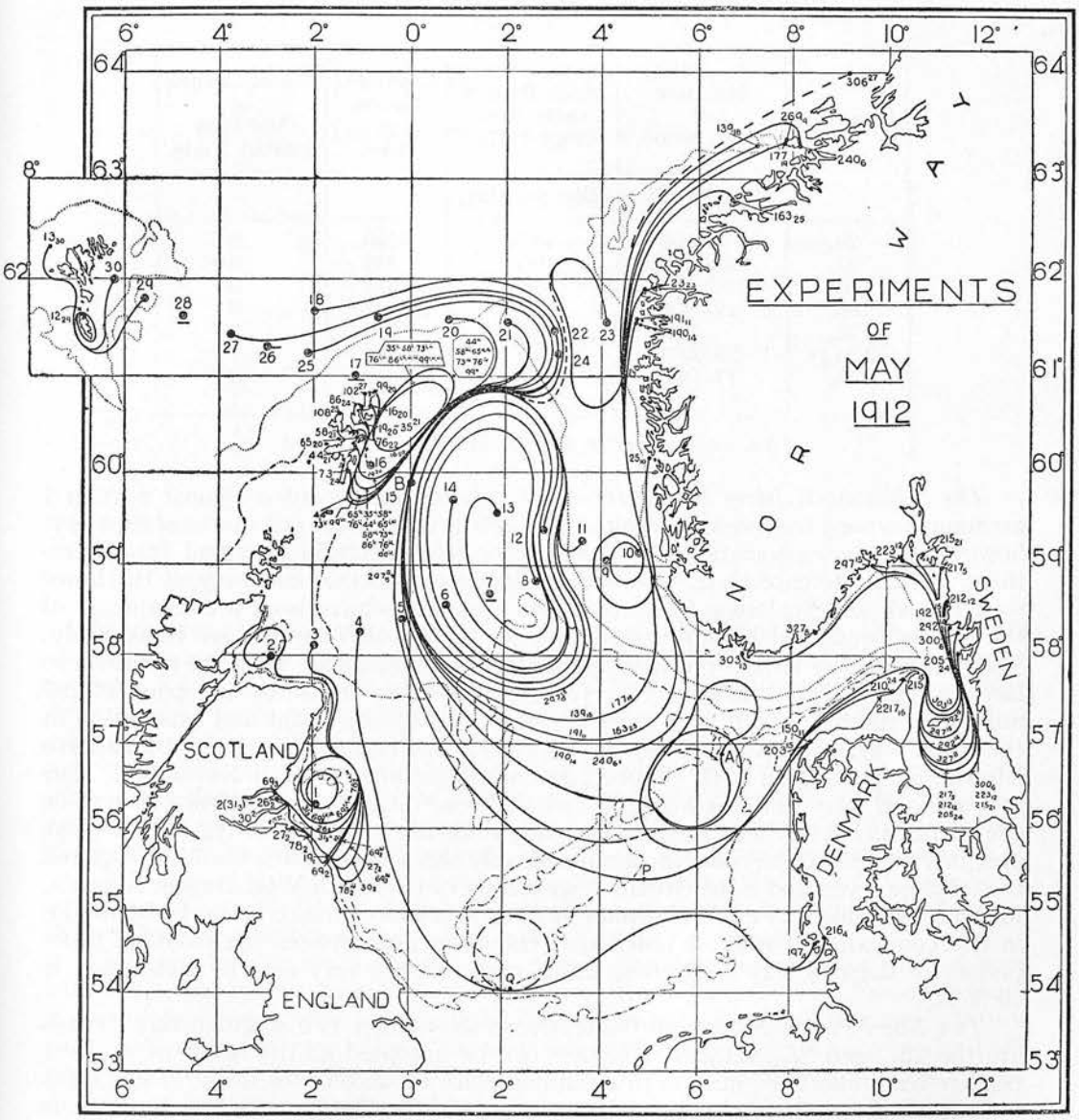

EXPERIMENTS
OF
MAY
1912
NORWAY
SWEDEN
DENMARK
SCOTLAND
ENGLAND
NORTH SEA

FIG. 39.

TABLE XLVII.

MAY 1912 *LIBERATIONS.*

British East Coast Recoveries from Stations 2 *and* 3.

Recovery.	Mid-date of Drift-Period. Day/Month.	Mean Rate of Drift, from Figure 47. Miles per Day.	Estimated Course in Miles.	No. of Circuits of Mid-East Scottish Eddy.
26_2	27/5	10·75	280	0
27_2	27–28/5	10·7	289	0
30_2	29/5	10·6	318	0
69_2	17–18/6	9·6	662	3
78_2	22/6	9·4	733	3
$2(31_3)$*	29–30/5	10·6	329	1
69_3	17–18/6	9·6	662	3

* i.e. two recoveries, each of 31 days' drift-period.

The Schleswig-Holstein Recoveries.—The two returns recorded against Station 4 are unique among the month's results. As regards their times and places of recovery, however, they are associated with similar records from certain June and July liberations, and in reference to these it will be demonstrated that recovery on the lower west Danish and Schleswig-Holstein coasts appears to have been a consequence of the bottles concerned having passed through the South-West Dogger Bank Eddy. That the two May bottles did likewise is practically obvious. Both are reckoned to have entered the swirl at Q on 10th June, having run a course to that point of 290 miles at a speed of about 10·7 miles per day. By measurement and calculation in the usual way, i.e. with reference to Figure 47, the earlier bottle appears to have left the eddy at Q on 28th October, and the later one on 18th November. One hundred and forty and one hundred and sixty-one days respectively are thus to be considered as having been spent under eddy influence. By the analysis of the June and July records, these times are almost exactly the periods which would be required to complete seven and eight circuits respectively of the South-West Dogger complex, in respect of which a Period of Circuit of 20 days seems characteristic. Incidentally, in this connexion, it may be noted that the difference between the recorded drift-periods of the two May recoveries, which were effected very near to each other, is 19 days.

Two Short-Period Norwegian Coast Recoveries.—Other two singular May records are the 25_{10} and 23_{23} returns. Neither can be accepted as the result of a direct passage from liberation-station to stranding-place on account of the very low rates of drift which are thereby entailed. The most feasible route for the 23-day bottle is that given on Figure 39. This complies with an estimated mileage of 233, accomplished in the time given at an average speed of 10·15 miles per day.

In the region of Station 10, i.e. off Stavanger, Böhnecke (**1**) has shown that, occasionally, a small counter-clock eddy may function. As will be evident later there is further reason for accepting this as the explanation of the 25-day drift-period registered by the only Station 10 bottle to be subsequently recovered. The distance from liberation-station to stranding-place is only about 60 miles. Actually, 266 miles are estimated to have been overtaken at a mean speed of 10·65 miles per day.

The Shetland Recoveries.—These, as pointed out on page 18, constitute one of the

main features of the month's results, recalling the like records of May 1910, as also the fact that, despite equally widespread liberations in May 1911, similar results did not ensue. The following table gives, to within 15 or 16 days, the time-frequency of the 1912 recoveries with reference also to the liberation-stations involved.

TABLE XLVIII.

MAY 1912 *LIBERATIONS.*

Time-Frequency of Shetland Recoveries.

Station No.	Period of Recovery.						
	June		July		August		Sept.
	1–15	16–30	1–15	16–31	1–15	16–31	1–15
20	2	—	—	1	—	—	1
21	—	1	1	1	—	—	—
22	—	—	—	—	1	—	—
24	—	—	—	—	1	1	—
25	—	—	—	—	—	—	1
27	—	—	—	—	—	—	1
Totals	2	1	1	2	2	1	3

In contradistinction to the corresponding data for May 1910, the May 1912 records contain no Orkney return, and no secondary winter group of recoveries occurs in Table XLVIII analogous to that in Table XVIII. In both respects the analogy between the two years is to some extent sustained if the results from the first eleven series of the June 1912 liberations are included with those of the previous month, and since these June experiments, begun on the first three days of the month, are almost the exact counterpart of certain of the later May 1910 operations, their results may be held to be comparable on a preliminary comprehensive principle. This, however, is as far as the analogy may be carried, for a closer examination of the 1912 records in question, of their sources, stranding-places and drift-periods, is indicative of events which, while probably not exclusive to the period under review, lead to a differentiation between the May and June results.

Those of the May 1912 stations from which Shetland recoveries originated were much less widespread than was the case two years before. The Faroe-Shetland Channel area is represented in Table XLVIII by only two stations, the single return from each of which came from the west side of Shetland. A feature of the 1910 results was that even Faroe-Shetland Channel stations yielded recoveries on the eastern, or North Sea shores of the islands, where in fact, the ten remaining 1912 bottles were found. These were liberated just outwith the North Sea, between latitudes 61° N. and 62° N. and longitudes 0° and 4° E., almost within the narrower longitudinal limits of 1° E. and 3° E. They include two recoveries, both belonging to Station 20, for which the relatively short drift-periods of 16 and 19 days are recorded. In view of previous findings concerning the direction of the surface drift in the southern Norwegian Sea bordering upon the Continental Shelf, it is unlikely that even these short-period bottles proceeded at once and finally towards Shetland. Moreover, an assumption to this effect implies average daily speeds of only between four and five miles per day, the reality of which, for the time of year and the region

involved, there is now sufficient reason to doubt. The shortest-period June record, referred to on page 14 and which falls within the period of these earliest May returns, gives further reason for disclaiming such low estimate.

The drift-periods of the later east Shetland returns are markedly in excess of those of the two quickest bottles, pointing to some fundamental difference in the histories of the two sets of recoveries. A similar classification was evident among the corresponding records for 1910, and on Figure 9 the cause of this division is graphically indicated. Another point of affinity between these May records of 1910 and 1912 is the fact of east Shetland strandings having resulted from liberations made within 60 miles of the Norwegian coast, i.e. from just eastward of longitude 3° E., and further, the two sets of drift-periods are of the same order. In short, the analogy between the two years appears to be so close that similar hydrodynamical conditions in the surface of the north-western part of the North Sea during the summers of both years might reasonably be inferred. It is the case, however, that a satisfactory cartographical interpretation of the 1912 data on the basis of this inference is impracticable, and the reason therefor is doubtless given by the following considerations.

The east Shetland returns from the May 1912 liberations belonged to Stations 20, 21, 22 and 24, from none of which resulted any other type of British recovery. Also, in the interval embraced by some of the drift-periods, further liberations were carried out in the region between Fair Isle and the Moray Firth and, except for foreign recoveries, only Scottish east coast and Orkney returns ensued from these liberations, none in or near Shetland. The two sets of experiments are then, by their results, distinct. Accordingly, the interpretation of the east Shetland recoveries is that the bottles concerned remained in the Shetland neighbourhood until they were beached. This interpretation, with the aid of the velocity-curve as finally adjusted, is given effect in Figure 39, where the courses of the several drifters are to be followed by the sequence of the small Roman numerals attached to each drift-period, the latter being repeated at intervals along the appropriate curve. The following table contains the data from which these curves were constructed.

TABLE XLIX.

MAY 1912 *LIBERATIONS.*

Data pertaining to East Shetland Recoveries.

Recovery.	Mid-date of Drift-Period. Day/Month.	Mean Drift-Speed from Fig. 47. Miles per day.	Estimated Course in Miles.
16_{20}	2/6	10·4	166
19_{20}	3–4/6	10·3	196
35_{21}	12–13/6	9·85	345
44_{21}	17/6	9·6	422
58_{21}	24/6	9·3	539
65_{20}	26–27/6	9·2	598
73_{24}	1–2/7	9·0	657
76_{22}	3/7	8·9	676
86_{24}	8/7	8·7	748
99_{20}	13–14/7	8·5	842

Although the final stage of every course is assumed to have been northward along the eastern shores of Shetland, courses passing finally northward to the west of Shetland, and involving no change in the respective mileages as given in the above table, can be postulated for the two longest-period recoveries. Courses finishing thus, after complications in the east Shetland area, appear to be the most reasonable ones to advance in respect of the two definitely west Shetland strandings from Stations 25 and 27 respectively, for the bottles in question almost certainly passed into the North Sea as indicated on Figure 39, and it may be taken from the November analysis (Figure 44), alongside the foregoing interpretation of some of the May results, that the eddy in east Shetland waters established by the latter probably persisted throughout the intervening period.

The Skagerak Recoveries.—It will be observed from Figure 39 that the Great Eddy obviously influenced the above May bottles in shaping their courses into east Shetland waters. The existence of the Great Eddy at this time is deduced from certain aspects of the Skagerak returns from the month's liberations. These returns have already been mentioned on account of their numerical strength relative to the recoveries in other districts. Table L gives their time-frequency with reference also to the liberation-stations involved, the recovery belonging to Station 16 being omitted from the table on account of its extraordinarily long drift-period of 2,217 days.

TABLE L.

MAY 1912 *LIBERATIONS.*

Time-Frequency of Skagerak Recoveries.

Station No.	Period of Recovery.											
	1912 Oct.	Nov.		Dec.		1913 Jan.		Feb.		March.		Apr.
	15th	1–15	16–30	1–15	16–31	1–15	16–31	1–14	15–28	1–15	16–31	1–15
5	—	—	—	—	1	—	—	—	—	—	—	—
6	—	—	—	—	—	—	—	—	—	1	—	—
8	—	—	—	—	—	—	—	—	—	—	—	1
11	1*	—	—	—	—	—	—	—	—	—	—	—
12	—	—	—	—	2	—	—	—	—	—	—	—
13	—	—	—	—	—	—	—	—	—	—	1*	—
14	—	—	—	—	—	—	—	—	—	1	—	—
15	—	—	1	1*	1	—	—	—	—	1	—	—
21	—	—	—	—	1	—	—	—	—	—	—	—
24	—	—	—	—	2	—	—	—	—	—	—	—
Totals	1	—	1	1	7	—	—	—	—	3	1	1

* Two of these bottles stranded a few miles to the south of Hanstholm and the third a little to the west of Lindesnaes. They are not therefore included among the true Skagerak recoveries of Table XLVI, page 12.

The obvious feature of Table L is the division of the entries into two groups. Reference to the records themselves shows that, except for the shortest-period return which belonged to Station 11, nine drifters were found in the month between 27th November and 27th December 1912, while the remaining five returns were similarly concentrated between 7th March and 7th April 1913. Investigation as to

the probable cause of this division reveals the fact that, with one exception, the liberation-stations involved also fall into two groups, corresponding with the above division of the recoveries. The earlier group of returns is associated with Stations 5, 11, 12, 15, 21 and 24, and the later group with Stations 6, 8, 13, 14 and again Station 15.

Referring these matters to a chart such as Figure 15, for instance, which applies to the second quarter of 1910, it is evident that the explanation lies in the positions of the liberation-stations in relation to the Great Eddy, those of the first group being situated without, on, or near to its boundary, while those of the second group, with the exception of Station 15, were definitely within the closed circulation. The position of Station 15 would appear to have been almost exactly on the eddy periphery.

The only difficulty in regard to this explanation arises in connexion with the positions, relative to each other and to the Great Eddy boundary, of Stations 8 and 12, which belong to the second and first groups respectively. The difficulty, however, appears to be solved as a result of the interpretation given to the 25_{10} recovery. The significance of a small eddy off Stavanger in relation to the Great Eddy would probably be to cause an indentation in the adjacent periphery of the latter, as shown on Figure 39. This brings Station 12 considerably nearer to the boundary influence of the Great Eddy than Station 8.

In short, then, the foregoing classification of the Skagerak returns which follows from the wide difference to be observed between the collective drift-periods of two well-marked groups of recoveries is to be attributed to a difference in the times spent by the drifters under the influence of the Great Eddy, these times depending upon the positions of the several liberation-stations relative to the eddy boundary.

Further insight into the histories of these May bottles to the Skagerak is afforded by the following considerations.

Comparison of the results from Stations 3, 4, 5 and 6 leads to the conclusion that, from Station 5, which yielded only a Skagerak recovery of the earlier group, the bottle in question proceeded at once into the Middle North Sea area ; in other words, it did not become involved within the Great Eddy. This latter condition may be taken to apply also to the remaining recoveries of the earlier group, i.e. to those emanating from Stations 12, 15, 21 and 24, and especially to the shortest-period Skagerak recovery of all, namely, that which originated at Station 11. As regards this particular bottle, a direct or almost direct course is out of the question, in view not only of the proximity of Station 11 to the Great Eddy boundary and to the Stavanger Eddy, but also because of the complications which undoubtedly operated off the entrance to the Skagerak, restricting the passage of drifters into that region until towards the end of the year. The Station 11 drifter to the neighbourhood of Hanstholm on the north-west corner of Jutland was almost certainly carried round on the outside of the periphery of the Great Eddy through the positions, approximately, of Stations 15 and 5, and the same no doubt happened to the Skagerak drifters from Stations 21 and 24 and to the earlier one from Station 12, after it had, somewhere on the northern boundary of the system, passed to the outside of the periphery as indicated on Figure 39. In short, none of these earlier Skagerak bottles is reckoned to have made a complete circuit of the Great Eddy.

The Station 5 bottle above mentioned was not even the second of the May drifters to reach the Skagerak, but at least the fourth, being preceded, in addition to the shortest-period bottle, by two drifters from Station 15, and accompanied, more or less, on the latter stages of its course, by one bottle from Station 12 and another from Station 24. The cause of these irregularities is almost certainly to be attributed to the influence of the North-East Dogger Bank Eddy, through which, apparently, all drifters to the Skagerak are liable to pass.

On account of the changes which, according to the analyses of the June and subsequent records, took place in regard to the form and situation of the North-

East Dogger complex during the period when these May bottles would be under its influence, it is almost impracticable, without a multiplicity of diagrams capable of superposition one upon another, to give a complete and satisfactory cartographical representation of the course of every bottle, even of the shorter-period recovery group. As illustrating sufficiently the complications encountered in the North-East Dogger-Lindesnaes region, only that for the 150_{11} recovery is entered on Figure 39. Consider this course. Its initial peculiarity is conditioned by the position of Station 11 relative to the Stavanger Eddy and to the Great Eddy boundary. Again, by reference to and calculation from Figure 47, the bottle in question is estimated to have reached the point **A** on 23rd July, which is the date determined from a particularly favourable June record as that of the coalescence of the Lindesnaes and North-East Dogger Eddies in 1912. The fact that the May bottle was in such a position when coalescence occurred probably accounts, in some way, for its markedly shorter drift-period in relation to the other bottles of the group, for it can be argued that none of these was so favourably situated, when coalescence took place, as to maintain a cruising position on the boundary of the resultant system conducive to its early delivery therefrom. These other bottles, all of which evidently entered the original North-East Dogger Eddy in advance of the Station 11 drifter, are estimated to have been situated at some distance from the region of coalescence when this event took place. Its immediate effect upon the drifters may therefore conceivably have been to attract them somewhat towards the interior of the system during the actual process of coalescence, the attraction deteriorating as the resultant circulation achieved a measure of stability.

The former and the latter sections of the courses of the other Skagerak bottles belonging to the earlier group are shown, or indicated, on Figure 39, and Table LI furnishes the details of the complete routes overtaken.

TABLE LI.

MAY 1912 *LIBERATIONS.*

Analytical Details of Earlier Group of Skagerak Recoveries.

Recovery.	Mid-date of Drift-Period. Day/Month.	Mean Drift-Speed from Figure 47. Miles per day.	Estimated Course in Miles.	No. of Circuits of Original N.E. Dogger Eddy.	No. of Circuits of Resultant N.E. Dogger Eddy.
217_{5}	31/8–1/9	7·35	1,595	2	2
192_{15}	23/8	7·45	1,430	2	2
203_{15}	28–29/8	7·38	1,498	2	3
215_{15}	3–4/9	7·33	1,576	2	3
205_{24}	5–6/9	7·33	1,503	1	2
210_{24}	8/9	7·33	1,539	1	3
215_{21}	10–11/9	7·33	1,576	1	2
212_{12}	1/9	7·35	1,558	1	2
223_{12}	6–7/9	7·33	1,635	1	2

Although in all cases it has been found possible to construct courses to the above specification, which are consistent with one another in the Dogger Bank-Lindesnaes area, this does not mean that the circuits, either of the original or of the resultant North-East Dogger Bank Eddy, were all of the same dimension. Depending upon the position of the drifter at coalescence the last circuit of the original system and the first of the new circulation were more or less deformed.

As already suggested, the division of the Skagerak recoveries from the May liberations into two groups is to be ascribed to the different times spent by the drifters concerned in the region of the Great Eddy. The bottles of the earlier group, as demonstrated above, were apparently influenced by the gyration only so far as to guide them more or less immediately into the southerly drift along the western boundary of the system and heading into the Middle North Sea area. On the other hand, the positions of all save one of the liberation-stations from which the second group of bottles originated clearly indicate that at least one and probably more than one circuit of the Great Eddy was accomplished by these drifters before they passed into the Middle North Sea and towards the North-East Dogger Swirl, through which, by inference from contemporaneous Skagerak recoveries from the liberations of other months (see Table XLVI), these later May bottles must also be assumed to have drifted. Again, by the analyses of the 92_7 September record (see Figure 43), and unless the conditions represented by the curves on Figure 44 held only for a limited period (until perhaps towards the end of the year), the southward passage of the May drifters from the Great Eddy region in the Middle North Sea must have taken place before the beginning of November.

Proceeding on this assumption, the histories of the five bottles concerned are estimated to have been somewhat as follows. The main sections of the courses—all in fact, except north-east Dogger gyrations—are entered on Figure 39. All five bottles are considered to have withdrawn from the dominant influence of the Great Eddy at the point **B**, which is the position of Station 15, and to have drifted thereafter along the curve connecting **B** with **P**, the bottom dead-centre, as it were, of the North-East Dogger Bank Eddy.

TABLE LII.

MAY 1912 *LIBERATIONS.*

Analysis of the Later Group of Skagerak Recoveries.

Recovery.	Complete Course* estimated from Fig. 47. Miles.	Great Eddy Course to **B.** Miles.	Date of Withdrawal from **B.** Day/Month.	Measured Course from **B** to **P.** Miles.	Date of Arrival at **P.** Day/Month.	Measured Course from **P** to Stranding-Place. Miles.	N.E. Dogger Eddy Course. Miles.	No. of Circuits of N.E. Dogger Eddy.
300_6	2,280	850	18/8	355	6/10	445	630	3
327_8	2,615	1,090	24/9	355	9/11	540	630	3
303_{13}	2,335	840	21/8	355	8/10	510	630	3
292_{14}	2,220	845	23/8	355	10/10	390	630	3
297_{15}	2,270	1,040	18/9	355	4/11	455	420	2

* To the nearest five miles.

As is evident from Figure 39, irregular complications in the routes of the later May bottles to the Skagerak—considering the group as a whole—occurred in the Great Eddy area, and not, as in the case of the earlier recovery group, in the region of the North-East Dogger complex, which, by the time these later May bottles came under its influence, had apparently assumed, under stable conditions, its southmost position for the time being. This part of the foregoing analysis, as will be seen later, is in agreement with the findings from other records for the year.

The Remaining Norwegian Recoveries.—To conclude this survey of the month's results, reference may be made to at least the nearer, longer-period, Norwegian coast recoveries outwith the Skagerak. The two shortest-period returns, the 25_{10} and 23_{23} records, have already been dealt with.

On the same day, 25th November 1912, two May drifters of different origin were found almost at the same place in latitude 61° 34′ N. These are the 191_{11} and 190_{14} recoveries.

Take first the 190_{14} bottle. It is reasonable to suppose that this drifter emerged from the Great Eddy at **B** along with its Skagerak fellow, having travelled, by Table LII, 845 miles to this point. Thereafter, in order to meet the condition of a total mileage of 1415, accomplished at an average rate of 7·45 miles per day, the bottle is considered to have passed across the Middle North Sea and into the Norwegian coast current as indicated by the appropriate curve on Figure 39.

The Station 11 bottle, to satisfy a course of about 1,425 miles overtaken at the same rate as the above, would appear to have made a complete circuit of the Great Eddy, before, on its second circuit, emerging therefrom at **B**, to cross the Middle North Sea as shown on the chart. Then, a circuit of the Stavanger Eddy, as outlined on Figure 40, was evidently accomplished before the drifter proceeded finally northwards to its stranding-place. The composition of the full course works out thus :— to **B**, 750 miles ; thence to stranding-place exclusive of Stavanger Eddy circuit, 535 miles ; Stavanger circulation, 140 miles.

This allocation to the Stavanger Eddy is supported by the following analyses.

From the interior of the Great Eddy, namely, from Station 6, came one of a group of four May bottles, picked up on, or near, the island of Smölen. Assuming again that this bottle withdrew from the Great Eddy at **B** along with a companion drifter which ultimately found the Skagerak, and giving the Norway bottle a course through the Middle North Sea identical with that of the 190_{14} drifter, 850 (to **B**)+770 miles of its estimated course of 1,760 miles are thus accounted for, leaving 140 miles to be explained, as in the case of the Station 11 drifter, by a single circumnavigation of the Stavanger Eddy.

Likewise, in the case of the 139_{18} recovery, which took place at sea while the bottle was still afloat, the course given on Figure 39, passing along the western boundary of the Great Eddy, is short of the calculated course of 1,090 miles by the amount (140 miles) which may be taken as having been the measure of the periphery of the Stavanger Swirl.

The 163_{25} drifter also seems to have passed into the Middle North Sea by way of the Great Eddy boundary. Its estimated course of 1,220 miles is shown on the chart, save for 280 miles to be assigned to two circuits of the Stavanger complex.

Lastly, of those returns which can conveniently be considered now, the 177_{19} drifter appears to have included three Stavanger gyrations in its full run of nearly 1,320 miles, completed in the time given at a mean rate of 7·45 miles per day.

* * * * * * *

June Liberations.

The first three days of June 1912 were occupied in the completion of a cruise to Faroe begun from Lerwick, Shetland, on 30th May. On the return passage, 56 drifters were liberated in groups of eight from seven points on a line from Suderö, Faroe, to Fair Isle, between Shetland and Orkney. Eleven of these bottles were subsequently recovered, one on the west side of Shetland, three among the Orkney Islands, and the remainder on the Norwegian coast north of latitude 62° 30′ N. Except for two of the Orkney recoveries, found after 21 and 31 days respectively, the drift-periods in all cases were considerably over 100 days.

The only return from liberations at Station 1 came from Finmark, after more

than a year. On this account, the particular analysis of the record is scarcely practicable. Something, however, may be said, in the light of other results, regarding the route which was in all probability followed by this bottle. The liberation-station was situated only a few miles south of Suderö, and by inference from certain May results embracing this region (see Figure 39), it can be accepted that these first

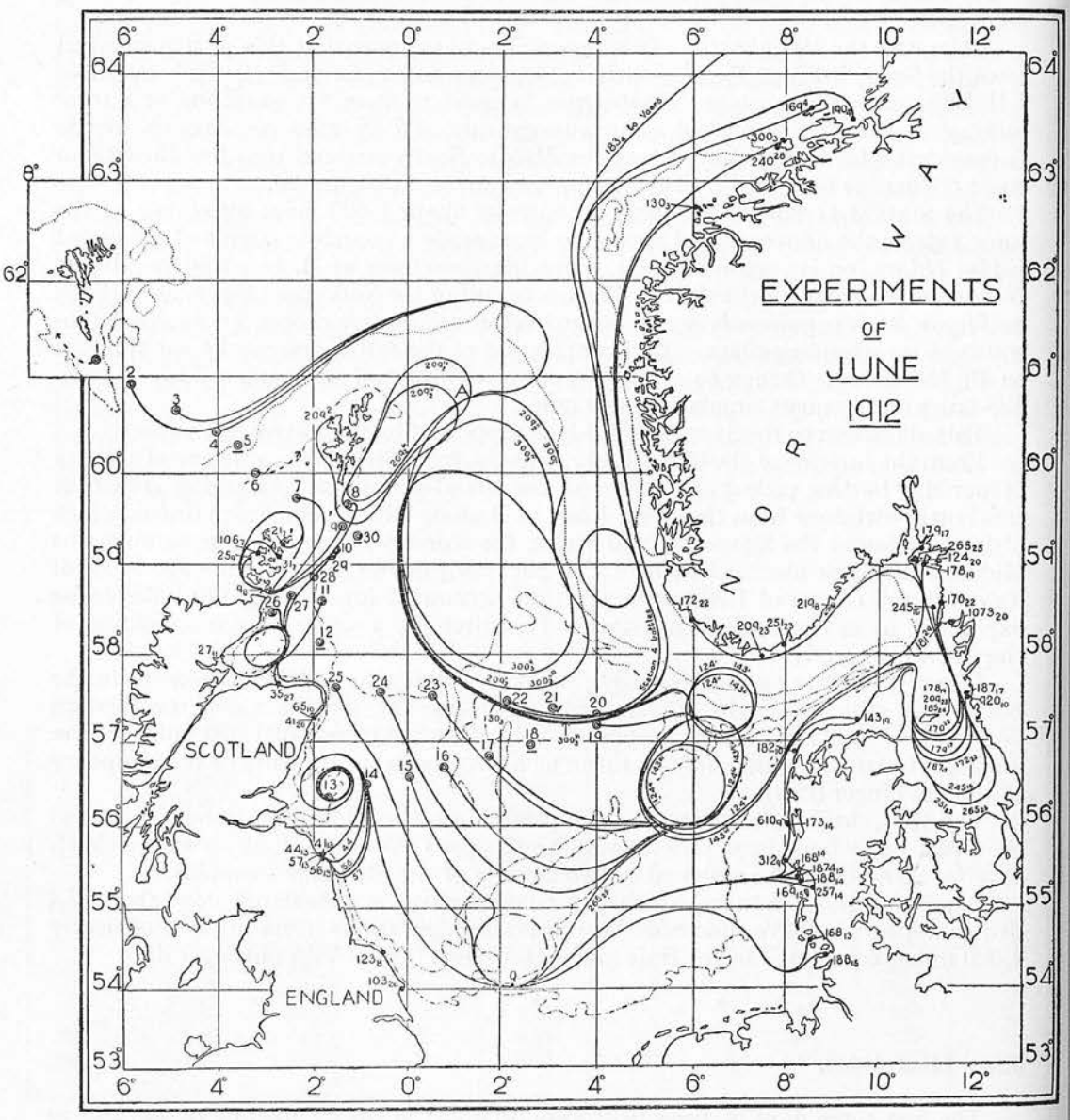


FIG. 40.

June bottles set off westwards and then almost immediately north past Faroe. Thereafter, in the case of the recovered bottle at least, it can be taken as having drifted by way of the north of Faroe into and across the Faroe-Shetland Channel, and thence into the Northern North Sea ; for, despite the lack of direct evidence from the records themselves of bottles from the Faroe-Shetland Channel region in 1912 having entered and cruised for a time within the North Sea, the cartographical

analysis of the above northerly Norwegian recoveries, as well as of some of the May records, strongly supports the assumption, which, moreover, is in conformity with the findings for the corresponding periods of the previous two years. The reason why no 1912 bottle of Faroe-Shetland Channel origin ultimately beached on North Sea or Skagerak shores is probably that, entering the North Sea almost midway between Shetland and Norway, they were retained in the more open waters of the Northern Area until they succeeded in passing into the northerly-flowing current along the Norwegian coast.

Evidence in support of this argument is contained in the cartographical interpretation of the single recovery pertaining to Station 2. This drifter is reckoned to have attained the western mainland of Shetland only after considerable complications in the Northern North Sea, making a total run of about 1,530 miles at an average rate of $7\frac{1}{3}$ miles per day. A circuit of the Great Northern North Sea Eddy was apparently completed before the bottle passed into the elongated circulatory system in east Shetland waters established by the analysis of a group of May results and which, from these records and certain results from the November Station 3, would appear to have been operative for the greater part of the year. Entry into, and escape from, the dominant influence of the Great Eddy are considered as having taken place in the region of **A**, the former event, by measurement and calculation, about the 9th or 10th of July, and the latter towards the middle of September. In the interval, there is reason to suppose that the position of the Great Eddy did not alter very appreciably from that which is assigned to it as a result of the analysis of a number of the May 1912 results and which is defined on Figure 40 by a part of the course laid down for the 209_2 recovery. After mid-September, however, the trend of the velocity-curve (Figure 47) can be interpreted as signifying an increase in the intensity of the southerly impulse into the North Sea, which would tend to displace the northern boundary, at all events, of the Great Eddy. A similar effect on the east Shetland system as a whole is illustrated by the curve which represents the course of the 209-day June drifter in these waters.

The earlier Station 3 recovery, i.e. the 130-day return from Haram, Norway, admits of the following simple explanation. Passing into the **A** region of the Great Eddy boundary, this particular drifter appears, nevertheless, to have remained outwith the circulation proper, gradually, as it progressed into the North Sea, sheering off from the periphery of the system until it passed into the Norwegian coast current and so to its stranding-place. One thousand and fourteen miles appear thus to have been accomplished at an average daily rate of about 7·8 miles.

The course of the 300_3 recovery, which is reckoned on the basis of a mean drift-speed of 8·1 miles per day to have been about 2,430 miles, was certainly more complicated, and in view of the non-recovery of any 1912 Faroe-Shetland Channel bottle within North Sea limits, all complications in the routes of those which ultimately stranded in northern Norway must be considered to have been confined more or less to the Great Eddy region. The course of the above drifter is entered in full on Figure 40 and can be followed by the sequence of the small Roman numerals attached to the drift-period 300.

The Station 4 drifters do not appear to have become involved in the Great Eddy to the extent of making a complete circuit of it, but, like the shorter-period Station 3 return, with which two of the Station 4 bottles are in some measure associated from the point of view of their stranding-places, the latter evidently passed from the western boundary region of the Great Eddy over towards, and into, the Norwegian coast current. Some complications, however, in the route of the third recovery at least, is indicated by its drift-period in relation to those of the other two. This probably occurred in the region of Stavanger. The 169-day bottle is estimated to have travelled once round the Stavanger Eddy, and the 190-day drifter, twice, in addition to the progressive routes given on Figure 40, in order to satisfy calculated mileages of 1,254 and 1,396 respectively. The 183-day bottle to the Lofoten Islands,

on the other hand, appears to have avoided circulating within the Stavanger Eddy, running 925 miles to latitude 62° N. at about longitude 3° 30′ E., and thereafter 420 miles on a direct passage to Vaerö, Lofoten, thus covering the total distance of 1,345 miles calculated on the basis of an over-all mean drift-speed of 7·35 miles per day.

The 770-day recovery recorded against Station 6 need not be discussed.

All three Station 7 recoveries took place in the Orkney Islands, and for this reason they are associated with other two returns, one each in respect of liberations at Stations 8 and 9 to the eastward of the Shetland-Orkney passages. The quickest (9-day) Orkney recovery belonged to Station 8. In the time given the drifter in question is estimated to have travelled 91 miles to the east coast of South Ronaldshay, as shown on Figure 40. The point **D′** on Figure 47, which was derived from this record, is thus translated to the position **D**. The Station 9 recovery was effected after 25 days on the *west* side of the Orkney mainland. To complete the calculated course of 242 miles, this drifter evidently circumnavigated the entire Orkney group before passing for the second time westwards through the Pentland Firth and so to its stranding-place at Marwick Head.

The latter course especially gives the clue to the interpretation of the two shorter-period Station 7 returns, in respect of which mean daily rates of drift of 9·85 and 9·6 miles are read from Figure 47. These entail routes of 207 and nearly 298 miles respectively, which are represented by the appropriate curves about the Orkney Islands on Figure 40.

The third Orkney recovery resulting from the Station 7 liberations did not take place until the 16th of September, after 106 days' drifting presumably. It seems fairly certain on the evidence available that this drifter, to cover 860 miles at an average rate of 8·1 miles per day, encircled the Orkney Islands three times, passed southwards into the Moray Firth, and after two complete circuits of the Moray Firth Eddy, emerged therefrom on the third circuit, to return to the west Orkney region by way of the Pentland Firth. In addition to the foregoing records which demonstrate the clockwise circulation round Orkney, other results favouring the above interpretation of the 106-day return are (1) the Moray Firth and mid-east Scottish coast returns from the June liberations at Stations 10, 11, 26 and 27, which indicate the continuance of the Moray Firth Eddy until the end of July at least—probably longer—and (2) the singular recovery from the September Station 8, which suggests still the influence, although perhaps somewhat modified, of the Moray Firth Eddy, besides furnishing direct evidence of a drift from the Moray Firth region and through the Pentland Firth in the month of September.

The above-mentioned recoveries pertaining to Stations 10, 11, 26 and 27 may next be detailed. The several courses, as entered or indicated on Figure 40, are explained by reference to the following table.

TABLE LIII.

JUNE LIBERATIONS.

Analysis of Scottish Coast Recoveries from Stations 10, 11, 26 *and* 27.

Recovery.	Mid-date of Drift-Period. Day/Month.	Mean Drift-Speed from Figure 47. Miles per Day.	Estimated Course in Miles.	No. of Eddy Circuits.
27_{11}	16–17/6	9·65	260	2
35_{27}	5–6/7	8·82	309	3
41_{26}	8–9/7	8·70	357	3
65_{10}	5–6/7	8·82	573	5

Since the actual representation on Figure 40 of the probable histories of the remaining recoveries listed against Stations 8 to 11 and 26 to 29, in the north-western North Sea, would tend only to confuse the chart and would answer no useful purpose beyond that which is already served by the various curves entered thereon, the reader is asked to accept that in all cases, except those for which inordinately long drift-periods are recorded, satisfactory courses, involving sometimes alternative sites where complications intervened, can indeed be made out cartographically in accordance with the principles laid down to govern these analyses. The recoveries in question, tentative explanations of which can readily be devised by the reader from the structure of Figure 40 in its submitted form, include two returns from the Yorkshire coast, England, one from the west Danish coast south of latitude 56° N., three from the Skagerak-Kattegat region or thereby, and one from the Norwegian island of Smölen in latitude 63° 22′ N.

We pass now to the results of liberations carried out between the 12th and 15th of June from Stations 13 to 25 inclusive, which were disposed along two lines converging on the Great Fisher Bank from Fife Ness and Buchan Ness respectively. Out of the 104 bottles liberated, 25 were subsequently recovered in the Skagerak area, 8 on the lower west Danish coast and 4 on the Northumberland coast, England.

The last-mentioned belonged to Station 13 in the mid-east Scottish area. The particulars of their cartographical interpretation are as follows :—

TABLE LIV.

JUNE LIBERATIONS.

Analysis of Station 13 *Recoveries on Northumberland Coast.*

Recovery.	Mid-date of Drift-Period. Day/Month.	Mean Drift-Speed from Figure 47. Miles per day.	Estimated Course in Miles.
41_{13}	2–3/7	8·95	367
44_{13}	4/7	8·90	391
56_{13}	10/7	8·65	484
57_{13}	10–11/7	8·63	492

The courses of the two earlier bottles are shown in full on Figure 40. In regard to the two later recoveries, one has to imagine an additional circuit in the interior of the Mid-East Scottish Coast Eddy before the drifters concerned finally escaped therefrom on the paths indicated by the appropriate curves.

Liberations at Station 13 resulted also in a recovery on the Schleswig-Holstein coast, thus linking this station's results with the entire return from Stations 14 and 15, and also, as already mentioned, with certain May and July records. In the analysis of the latter it will be shown that the South-West Dogger Bank Eddy apparently introduced a systematic complication into the bottles' courses. A similar state of affairs doubtless held in regard to the June bottles, which show a drift-period difference of 20 days in two instances and 19 days in a third. The inference is borne out by the following analysis of the June records.

TABLE LV.

JUNE LIBERATIONS.

Analysis of Lower West Danish and Schleswig-Holstein Coast Recoveries.

Recovery.	Measured Course to **Q**. Miles.	Mean Drift-Speed to **Q**. Miles per Day.	Date of Arrival at **Q**. Day/Month.	Measured Course from **Q**. Miles.	Mean Drift-Speed from **Q**. Miles per Day.	Date of Withdrawal from **Q**. Day/Month.	No. of Days in S.W. Dogger Eddy.	No. of Circuits of Eddy.
168_{13}	500	8·6	9/8	270	8·85	27/10	79	4
168_{14}	195	9·4	3/7	230	9·00	1/11	121	6
173_{14}	195	9·4	3/7	260	9·25	4/11	124	6
188_{14}	195	9·4	3/7	230	10·25	24/11	144	7
169_{15}	195	9·4	3/7	230	9·05	2/11	122	6
188_{15}	195	9·4	3/7	270	10·15	20/11	140	7

The course of the Station 13 bottle within the Mid-East Scottish Coast Eddy appears to have been that of all the other drifters from this station with the exception of the 57-day recovery. On emerging from the circulation, the 168-day drifter to Schleswig-Holstein may be considered to have followed the same route to the South-West Dogger Eddy at **Q** as the Station 14 bottles.

The final stages of the routes given on Figure 40 for the 168_{13} and 188_{15} bottles suggest that Wendicke's German Bay Swirl (**11**) was in operation when these recoveries were effected, but, according to this analysis, neither of the drifters referred to appears to have been absorbed in the circulation.

Two recoveries belonging to the group under consideration are omitted from the above table, one of them on account of its extraordinarily long drift-period of 1,874 days. In the other instance it is feasible to examine the record in some detail, although not in the same manner as those enumerated in Table LV.

The 257_{14} drifter found at Hviding, Schleswig, by reference to the velocity-curve at the mid-date of its drift-period, is calculated to have cruised, in all, nearly 2,000 miles at an average rate of $7\frac{3}{4}$ miles per day. To the South-West Dogger Swirl at **Q** the distance covered would, as in the cases of the other bottles from the same station, be 195 miles, and from **Q** to Hviding, by the route indicated on the chart, a further 240 miles are accounted for. This leaves 1,565 miles to be ascribed, presumably, to gyrations in the South-West Dogger Eddy. This figure represents, to within 10 miles, nine circuits of the system, which, as outlined on Figure 40, is of such dimensions that the 20-day Period of Circuit suggested by the analytical details of Table LV is consonant with the average drift-speed during the interval when the drifters concerned were involved in the circulation.

Coming now to the largest group of recoveries from the month's experiments, namely, the Skagerak recoveries, which are the only type of results recorded against Stations 16 to 25 inclusive, it is evident from the drift-periods, none of which was under 100 days, that a direct passage from liberation-station to stranding-place cannot, in a single instance, be assumed. The shortest-period returns are those in respect of Stations 19 and 20, which were situated nearest to the Skagerak entrance. The 124_{20} recovery, which took place in the Hvalöarne at the mouth of Oslofjord on 16th October 1912, was actually the first Skagerak recovery to ensue from the year's liberations, with the exception of a March bottle which stranded on Laesö Island in the Kattegat on 26th September.

Delay in the progress of the June drifters from the Middle North Sea area into the Skagerak is, of course, to be attributed to the influence of the North-East Dogger Bank Eddy. From the positions of Stations 19 and 20 relative to the outward region of modified influence of the Great Eddy circulation, however, it seems improbable that the drifters liberated at these two points passed at once into the North-East Dogger complex, supposing the same to have occupied even the most northerly position hitherto ascribed to it as a result of these investigations. It seems that conditions similar to those of the previous summer were in operation between Great Fisher Bank and the entrance to the Skagerak, during the passages of the drifters concerned. In short, the most satisfactory interpretation of the records in question depends upon the assumption of two eddy systems, the Lindesnaes Swirl and the North-East Dogger Eddy, which, about a certain time, came together and coalesced, the combined circulation thereafter moving gradually southwards towards the Tail End of the Dogger Bank.

Drifters from Stations 19 and 20 passed first of all into the Lindesnaes Eddy. The course of the 124_{20} bottle, calculated, on the basis of a mean drift-speed of 7·55 miles per day, to have been about 936 miles, is represented in full on Figure 40. Two circuits of the Lindesnaes Eddy appear to have been accomplished before this system amalgamated with the North-East Dogger Swirl, after nearly 360 miles of the above drifter's course had been run. This means that coalescence of the two systems took place about the 24th of July.

The 143_{19} drifter is estimated to have attained the Lindesnaes circulation a day or two in advance of the Station 20 bottle, and to account for its total course of 1,065 miles, overtaken at a mean speed of 7·45 miles per day, an additional circuit of the resultant eddy, after coalescence, is assumed, as indicated on the chart. Amalgamation of the two systems in this case works out as having taken place on 23rd July.

For the 178_{19} recovery, the course determined, by calculation, is 1,305 miles, and it is at once evident that the difference of 240 miles between this and the distance covered by the 143_{19} drifter can be absorbed by assuming deviation into the Kattegat in respect of the later recovery, an assumption for which there is sufficient justification throughout the 1912 analysis.

Again, however, it has to be submitted that full representation on Figure 40 of the courses estimated for the remaining Skagerak bottles from the Stations under consideration is almost impracticable on account of the confusion which would thereby ensue in the region of the Lindesnaes and North-East Dogger Eddies, and it seems unnecessary for the purpose of this report merely to multiply the diagrams with the sole object of rendering the complete course for each drifter. To do so would only be to substantiate much that is more conveniently demonstrated elsewhere in these pages. Beginning and ending as shown on Figure 40, complete courses can, in fact, be made out to the following specification and conforming to the rules of consistency observed throughout.

[TABLE LVI.

TABLE LVI.

JUNE LIBERATIONS.

Analysis of Skagerak Recoveries from Stations 16, 17, 22, 23 *and* 24.

Recovery.	Estimated Course in Miles.	No. of Circuits of original N.E. Dogger Eddy.	No. of Circuits of original Lindesnaes Eddy.	No. of Circuits of Resultant Eddy after Coalescence.
179_{17}	1,312	1	—	2
187_{17}	1,373	1	—	3
245_{16}	1,870	1	—	4
170_{22}	1,246	—	1	2
172_{22}	1,260	—	1	1
209_{23}	1,547	1	—	3
251_{23}	1,945	1	—	4
185_{24}	1,356	—	—	3

The only record which has not been dealt with above is the 265_{25} recovery in the Hvalöarne, Norway. It is difficult to conceive how this bottle can have avoided passing through, or at least partly round, the South-West Dogger Swirl, and on this latter assumption the record is in fact soluble, the bottle in question being considered to have circulated five times round the resultant North-East Dogger Bank Eddy in a total run of 2,120 miles overtaken at the average rate of eight miles per day.

* * * * * * *

July Liberations.

Liberations during July 1912 were confined to a few days early in the month. From the 5th to the 9th inclusive, 54 bottles were set adrift from seven points in the mid-east Scottish area, and a further 20 bottles from a station in the Moray Firth.

Three of the eight series of liberations produced no result. British coast returns are recorded against only two stations, Station 1 in mid-east Scottish waters and Station 6 in the Moray Firth. Of the eight remaining recoveries, six were concentrated between latitudes 55° N. and 56° N. on the west Danish coast, one took place at the entrance to Oslofjord, and another in the region of Stavanger.

The Moray Firth Eddy, established from previous years' analyses, doubtless affected the bottles set adrift at Station 6, as can be inferred from the drift-periods, 15 and 26 days, of the two recoveries effected near Lossiemouth on the south shore of the Firth. With reference to the velocity-curve, which gives values of 8·45 and 8·25 miles per day for the mean drift-speeds of the two bottles concerned, courses of 127 and 215 miles respectively are estimated ; by which it can be shown, cartographically, that the longer-period bottle completed a circuit of the eddy before traversing the same route as its shorter-period fellow.

The Skagerak recovery pertaining to Station 6 is probably connected with certain September records of which a detailed analysis is given later. It is not therefore treated here, nor again the west Danish coast return on account of the magnitude of its drift-period, which extends to over a year.

The interpretation of the five results from Station 1 may readily be followed from the chart, Figure 41, in conjunction with the following table. The Mid-East Scottish Coast Eddy was, of course, involved.

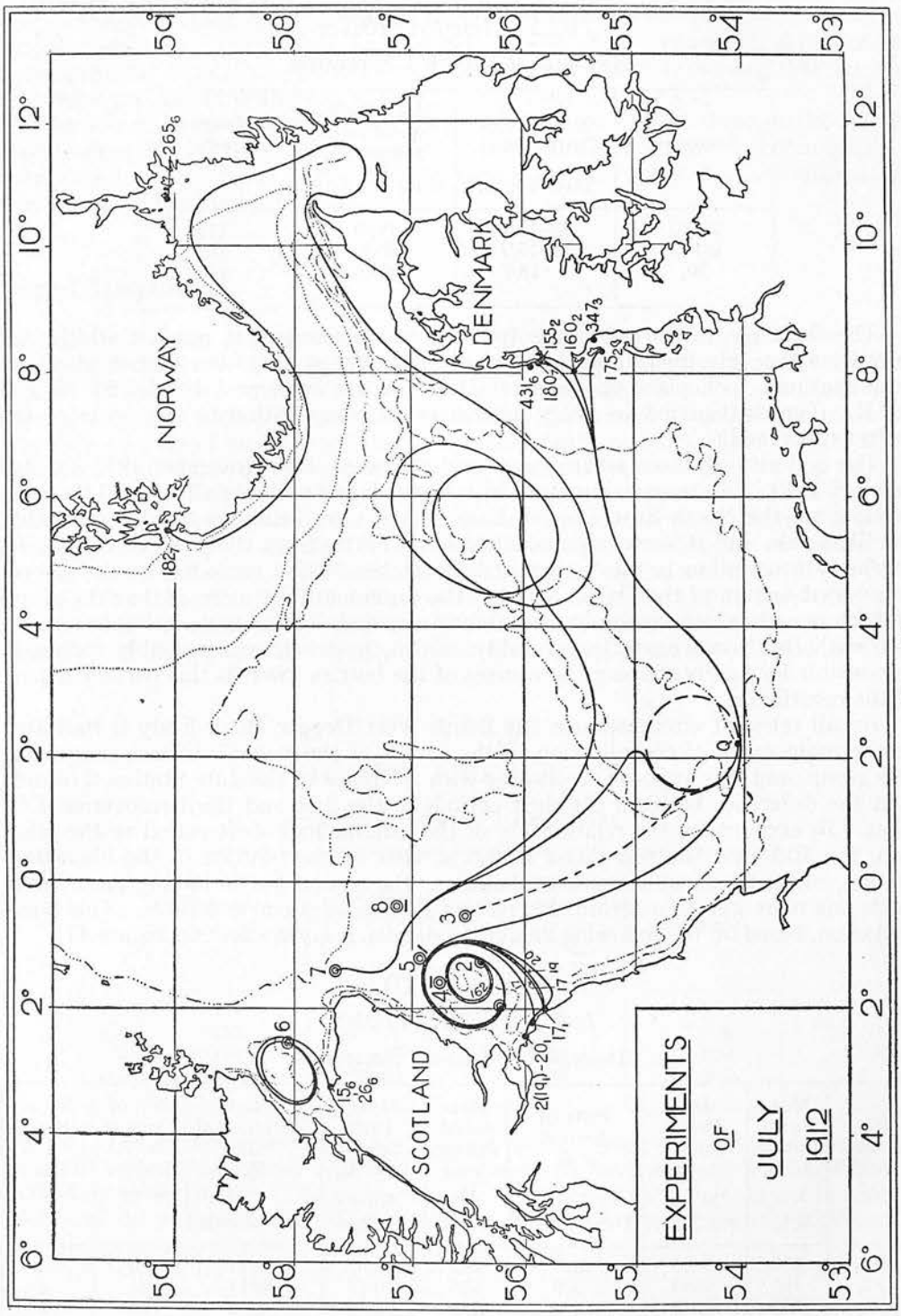


FIG. 41.

TABLE LVII.

JULY LIBERATIONS.

Analysis of Station 1 *Recoveries.*

Recovery.	Mid-date of Drift-Period. Day/Month.	Mean Drift-Speed from Figure 47. Miles per Day.	Mileage of Course.
$2(17_1)$	13–14/7	8·50	145
$2(19_1)$	14–15/7	8·50	162
20_1	15/7	8·45	169

The three recoveries pertaining to Station 2 are among a number which, not only from the July liberations, but, as already pointed out, from certain May and June stations, took place on the west Danish coast between latitudes 54° N. and 56° N. The drift-period in every case signifies complication in the route of the drifter concerned.

The majority of these returns was made between 27th November 1912 and 4th January 1913. In the same interval, drifters which had undoubtedly passed through, or close to, the North-East Dogger Bank Eddy were being returned from within the Skagerak, and it seems significant that no bottle from this system, despite its southerly orientation in November and December 1912,* stranded on the above-mentioned section of the Danish coast. The argument, of course, is that the group of drifters with which we are immediately concerned did not have intimate association with the North-East Dogger Eddy, which, however, was probably indirectly responsible for finally shaping the courses of the bottles towards this particular part of the coastline.

By all relevant circumstances the South-West Dogger Bank Eddy is indicated as the main cause of complication in the routes of the several drifters comprising this group, and it is apposite to observe with reference to the July Station 2 records that the difference between the drift-periods of the first and third recoveries is 20 days. To account for the relationship of the intermediate drift-period to the other two, the Mid-East Scottish Coast Eddy, in view of the position of the liberation-station, offers the most feasible explanation, the second bottle having presumably made one more gyration within this system than bottles one and three. This interpretation, based on the following analytical details, is given effect on Figure 41.

TABLE LVIII.

JULY LIBERATIONS.

Analysis of Station 2 *Recoveries.*

Recovery.	Measured Course to **Q.** Miles.	Mean Drift-Speed to **Q.** Miles per Day.	Date of Arrival at **Q.** Day/Month.	Measured Course from **Q.** Miles.	Mean Drift-Speed from **Q.** Miles per Day.	Date of Withdrawal from **Q.** Day/Month.	No. of Days in S.W. Dogger Eddy.	No. of Circuits of S.W. Dogger Eddy.
155_2	390	7·95	24/8	245	9·65	12/11	80	4
162_2	460	7·80	3/9	225	10·15	23/11	81	4
175_2	390	7·95	24/8	235	10·75	2/12	100	5

* This is shown particularly by the courses laid down on Figure 44 for the 53_1 October and 46_1 November bottles.

Station 7 also yielded a recovery in the above group and another on the south-west Norwegian coast near Stavanger, the drift-periods of the two bottles differing by only two days. The former, i.e. the west Danish coast recovery, is estimated to have spent 121 days in the South-West Dogger Bank Eddy, traversing 290 miles at 8·10 miles per day to **Q** and 250 miles at 11 miles per day from **Q**.

The second return must obviously be held to have drifted through the North-East Dogger Eddy. By the route entered to scale on Figure 41 the drifter in question is reckoned, on the basis of the velocity-curve, to have covered 1,365 miles at an average rate of 7·5 miles per day.

* * * * * * *

August Liberations.

Only one group of drifters was liberated during August 1912, 20 bottles being despatched on the 20th from the intersection of the prime meridian with latitude 57° N. Of the six returns, all of which came from Swedish and south Norwegian coasts, only five, with drift-periods of under 200 days, need be considered in detail. The drift-periods of all five records clearly show that the North-East Dogger Bank Eddy was implicated in every case. Owing to a continuous change in the position of this system, which was evidently taking place during the period when the August drifters were involved in it, it is almost necessary to indicate on the chart the actual course, including eddy circuits, taken by each bottle. The lengths of the various routes are calculated by reference to the velocity-curve at the mid-dates of the drift-periods. The first four bottles are considered to have kept together until after they had rounded the Skaw and passed into the Kattegat, where their routes diverged as indicated on Figure 42. The details of their analysis are given in the following table.

TABLE LIX.

AUGUST LIBERATIONS.

Analysis of Station 1 *Recoveries.*

Recovery.	Mid-date of Drift-Period. Day/Month.	Mean Velocity from Figure 47. Miles per Day.	Estimated Course in Miles.
102_1	10/10	7·55	770
106_1	12/10	7·60	805
114_1	16/10	7·70	880
135_1	26–27/10	8·00	1,080

The 172-day recovery on Karmö, Norway, is in different case from the four above. From **P'**, where these four bottles are supposed to have escaped from the North-East Dogger Swirl, the 172-day bottle may be assumed to have completed another circuit of the system, as shown, and to have proceeded thereafter from **P** by way of the Skagerak and Kattegat to its stranding-place. This route, however, accounts for only 1,340 of the 1,550 miles estimated to have been accomplished by the drifter at a mean speed of 9 miles per day. The distance of 210 miles is, by the analysis of the September records, to be explained by still another circuit of the eddy having been completed before the bottle finally departed from **P**.

* * * * * * *

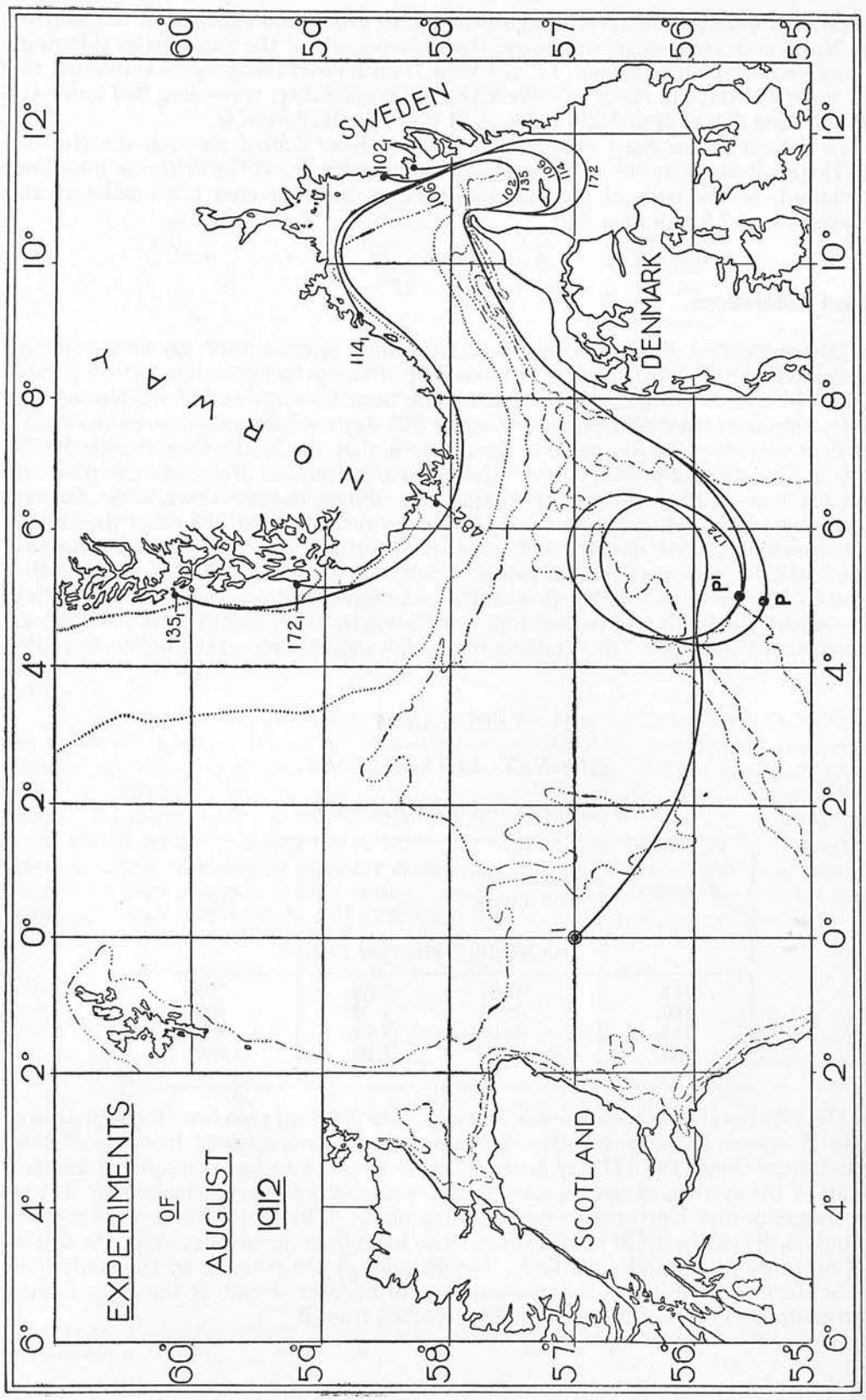

EXPERIMENTS
OF
AUGUST
1912
SWEDEN
DENMARK
SCOTLAND
NORWAY
P
P'
1
102
114
135
172
202

FIG. 42.

September Liberations.

Seven series of liberations, involving 56 bottles, were carried out on the 12th, 13th and 14th September in the mid-east Scottish area. On the 20th a further eight bottles were set adrift at a point in the Moray Firth. (The liberation-stations, although not in the same order, were the same as those visited in July.)

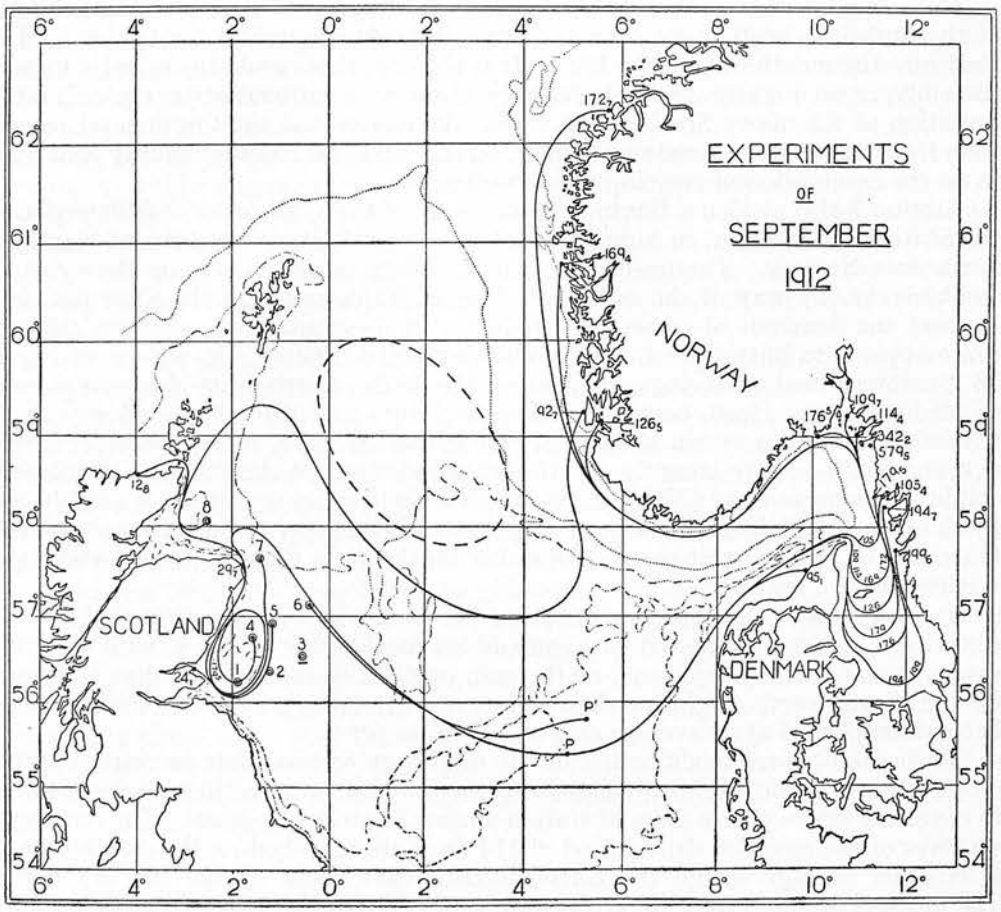


FIG. 43.

From the last group only one recovery was effected. This is the record from which the point **E′** on Figure 47 is derived. In its finally accepted form the course of the drifter in question to Strathy Bay on the north coast of Scotland is estimated to have measured 89 miles, overtaken in 12 days at the rate of about 7·4 miles per day. **E′** thus becomes **E** on the time-velocity diagram.

From the mid-east Scottish coast area liberations, two returns are recorded from the adjacent coastline, after 24 and 29 days respectively, from Stations 1 and 7. The Mid-East Scottish Coast Eddy was undoubtedly involved in the histories of these drifters, for which, on the basis of Figure 47, courses of about 180 and 215 miles are drawn to scale on Figure 43.

The 95-day bottle from Station 1 to N. Tornby, Denmark, establishes a link between these September liberations and the only batch of drifters liberated in October, the September bottle being found two days before, and almost at the same place as the 53-day October drifter. As can be seen from Figures 43 and 44, the courses laid down for these two bottles are very similar, that of the 95-day September

bottle representing 775 miles, overtaken at a mean speed of 8·15 miles per day, thus conforming to velocity-curve requirements. The two routes mentioned, in conjunction with that of the shortest-period November recovery, practically establish the position, towards the end of 1912, of the North-East Dogger Bank Eddy, which, as will be seen below, enters into the analysis of some of the later September recoveries, as, in this position, it has already done in the cases of certain May records.

First of all, however, it will be observed from Figure 43 that the elliptical form of the Mid-East Scottish Coast Eddy apparently functioned in September and at least into the month of October 1912. It is the case that, while the circular form of the eddy, as on Figures 38 to 41 inclusive, allows of a rational cartographical interpretation of the above Scottish recoveries, the analysis of the Continental returns from these September liberations cannot, on this basis, be so satisfactorily concluded as on the assumption of the elliptical circulation.

Station 7 also yielded a Continental recovery of the same order of drift-period as the Station 1 result, but in a different locality, namely, on the island of Karmö in south-west Norway. The most direct course which is permissible on the evidence available, i.e. by way of the north-east Dogger Bank area and the Skagerak, fails to meet the demands of consistency required in these analyses. Quite a different route appears to have been taken by this September drifter. As shown on Figure 43 it is interpreted as having accompanied the 29-day bottle from the same station, as far as Rattray Head, continuing thereafter into and through the Moray Firth, thence northward to within 15 miles of Fair Isle where, early in November, it turned east and south-east, to cross the North Sea as indicated on the chart. The requisite conditions as to mileage (750) and rate of drift (8·15 miles per day) are exactly met by this course, which, as will be seen, bears a striking affinity to the routes apparently taken by the two shortest-period November bottles from their respective liberation-stations, Nos. 1 and 2.

Turning now to the September Station 4 results, which are the next that need be considered, the course entered on Figure 43 for the 105-day return is, with the given extensions at the beginning and at the end, practically the same as that laid down for the 95_1 recovery. Eight hundred and eighty-five miles are thus reckoned to have been accomplished at an average rate of 8·45 miles per day.

With the obvious modification in the final part of this route in respect of the second Station 4 recovery, only about 108 days would, on a calculation, be required to cover the whole course from liberation-station to stranding-place. The remaining six days of the recorded drift-period of 114 days are absorbed on the assumption of a lengthier passage within the Kattegat than that taken by the 105-day bottle. The mean drift-speed over the entire course of 986 miles is thus 8·65 miles per day, which accords with the principle underlying Figure 47.

Two records in particular furnish the main evidence upon which courses deviating more or less considerably far southwards into the Kattegat are postulated in respect of the above and other drifters which passed through the Skagerak in the interval from December 1912 to the end of March 1913. These are the 187_{17} June and the 199_6 September recoveries which took place unusually far south on the west Swedish coast on 17th December and 31st March respectively.

Again, with the modification and extension indicated on Figure 43, the route of the 114-day bottle accounts for 1,320 miles of the 169-day drifter's course, which, on the basis of a mean drift-speed of 10·3 miles per day (derived from Figure 47 in the usual way), should measure, in all, 1,740 miles. As will become evident below, the difference of 420 miles is just sufficient to cover two circuits of the North-East Dogger Bank Eddy as outlined on Figure 43.

The 126-day bottle from Station 5 to the neighbourhood of Stavanger is reckoned to have travelled by the route indicated on the chart, without complication in the North-East Dogger Bank Eddy, accomplishing 1,140 miles at the rate of 9·05 miles per day.

The 176_5 recovery, on the other hand, apparently passed four times round this swirl. The complete course, overtaken at about 10·45 miles per day, measures 1,840 miles, 840 of which fall to be allotted to eddy circuits.

The analysis of the 179_5 record also entails four circuits of the North-East Dogger Eddy and, in addition, to account for an entire run of 1,880 miles at 10·45 miles per day, a complete circuit of the Mid-East Scottish Coast Eddy was apparently accomplished.

A direct passage into the North-East Dogger complex is almost certainly the correct assumption in respect of the 199_6 drifter, which is calculated to have covered 2,170 miles at the rate of 10·9 miles per day. These conditions are satisfied by the route suggested on Figure 43, which measures, exclusive of north-east Dogger complications, 700 miles, the remaining 1,470 miles being taken to represent seven eddy circuits. It will be observed that the drifter in question is considered to have entered the North-East Dogger Eddy when the system was in a more northerly position than that given on Figure 43. This is a deduction from a calculation based on Figure 47, by which the September bottle can be shown to have arrived at **P′** almost on the same day (about 14th October) as the 143_{19} June drifter left the system at that point (see Figure 40).

There remain to be considered of the September records only three of the five Station 7 results. The 109_7 bottle, by calculation, traversed nearly 940 miles at an average speed of 8·6 miles per day. Parting company with its shorter-period fellows, the 29- and 92-day drifters, in the neighbourhood of Rattray Head, this bottle apparently took the same route to the Dogger Bank area as the remainder of the Skagerak-recovered bottles from the mid-east Scottish coast, and, without becoming involved in the eddy in these waters, passed on into the Skagerak and finally to its recovery-point as shown.

The course of the 172-day bottle to Sondmore, Norway, by way of the Dogger Bank and the Skagerak, works out, cartographically, at 1,390 miles, exclusive of probable circuits of the North-East Dogger Bank Eddy. The total course, on the basis of an over-all drift-speed of 10·4 miles per day, is reckoned to have been one of 1,810 miles. The difference of 420 miles is obviously explained on the assumption of two eddy circuits.

Five complete gyrations of the North-East Dogger Eddy fall to be included in the 2,105 miles estimated as the length of the course of the 194-day recovery on Gasö, Bohuslan, Sweden.

* * * * * * *

October Liberations.

The only series of liberations to be made in October 1912 took place on the 26th, from a point about five miles south-east of the mouth of the River Ythan, Aberdeenshire. On the following day no fewer than 11 of the 20 bottles set adrift were found stranded a little way into the above river-mouth. A day later other two bottles were recovered about four miles farther north along the coast.

For three days prior to these liberations moderate to strong south-easterly winds were registered at Aberdeen, reaching their climax the day following liberations. This doubtless explains the foregoing recoveries.

At least two of the October bottles escaped the immediate effects of the above conditions, however, and the 14-day recovery at Newburgh on the Ythan is estimated to have overtaken about 116 miles, as shown on Figure 44, at a mean rate of 8·3 miles per day. The course, as given, embraces part of the region which may be influenced by the Mid-East Scottish Coast Eddy, but the bottle concerned does not appear to have been affected by this circulation, at all events in its normal position.

It is to be remembered, however, that strong or persistent south-easterly winds are inimical to the operation of the eddy, and at the period involved it was probably either " washed out " completely, or pushed to the northward, as, indeed, may be taken to be the meaning of the course estimated for the 14-day recovery.

The last October bottle to be returned came from the north-west coast of Denmark after only 53 days, suggesting an almost direct passage from liberation-station to stranding-place at an average speed of between 7 and 7½ miles per day. This October record, however, overlaps in a common period of 28 days, from 21st Novem-

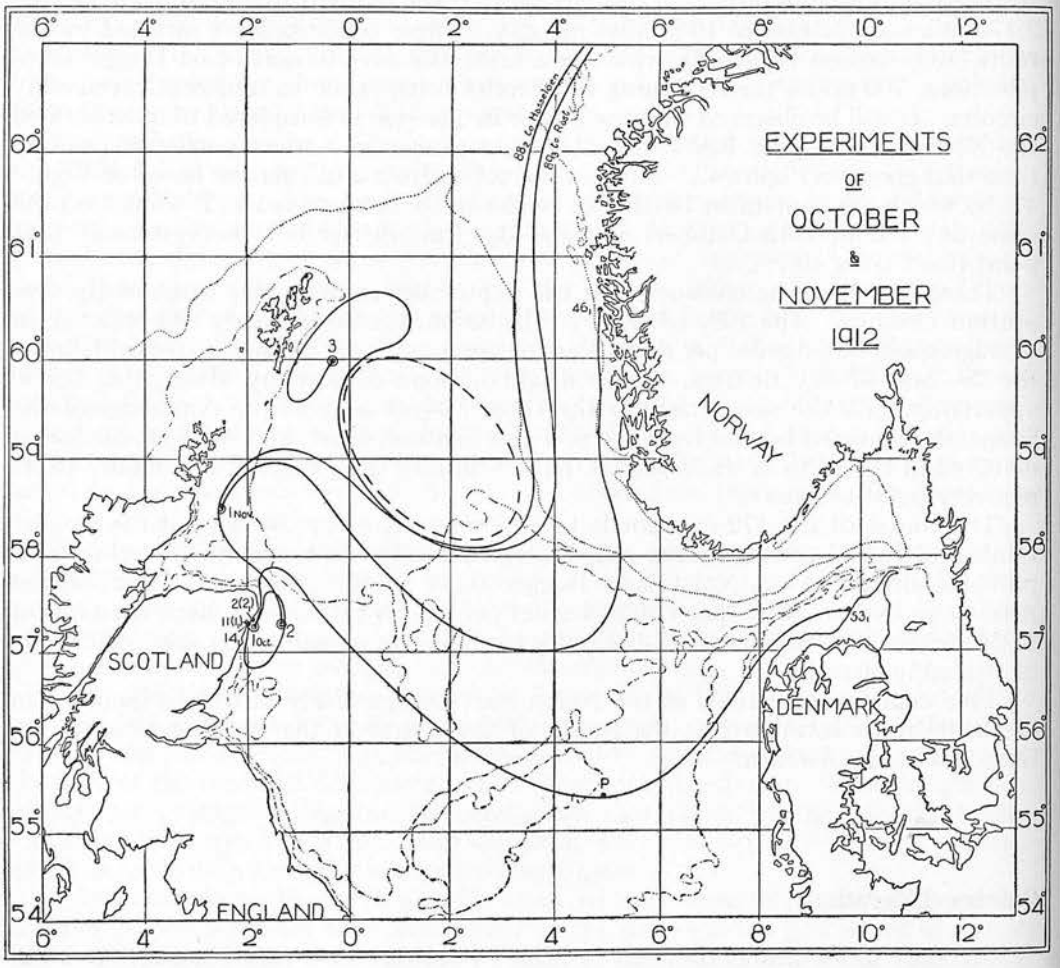


FIG. 44.

ber to 18th December, the shortest-period November result, and in view of the course laid down in that instance, the route of the October drifter cannot be accepted as having been almost due east across the Middle North Sea. Moreover, there is the contingency of the North-East Dogger Bank Eddy to be reckoned with. The results of previous months' liberations leave no doubt as to its existence during the last two months of the year. The November bottle above mentioned, although it evidently approached the area where this system may be found to function, did not apparently come within its region of influence. The circulation therefore must have been situated somewhat to the south of latitude 57° N., and the October bottle most probably passed round its southern boundary over towards Denmark and into the Skagerak, as represented on Figure 44. The course charted measures to scale

a little over 500 miles and entails a mean rate of drift of 9½ miles per day, so that **F′** on Figure 47 becomes **F**.

* * * * * * *

November Liberations.

On 21st and 22nd November 1912 three sets of 12 drifters were put out from three positions on the western margin of the North Sea between latitudes 57° N. and 60° N. Despite the nearness of the liberation-stations to the east coasts of Scotland and Shetland, no British recovery resulted from these operations. On the other hand, at least one drifter from each station made a remarkably quick passage to Norway, recalling, in the case of the quickest, some similar results obtained by Fulton from his drift-bottle experiments of the same period of 1894 (**4**).

The quickest recovery above mentioned was the only one from the November 1912 liberations to take place within the limits of the North Sea. Forty-six days after liberation at Station 1, which was situated almost within the Moray Firth in its northern part, the bottle in question was found on an island in the neighbourhood of Bergen. Assuming a direct course, this drifter must have travelled, on the average, no less than 5·65 miles per day. Apart from the improbability of such a course being in fact the true one, there is evidence among the remaining records for the month of much higher drift-velocities in the region and for the period concerned, and therefore, in the above case, of a longer route.

Four November bottles were recovered within ten days of one another in the Vesteraalen and Lofoten region, between about latitudes 67° 30′ N. and 68° 30′ N. Two of these originated at Station 2, off the north-east coast of Aberdeenshire, and two at Station 3, in east Shetland waters, and since all four bottles were liberated on the same day, their mean daily rates of drift cannot have differed very considerably, likewise the lengths of their respective routes.

A minimum average drift-speed of over 9 miles per day is entailed by the assumption of the most direct course in respect of the quickest of these four bottles, namely, the 88-day bottle from Station 2 to Hasselöen, in the Vesteraalen. The discrepancy between this and the foregoing velocity, derived from the Station 1 recovery near Bergen, cannot be held to be accounted for entirely by the probability of a faster rate of drift along the Norwegian coast outwith the North Sea than in the Northern Area itself. Moreover, direct courses in respect of the two bottles in question are incompatible with each other, for, being contemporaneous, their somewhat abrupt intersection almost in the middle of the Northern Area is not permissible, by one of the guiding principles of these analyses. In addition, both routes cut across the region normally believed to be occupied by the Great Northern North Sea Eddy and, as is evident from Figure 44, this system did apparently exercise an important influence on the November drifters, especially on those from Stations 2 and 3.

The above-mentioned close association among the four short-period returns relative to these two stations is almost certainly of important significance, in view of the wide separation between the two liberation-stations. Allowing that the drift along the Norwegian coast north of about latitude 62° N. was, in fact, appreciably faster than in the North Sea, this association means that the courses of all four bottles *within the North Sea* were of approximately the same length. Another fact which should be given due consideration, in view of the relative positions of Stations 1 and 2, is the non-recovery of a Station 2 drifter within the limits of the North Sea.

In short, a satisfactory interpretation of the principal records for November 1912 depends first upon the assumption of the Great Eddy, which, in conjunction with a smaller eddy in east Shetland waters* affecting the Station 3 bottles and the development of a northerly drift off the Scottish east coast, first revealed by

* See analysis of May results.

the September results, was the means of bringing the Stations 2 and 3 bottles together early in their respective careers. The northerly drift off the Scottish east coast, between latitudes 57° N. and 59° N. at least, affords also an explanation of the apparent incompatibility of a North Sea recovery from Station 1 and none from Station 2. The cartographical resolution of the case is given on Figure 44, of which the following is explanatory.

In order to conform to the rules of consistency laid down to govern these analyses, a mean drift-speed of 10·65 miles per day, over a course of 490 miles, is estimated in respect of the 46-day Station 1 recovery. Hence is derived the point **G** on the velocity-curve, Figure 47. It will be observed that the route given for this bottle does not proceed so far south and east as to entail the probability of the bottle's passage into the Skagerak, for other records for the year indicate that at the time when this bottle might be in the neighbourhood, i.e. in December, the immediate entrance to the Skagerak was free of complication in the way of eddies.

For the 88_2 recovery a mean drift-speed of 11·36 miles per day covers a route of 1,000 miles, the North Sea section of which (520 miles) is shown in Figure 44. The same average speed which corresponds to the point **H** on Figure 47, leads to the estimation of a course of 1,011 miles for the 89_3 drifter, 611 of which were overtaken in the North Sea south of latitude 62° N.

The two remaining short-period returns from the Vestfjord coast can obviously be taken to have pursued courses varying only in degree from those given in respect of the above recoveries, and no immediate purpose is to be served by the detailed investigation of the longer-period records associated with Stations 1 and 2.

This, then, concludes the cartographical analysis of the 1912 Scottish surface drift-bottle records.

Figure 47 (page 49) represents the time-velocity curve for 1912 as derived from these records and upon which, in the final essay, the greater part of their analysis was based.

* * * * * * *

DISCUSSION OF THE 1912 RESULTS.

As the work of analysing these Scottish surface drift-bottle records proceeds, it becomes evident that their cartographical interpretation can, with the closest possible adherence to the principle of consistency, be carried to a stage which was not anticipated when these experiments were begun. For this, granted first a sufficiency of data, it is necessary to study individually, as well as collectively and to some extent simultaneously, the numerous dates and positions of liberation-operations and, also, the more numerous and more complex dates and positions of recovery. The result, as represented by this and previous publications, would appear to justify the labour involved, for, not only has such knowledge accrued as must obviously be of value to fisheries research in more than one direction, but these experiments, also, or rather their results, yield more detailed information than has hitherto been available regarding the hydrodynamical structure, as it were, of Northern and Middle North Sea surface waters, and moreover, point at least to the more immediate causes of the physical variations and fluctuations which can be said now to constitute the major oceanographical problem, from a fisheries standpoint, in the regions dealt with.

Again, as in the case of the 1911 analysis, a connexion was first of all established, by means of a smooth time-velocity curve, among those of the 1912 records which lent themselves at once to simple and apparently reliable cartographical interpretation. Then, on the basis of this curve, which, in the process, underwent a number of adjustments until it took the form given in Figure 47, the remainder of the records

were submitted to a more or less exacting analysis with the results set forth in the preceding pages.

On the whole, it can be said that the main features of the Northern and Middle North Sea surface drift system, as established by the 1910 and 1911 analyses, were repeated in 1912. More or less considerable differences are, however, to be observed when the characteristics of 1912 are more closely examined in relation to those of the previous two years.

The Great Eddy of 1912 is estimated to have occupied, for the greater part of the year, a position analogous to that of 1910, the major axis of this almost elliptical system lying approximately on the longitude of 2° E. The 1911 Eddy, however, with its major axis slewed round about 45° into the N.W.-S.E. position, was evidently reproduced in the last quarter of 1912. A peculiarity also in the eastern boundary of the Great Eddy, which was not apparent from the examination of either the 1910 or the 1911 data, was revealed by certain 1912 results and was caused by the operation of a small counter-clock eddy off Stavanger—the Stavanger Eddy, first noticed by Böhnecke in 1922. This system encroached, as it were, on the field of the Great Eddy, causing a concavity in the adjacent boundary of the latter while it was in its " upright " position. There is no evidence of the Stavanger Eddy having been in existence when the Great Eddy took up its " oblique " situation towards the end of the year.

In the north-western part of the North Sea we have more clearly defined by the 1912 analysis a closed system of circulation of which there have been indications from the records of previous years. From May until November at least, the east Shetland area, from the latitude of Fair Isle northwards to about latitude 61° N., was occupied by an elongated form of eddy, clearly to be deduced from the tracks of a number of Shetland-recovered drifters belonging to the liberations of May and June. The 1911 results produced practically no evidence of this circulation which is probably of frequent occurrence in the east Shetland area. In 1910, on the other hand, such a system as obviously functioned in 1912 would appear to have been incorporated in a larger circulation embracing the entire north-western area from the Moray Firth to the north of Shetland.

The anticyclonic circulation enveloping Orkney, as established by former investigations, was again operative during the summer of 1912, as was also the Moray Firth Eddy.

In regard to the Mid-East Scottish Coast Eddy, a new feature emerges from the 1912 analysis. Two forms of this system, one circular and the other elliptical in outline, have already been noted in previous publications. The former, that is the circular eddy, evidently favours the beaching of drifters which escape from its influence on the Scottish-English coastline south of about Tay estuary, while the elliptical system appears to be associated with recoveries to the northward of Tay as far as Kinnaird Head, perhaps even into the Moray Firth ; so that, from the British coast landings of drift-bottles which are known to have cruised in the mid-east Scottish area, one may, under ordinary circumstances, postulate as to which form of the eddy is in operation at the time.

Passing to the Dogger Bank region, the two eddies deduced by Böhnecke (**1**) as functioning one at either end of the bank, are again revealed by the foregoing interpretations. The South-West Dogger Eddy, which hardly entered into the 1911 analysis, was in a measure responsible for a particular batch of recoveries effected towards the end of 1912 and early in 1913 between Blaavandshuk, Denmark, and the mouth of the River Elbe. Special significance, which will be explained later, attaches to this group of drift-bottle returns.

The approximate dimensions, also, of the South-West Dogger Bank Eddy are implied in the 20-day Period of Circuit deduced in respect of the closed circulation during the summer and autumn of 1912.

With reference to its position and superficial area, the south-west Dogger system

apparently functioned with greater constancy than the swirl at the other end of the Bank. As in 1911, the North-East Dogger Eddy in the following year again joined forces with the smaller circulation sometimes situated in the Lindesnaes region, and for the second time it has been possible, by cartographical measurement and calculation, to estimate, with some precision, the actual date of amalgamation of the two eddies. In 1911 this event occurred about the 1st or 2nd of August. The corresponding dates in 1912 were 23rd–24th July. After coalescence, the resultant system moved gradually south until, in the last two months of the year, it took up a comparatively stable position over the Tail End of the Dogger Bank.

What would appear to be a new feature of these analyses is the representation in respect of the majority of the Skagerak recoveries from the 1912 liberations, of more or less extensive courses within the Kattegat, indicating a cyclonic circulation in that area somewhat analogous to that which is the foundation, really, of the complex surface system of the Northern and Middle North Sea as a whole. The particular recoveries, however, which, because of their southerly location on the west Swedish coast, led to the inference of such a circulation in the Kattegat, are not peculiar to the winter months of 1912–1913, which were those embraced by the above-mentioned routes. Similar conditions would in all probability have been indicated by previous investigations had the analyses in question been carried to such an advanced stage as were those of 1912. Secondly, the 1912 courses were probably not, in actual fact, so extensive as they are represented, since the velocities on which they are based are primarily North Sea velocities, which are probably in excess of those generally operating in the Kattegat, especially in winter months.

Routes, however, which do imply abnormal conditions in 1912 as compared with the corresponding periods of 1910 and 1911 are those deduced for the September drifter returned from Karmö, Norway, and for certain November bottles. Commencing some time towards the middle of October the usual northerly coastal drift associated with the Mid-East Scottish Coast Eddy, especially with the elliptical form of the system, began to extend beyond its usual limit of Buchan Ness, or Rattray Head, or even Kinnaird Head, passing round into and, as the tendency developed, across the Moray Firth towards Smith Bank and thereafter northward to within 15 or 20 miles of Fair Isle. Here it was apparently met by an opposing influence from the north which caused the drift from the south to turn eastward and then south-eastward, to become merged in, or to pass alongside, the western boundary of the Great Eddy.

One, in particular, of the November results, namely, the remarkably short-period return from the North Sea coast of Norway, recalls some similar results obtained by Fulton (**4**) from his drift-bottle experiments of the same period of 1894, i.e. 18 years earlier. From a long series of drift-bottle experiments it can be said that such results, and probably also the hydrodynamical conditions they represent, are unusual, and it may be observed in passing that this period of 18 years is one of those which some writers, notably of late, Le Danois (**8**), have associated with apparent periodicities in relation to certain phenomena in the North Atlantic Ocean, which have an undoubted bearing upon the currents of the Northern North Sea.

Once again, the analysis of the 1912 drift-bottle records provides no evidence of a current connexion between the Faroe-Shetland Channel and the Northern North Sea through the passages between Shetland and the mainland of Scotland. On the contrary, the inferences which are to be drawn from the cartographical resolution of the year's results are opposed to views hitherto expressed and, until recently, generally held on this point. There seems to be no such connexion normally established.

On the other hand, the route-charts for May and June 1912 clearly affirm the writer's previous findings to the effect that Faroe-Shetland Channel influence on the Northern North Sea circulation is by way of the north of Shetland and through the opening between Shetland and Norway, thus supporting the suggestion of Helland-

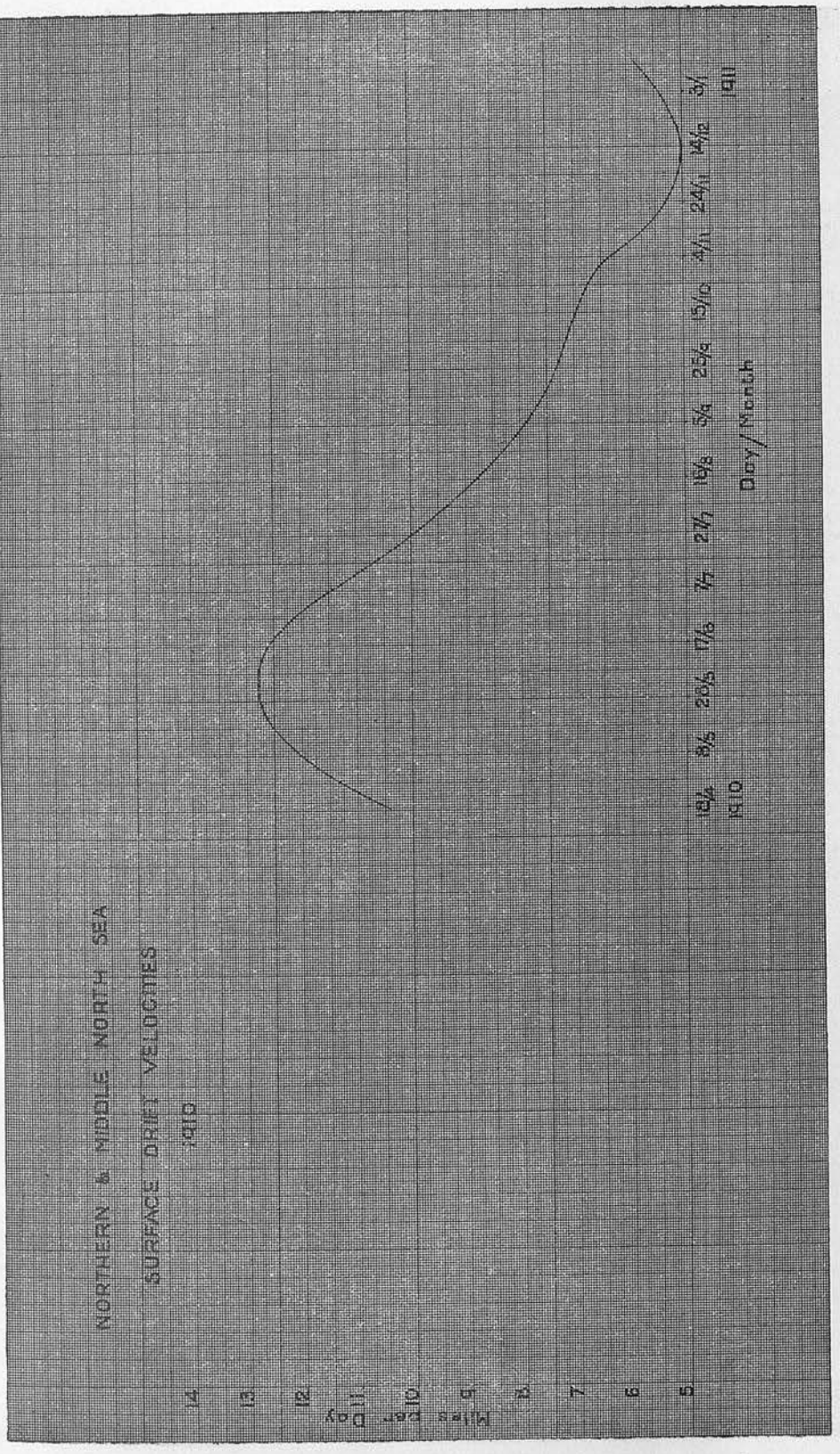

NORTHERN & MIDDLE NORTH SEA
SURFACE DRIFT VELOCITIES
1910
Miles per Day
14
13
12
11
10
9
8
7
6
5
13/4
8/5
20/5
17/6
7/7
27/7
19/8
5/9
25/9
15/10
4/11
24/11
14/12
3/1
1911
1910
Day/Month

FIG. 45.

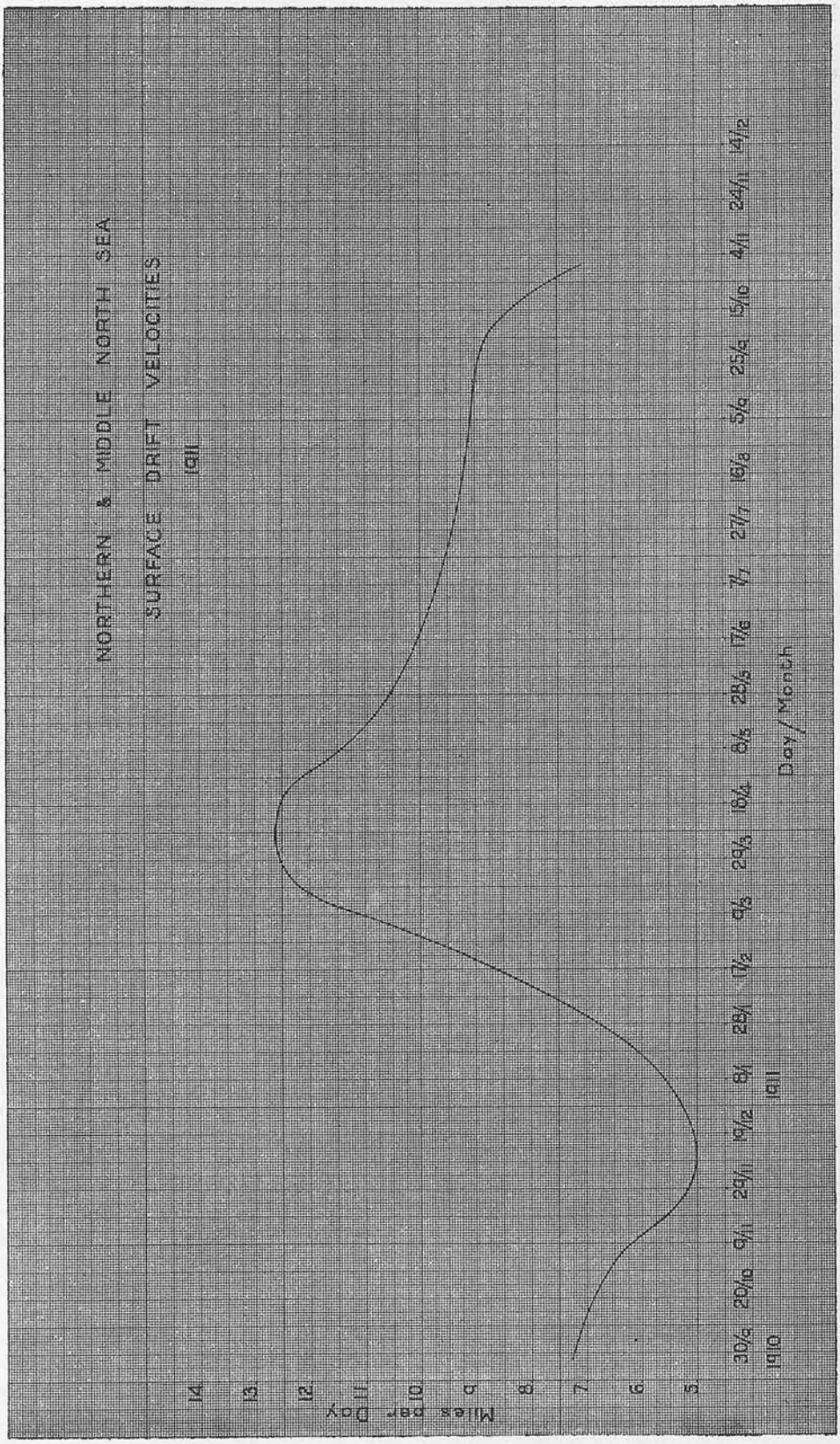

NORTHERN & MIDDLE NORTH SEA
SURFACE DRIFT VELOCITIES
1911
Miles per Day
14
13
12
11
10
9
8
7
6
5
30/9 20/10 9/11 29/11 19/12 8/1 28/1 17/2 9/3 29/3 18/4 8/5 28/5 17/6 7/7 27/7 16/8 5/9 25/9 15/10 4/11 24/11 14/12
1910
1911
Day/Month

FIG. 46.

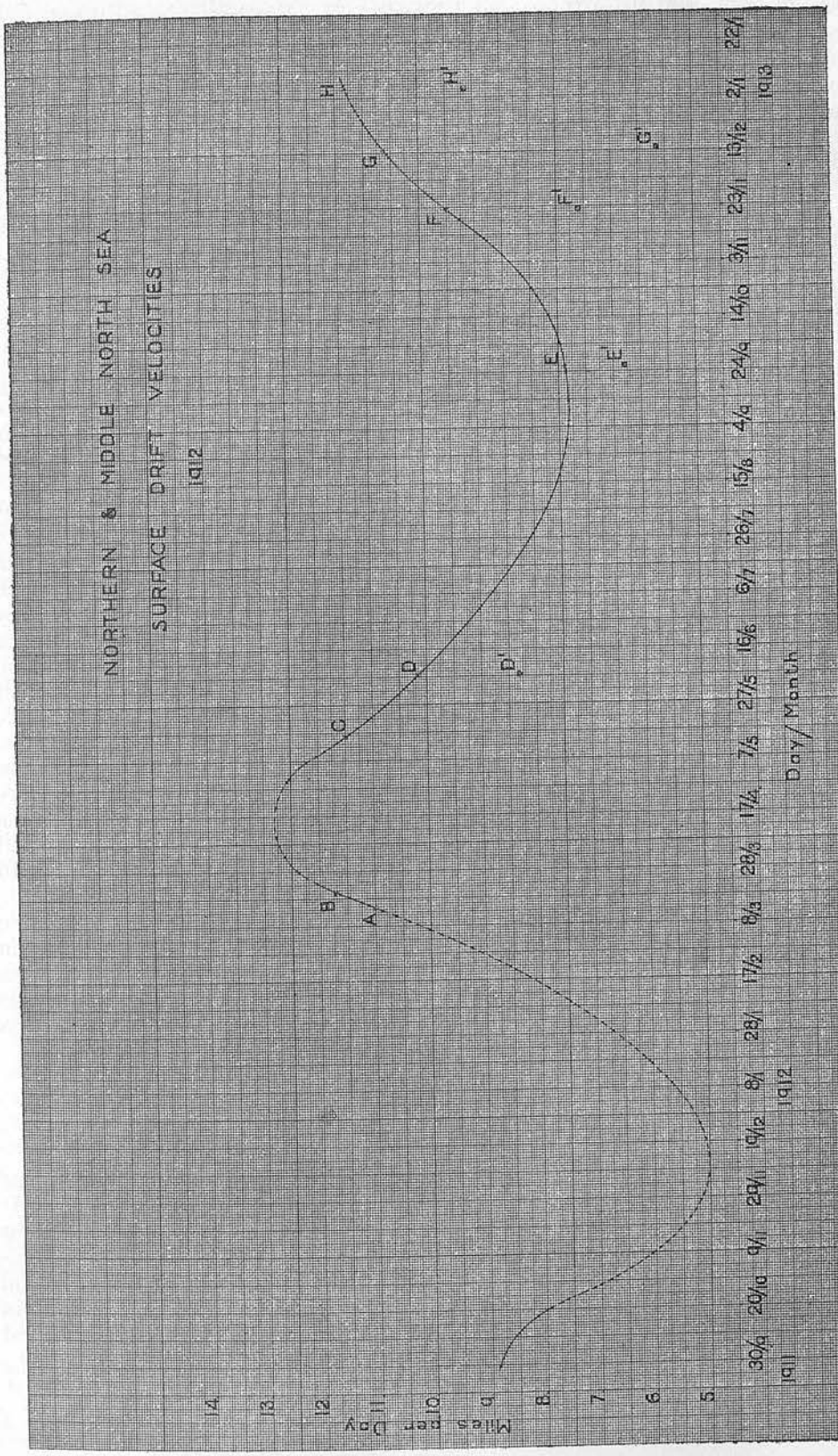

NORTHERN & MIDDLE NORTH SEA
SURFACE DRIFT VELOCITIES
1912
Miles per Day
14
13
12
11
10
9
8
7
6
5
A
B
C
D
E
F
G
H
D'
E'
F'
G'
H'
30/9 20/10 9/11 29/11 19/12 8/1 28/1 17/2 8/3 28/3 17/4 7/5 27/5 16/6 6/7 26/7 15/8 4/9 24/9 14/10 3/11 23/11 13/12 2/1 22/1
1911
1912
1913
Day/Month

FIG. 47.

Hansen (**6**) and of Helland-Hansen and Nansen (**7**). Further as regards this connexion, these same charts, as also the corresponding charts for 1910 and 1911, carry an implication which, if true in fact, is of considerable hydrographic importance. This will be dealt with later, but it may be noted here that, in all three years, drifters liberated all the way across the northern part of the Faroe-Shetland Channel in the month of May or early in June, evidently passed, without exception, into the Northern North Sea by way of the north of Shetland. *There is no evidence of a single drifter from this region at this time of the year having made a direct run towards, and immediately northwards along, the Norwegian coast.* Such evidence *is* contained in the results from the August liberations of both 1910 and 1911. No Faroe-Shetland Channel liberations were carried out in August 1912.

The hydrographical significance of these results is discussed in the appropriate section to follow. The surface drift-velocities of 1912 may now be considered.

Since a full discussion of the velocity conditions of 1912 cannot properly be entered upon without reference to the years already examined on lines similar to those adopted in this report, the time-velocity curves for 1910 and 1911 are, in Figures 45 and 46, reproduced in a form in which they have not hitherto appeared in this series of papers.*

That part of the 1912 curve between **C** and **H** is very fully substantiated by actual cartographical data, while the proximity of **A** and **B** leaves no doubt as to the form of the curve between these two points. Evidently maximum velocity in 1912 was attained in the interval between the dates represented by the points **B** and **C**, i.e. between about the middle of March and the middle of May, and as, by Figure 46, this is so nearly analogous to events in 1911, as are also the drift-speeds associated with the two periods mentioned, it may be taken that the maximum velocity registered in these two years was approximately the same, namely, about $12\frac{3}{4}$ miles per day, which was also, apparently, the maximum of 1910. But while the maxima of 1911 and 1912 were registered about the same period of each year, namely, towards the middle of April, that of 1910 was not reached until early in June. There is actually to be observed from Figures 46 and 47 a slight difference in the calendar periods of the respective maxima, that of 1911 falling within the 25-day interval between 26th March and 20th April, while the corresponding period of 1912 lay between the 2nd and the 27th of April. The comparable period of 1910 was from 22nd May to 17th June.

Associated with these differences in calendar times there would not appear to have been, as in the nature of things might be expected, appreciable differences in the actual maximum velocities attained during those three intervals. As read from the original curves, the values associated with the above terminal dates are as follows, the highest value registered between those dates being in each case, and as already pointed out, as nearly as may be, $12\frac{3}{4}$ miles per day :—

1910.		1911.		1912.	
May 22.	June 17.	March 26.	April 20.	April 2.	April 27.
12·63	12·65	12·50	12·50	12·60	12·65

Consider now the approach to the maximum on all three curves. On the extreme left of Figure 47 the final known portion of the 1911 velocity-curve is entered. It may be recalled that, for lack of data covering the ensuing winter months, this curve could not be extended beyond the third week of October 1911, but by inference from the similarities which are apparent between the curves for 1910 and 1911, it is probable that had sufficient data been available to embrace the season in question a minimum velocity of about five miles per day would have been recorded

* Acknowledgment is made to the International Council for the Exploration of the Sea for permission to include these diagrams, and Figure 48, in this report. They have already appeared, Figure 48 in slightly modified form, in (**10***d*).

early in, or towards the middle of, December 1911, as was the case almost exactly a year before. The broken portion of the curve on Figure 47, connecting the 1911 curve with the points **A** and **B**, is based on this inference, which is supported as a result of the following comparisons.

There is clearly a remarkable similarity between the final portions of the 1910 and 1911 curves and between the early parts of the curves for 1911 and 1912, signifying that the deceleration of velocity during the last three months of 1911, followed by its acceleration in the first quarter of 1912, took place at about the same rates as in the corresponding periods a year before.

In reference to the steep velocity-gradients prior to the maxima, and without regard to the approximation of calendar times, the analogy between the 1911 and 1912 curves may be carried a stage further back, namely, to the corresponding portion of the 1910 curve. Although only a part of this is established by drift-bottle results, enough is shown to point the moral of the likeness among all three curves on this section.

On closer examination the extended analogy carries a further implication, tending greatly to enhance the original conception that average velocities derived from records such as the two shortest-period March 1912 results (i.e. from records involving only a small part of the entire area under investigation and even somewhat on the verges of its major circulation) can, with an accuracy sufficient to subserve the immediate purposes of these experiments, be accepted as representing the rate of the drift anywhere in the area on certain determinable days.

On each of the three velocity-curves at least one point, determined from a short-period return, occurs shortly before the comparatively stable maximum is reached. The positions of these points in relation to the respective maxima are very much the same on all three curves, and their derivation, not only as from short-period returns, but by more or less precise cartographical measurement and calculation, leaves little room for doubt as to their inherent accuracy within reasonably narrow limits. In addition to these considerations, however, it is principally the examination, from a geographical standpoint, of the origins of the records so dealt with that establishes the point of this discussion.

The points **A** and **B** on the 1912 diagram are derived from drift-bottle records which refer exclusively to the mid-east Scottish area ; in other words, to a comparatively localised region on the western border of the Middle North Sea. Likewise, the entry on the 1911 curve against the date 17th March primarily depends upon the surface water circulation of the Moray Firth round about that day. The first two points on the 1910 curve, on the other hand, represent more open-sea waters which are definitely a part of the major North Sea circulation, the area involved extending from Great Fisher Bank—about the intersection of latitude 57° N. and longitude 4° E.—to the north coast of Jutland. Both types of results, i.e. from " deep-sea " and from " landward " areas, are, moreover, incorporated in the 1911 curve about the point above cited, for although, as already pointed out, this point is derived, in the first place, from a Moray Firth result, it is also " covered," and hence in a measure corroborated, by records involving deeper areas of the Northern and Middle North Sea.

The substance of these investigations, then, is that they afford strong justification for the contemporaneous applicability to any part of the North Sea north of about latitude 54° N. of the velocity-estimate furnished, according to the afore-mentioned principle, by a short-period drift-bottle record involving, it may be, only a somewhat localised area near land, but one which is definitely a part of the open North Sea. It is to be understood that the record must embrace an area in which open-sea influences, as opposed to coastal conditions, predominate. The Moray Firth, for example, especially in its inner reaches at certain seasons, although it possesses the characteristics of a bight of the North Sea (**10***e*), is a region from which drift-bottle results which have been confined to its waters from start to finish should be sup-

ported by other records before giving them their wider application to the surface circulation of the Northern North Sea as a whole.

Deceleration of velocity in 1912 was evidently much greater than in 1911, and almost to the same extent less than that of 1910, although taking place correspondingly earlier in the year. This deceleration of 1912, however, in contrast to the events of both the previous years, proceeded evenly towards a minimum, which, for the first time, by these investigations, was registered in the autumn of the year and not in winter, as was the case apparently in 1911 and in 1910. The difference in the incidence of the minima of 1911 and 1912 would appear to have been no less than two months, that of 1912 falling early in September, while the 1911 minimum, as already pointed out, probably occurred only in December, as was the case a year earlier. While, also, minimum velocities of about 5 miles per day were apparently characteristic of 1910 and 1911, the 1912 minimum appears on Figure 47 at no less than $7\frac{1}{4}$ miles per day. Thereafter, fairly rapid acceleration, reminiscent of spring conditions, again set in. The further significance of this phenomenon is considered, along with other matters, in the following section dealing with some hydrographical and biological implications of the drift-bottle analyses of 1910, 1911 and 1912.

* * * * * * *

SOME HYDROGRAPHICAL AND BIOLOGICAL IMPLICATIONS OF THE DRIFT-BOTTLE RESULTS OF 1910, 1911 AND 1912.

On the basis of the three years' analyses which have now been submitted, it is possible to formulate a theory regarding the Northern and Middle North Sea circulation, by which not only the drift-bottle courses, as they appear on the various charts published in these reports, are explained, but certain hydrographical and biological phenomena also receive a rational interpretation.

These drift-bottle analyses lead almost inevitably to the conclusion that at least the upper-water circulation of the Northern and Middle North Sea comprises essentially a number of stream-currents which, while not wholly independent of one another, pass more or less independently to different regions. Evidently, too, the boundaries of the several eddy systems mentioned in this and previous reports function as stream-currents.

The idea of stream-currents in the Northern and Middle North Sea and in the Faroe-Shetland Channel is conveyed by the concentrations of arrows on Figure 48, which is a representation, not of the " normal " or " average " current régime of the areas involved, but of the currents which, by drift-bottle investigations, are most frequently in operation in those areas. Primarily the arrows are intended to convey the idea of direction only, but the heavier arrows, which represent the mid-lines of stream-currents, involve also the idea of velocity as indicated below.

It will be observed that, about the intersection of latitude 59° N. with the prime meridian, the strong southerly-flowing stream-current into the Northern North Sea opens out into several subsidiary streams, each of which leads to a definite region, (1) to the Moray Firth; (2) to the mid-east Scottish coast area; (3) and (4) to the south-west and north-east Dogger regions respectively; (5) to the Lindesnaes area; and (6), in the case of that subsidiary stream which forms the boundary of the Great Eddy, to the eastern or Norwegian side of the Northern North Sea. In the light of this representation, the drift-bottle results from Stations $May_{12}3$, 4, 5 and 6, without any cartographical treatment to affirm the truth of conjectures which arise from a consideration of the positions of these four points in reference to Figure 48, are particularly striking. The station-positions, together with others on the same hydrographic section which was run while the drift-bottle liberations were being carried out, are indicated on the flimsy attached to Figure 48

Liberations at Station 3 yielded only Scottish coast returns, presumably through the Mid-East Scottish Coast Eddy. The sole results from Station 4 were two Schleswig-Holstein coast recoveries, the bottles having evidently passed into and through

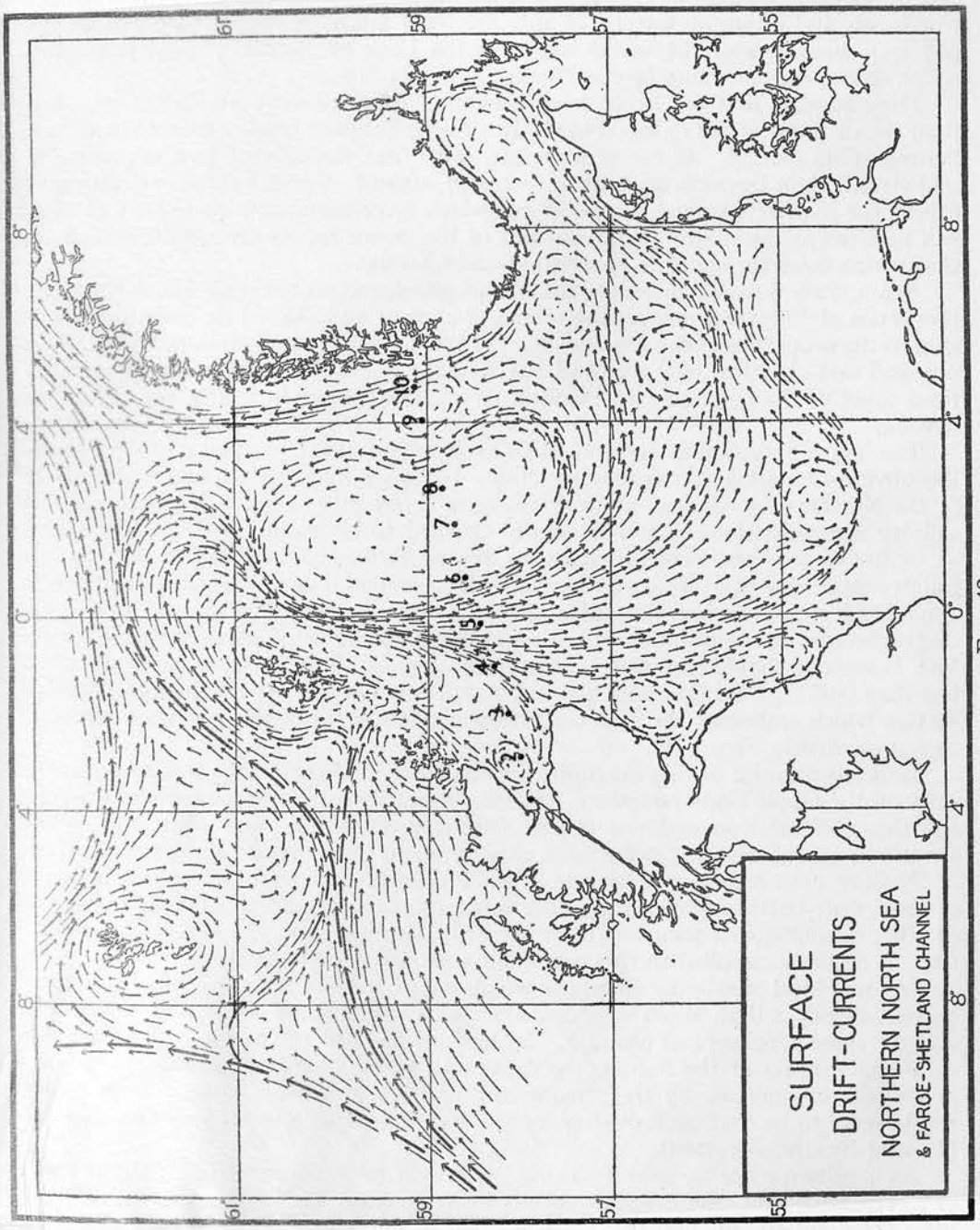


FIG. 48.

the South-West Dogger Bank Eddy. From Station 5 a single Skagerak recovery ensued, no doubt after the bottle had negotiated the North-East Dogger Swirl, towards which the " track " from Station 5 was probably almost direct, while from Station 6 it is reasonable, from the results, to infer that the drifters were first of all

carried over to the eastern side of the North Sea under the influence of the Great Eddy boundary circulation.

Apart from drift-bottle results such as the above, and their cartographical resolution, evidence in support of the stream-current theory, as applied to the Northern North Sea and adjacent waters, is afforded by a study of the distribution of the physical characters of the water itself, on the basis of certain general properties which stream-currents may be considered to have in common.

They appear, first, to be of fairly definite and somewhat limited width—less than the distance (*c.* 30 miles) commonly allowed between consecutive stations on a hydrographic section. It seems probable, also, that the rate of flow is greater in mid-stream than towards margins of a stream-current. Indeed there is evidence of this in the hydrodynamical computations which have been made in respect of what will be cited as the major stream-current of the entire region investigated, namely, that which flows through the Faroe-Shetland Channel.

Again, there is reason to believe that the physical, and probably also some chemical, properties of the water comprising a stream-current will bear their closest relationship to the properties of the source-waters of the current, in mid-stream, and that the physical and chemical characters of the stream as a whole may differ appreciably from those of the neighbouring medium through which, or in which, the current is flowing.

The last supposition at once offers an explanation of the marked and even of the less obviously marked differences in salinity which are frequently found, particularly in the Northern North Sea, at positions only a few miles apart. The accuracy of salinity determinations is now generally claimed to be within 0·02‰, sometimes, as in the case of the Scottish salinities among others, almost within 0·01‰. A salinity difference of 0·03‰ may therefore be considered as of probable significance, whilst real meaning doubtless attaches to a difference of 0·04‰ and over. On diagrammatic representations of hydrographic sections or of plane surfaces, therefore, isohalines should in general, in open-sea regions, be entered at intervals of no less than 0·05‰. On this principle, the distribution of salinity on the hydrographic section which embraces the above-mentioned drift-bottle stations of May 1912 was as represented in Figure 49.

In interpretation of this diagram it seems clear that Stations 5 and 8 lay practically on the Great Eddy boundary, Stations 6 and 7 being situated definitely within the closed circulation and the others definitely outside it, and while this is not strictly in accord with the deductions already made from the cartographical analysis of the May 1912 drift-bottle records, it is sufficiently near to demonstrate the value of these drift-bottle experiments in the interpretation of salinity, and doubtless also of other similar distributions. Conversely, the diagram gives support to the stream-current theory as applied to this particular period and region.

Another kind of salinity difference which is capable of explanation on the stream-current theory is that which sometimes occurs within a short interval of time at one and the same geographical position. Hitherto it has been customary to regard this as an illustration of the liability to rapid and radical hydrographical change in a given region, whereas, by the stream-current theory, a more rational explanation would seem to be that such differences are due to a slight alteration in the direction of a near-by stream-current.

As a consequence of velocity being greater in mid-stream than on the margins of a stream-current, there will doubtless be a tendency for the margins to sheer off from the main stream, and this tendency, when and where it is allowed to develop, will occasion the spread of waters with particular physical and chemical characteristics over wider areas than are served directly by the main stream itself. And not the water alone, with its inherent characters, would appear thus to be dispersed from the borders of a stream-current. The passive organisms, or plankton, which it carries will also be subject to this marginal tendency to deflexion, a tendency which, enhanced

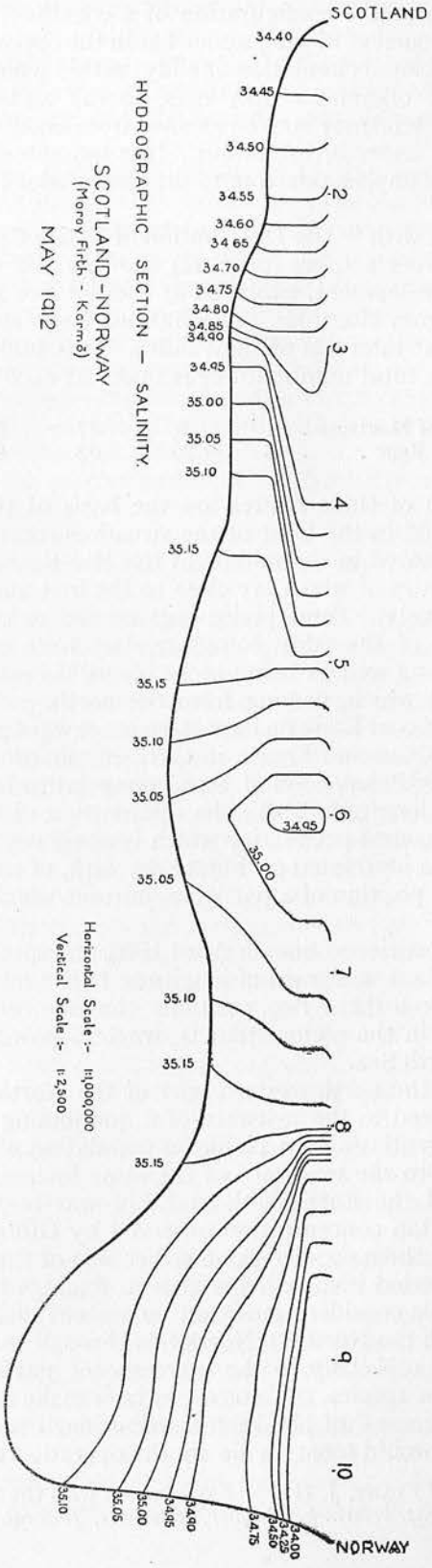

HYDROGRAPHIC SECTION — SALINITY.
SCOTLAND–NORWAY
(Moray Firth - Kormö)
MAY 1912
SCOTLAND
NORWAY
34.40
34.45
34.50
34.55
34.60
34.65
34.70
34.75
34.80
34.85
34.90
34.95
35.00
35.05
35.10
35.15
34.95
35.00
Horizontal Scale :- 1:1,000,000
Vertical Scale :- 1:2,500

FIG. 49.

by other factors such as the configuration of a coastline, or of the sea-bed, or the influence of a near-by current flowing somewhat in the opposite direction, may develop so far as to produce a closed circulation or eddy, within which there will be the further tendency for passive organisms—fish eggs, larvae and the like—to congregate. Evidence of the latter tendency is to be gleaned from much of the biological literature dealing with the area under investigation. It is too extensive to quote fully in this discussion, but two examples, referring to different regions in the North Sea, may be cited.

In a paper dealing with " The Distribution of Plaice Eggs in the Northern North Sea " Bowman (**2**) gives a table (page 41) showing the number of plaice eggs at different stages of development, captured at each of five stations on a line running practically due east from Montrose. The stations, beginning at one mile from Montrose, were occupied at intervals of eight miles. It is sufficient for the present purpose to show only the total number of eggs taken at each position, as follows :—

Distance E. of Montrose .	1	9	17	25	33 miles.
No. of Plaice Eggs . .	8	26	62	23	45

The interpretation of these figures, on the basis of the current system of the area as now understood in the light of the stream-current theory, is that the third station above was situated in the middle of the Mid-East Scottish Coast Eddy, the west and east boundaries of which lay close to the first and between the fourth and fifth stations respectively. Thus, plaice eggs tended to be relatively scarce in the faster-moving waters of the eddy boundary, but were concentrated towards the centre of the system, as well as being more plentiful immediately to the eastward of the stream-current which, coming from the north, evidently feeds, as it were, the Mid-East Scottish Coast Eddy on its eastern or seaward periphery.

More recently, Gibbons and Fraser, in their examination of some Scottish plankton collections of 1936,* have found that, along latitude 61° N., from a position north of Shetland to longitude 2° E., the distribution of the copepod *Calanus finmarchicus* showed a marked peculiarity which is obviously to be explained by reference to the currents as illustrated on Figure 48, with, of course, due allowance for a slight variation in the position of a particular current which may occur from year to year.

Along the above-mentioned line, in April 1936, the species in question was found to be relatively abundant westward of longitude 1° E. and eastward of about longitude 1° 30′ E. Between these two positions the numbers of *C. finmarchicus* fell away almost to zero, in the region, that is, where a powerful stream-current flows into the Northern North Sea.

Farther south, in the north-western part of the North Sea, a concentration of Rhizosolenia was noticed to the eastward of a line joining Fair Isle and Sumburgh Head, Shetland, differentiating the plankton population of this region from that of the area immediately to the westward of the same line. There can be little doubt that the operation of the East Shetland Eddy was responsible for this marked phenomenon in plankton concentration observed by Gibbons and Fraser. It may be remarked also that these conditions on either side of the Fair Isle-Sumburgh line corroborate, for the period involved, the general findings from drift-bottle analyses and other hydrographic considerations that no current directly connects the Faroe-Shetland Channel with the Northern North Sea through this opening.

As elsewhere also, especially in the more recent publications dealing with the occurrence of plankton species, the above authors make mention of a phenomenon referred to as " patchiness " of plankton distribution, the explanation of which, to an important extent, would seem to lie in the operation of stream-currents in the

* Gibbons, S. G., and Fraser, J. H. :—" Experiments with the ' Hardy ' Plankton Indicator in Scottish Waters." *Cons. Intern. p. l'Explor. de la Mer, Journal*, Vol. XII, No. 1, 1937.

regions concerned. Further investigation of this matter, in conjunction with other biological questions and their hydrographical relationships, is in progress, for, of course, as regards marine organisms in general, there are other than mere mechanical dependencies on the circumstances of environment which undoubtedly play a most significant part in all forms and probably at all stages of marine life.

In the discussion of the drift-bottle results of 1912 in relation to those of 1910 and 1911, it was shown that surface-drift velocities in the Northern and Middle North Sea varied in a like manner and almost between the same limits in all three years, pointing to some underlying natural law to which this variation is subject.

The variation is in direct relation to the seasonal variation which has for long been known to occur in the intensity of the Atlantic current in the Faroe-Shetland Channel, the most powerful stream-current in the whole region investigated, and temperature, but more especially salinity observations, collected during the past thirty odd years —as well as drift-bottle analyses—make it a matter of course to connect the stream-current entering the North Sea from the north with this powerful oceanic current passing through the Faroe-Shetland Channel.

Evidently, therefore, the motive power of the Northern and Middle North Sea circulation as a whole is derived, in greatest measure, from the stream-current of oceanic water which enters from the north between Shetland and Norway, fluctuations in the strength of this current being conditioned largely by events in the Faroe-Shetland Channel.

The Atlantic water influx into the Northern North Sea has always been looked upon as in the nature of an offshoot or branch from the major current in the Faroe-Shetland Channel, the greater part of which is supposed to continue its north-easterly course from the region north of Shetland over towards, and finally along, the Norwegian coast, although at some distance from it. Some doubt is cast upon the latter assumption by certain drift-bottle courses to which reference has already been made. These are the routes estimated in respect of drifters liberated all the way across the northern part of the Faroe-Shetland Channel in the months of May and/or June in each of the three years 1910 to 1912 inclusive. The significance of these routes would seem to be that, in surface layers at all events, and in the above months, none of the Atlantic water *which passes through the Faroe-Shetland Channel* proceeds into the higher latitudes of the Norwegian Sea—all of it apparently enters the Northern North Sea. The Atlantic water which *is* found at this season of the year off the coast of Norway beyond about latitude 62° N. would seem to have come by way of *the west and north of Faroe*, not through the Faroe-Shetland Channel. In August, conditions are obviously different. Then, apparently, a part of the Faroe-Shetland Channel Atlantic current does pass eastwards across the northern entrance to the North Sea and thereafter immediately northwards along the Norwegian coast.

To conclude this report, an attempt may be made, on the basis of the 1912 cartographical analysis, to assess the general hydrographic conditions of that year in terms of their chief factor, the Atlantic or oceanic influence, as opposed to the Baltic or continental influence.

As argued above, the Atlantic impulse into the Northern North Sea takes the form of a stream-current entering from between Shetland and Norway, and, secondly, the motive force of the Northern and Middle North Sea circulation as a whole is derived in greatest measure from this current. The velocity-curve, Figure 47, may therefore be taken to indicate the varying intensity of the Atlantic incursion throughout the year.

It is evident, then, that the Atlantic inflow in the first quarter of 1912 increased rapidly towards maximum intensity in the month of April. In support of this deduction there is the argument that, probably on account of increased pressure from the north, the Mid-East Scottish Coast Eddy changed its superficial form during

April from the elliptical to the circular, the change being accompanied by a more southerly orientation of the system.

Various circumstances point to the fact of the Atlantic incursion of 1912 having been, on the whole, relatively weaker than that of the previous year, although probably not so weak as that of 1910. Firstly, the gradient of the velocity-curve after the maximum, indicating diminution in the intensity of the Atlantic inflow, was much steeper in 1912 than it was the year before, but not so steep as in 1910. The inference that maximum intensity was registered two months correspondingly later in 1910 than in either of the two years following would seem to indicate a weaker spring oceanic impulse towards the Northern North Sea in that year.

The fact that all three velocity-curves show the same maximum as regards the actual velocity attained may be explained, with reference to the Atlantic incursion, by assuming that, while the *velocity* of the stream-current concerned was probably the same in all three years at the period of its maximum intensity, the *amount of water* borne by the stream differed from year to year to such an extent as to bring about the above-mentioned differences in the so-called intensity of the incursion.

The existence of these differences in the three years in question is further suggested by the relative positions of the Great Eddy in the spring or early summer period, particularly with reference to the northern boundary of the system, the position of which will obviously depend to a great extent upon the southerly force directed against it by the incoming water-masses. The drift-bottle data for all three years fortunately allow of a fairly accurate determination of the northern limit of the Great Eddy circulation about the months of May and June, and it is seen that this limit was most northerly in 1910, less so in 1912, and still more to the southward in 1911, when the Atlantic incursion seems to have been particularly strong.

Then, in the early part of 1911, a comparatively unusual but apparently significant group of recoveries took place on the shores of Denmark and Schleswig-Holstein south of Blaavandshuk—unusual from the point of view of their locality, and significant on account of the hydrodynamical conditions from which they probably resulted, and which, therefore, conversely, they may be taken to indicate. A similar group of returns was made in 1912, but at a different period of the year, namely, in the months of November and December. It is suggested that this class of recovery is associated with an accession to the strength of the Atlantic incursion from the north, an inference for which, on the basis of the deduction connecting the velocity-curves derived from drift-bottle data with the Atlantic inflow, there is sufficient justification in the trend of the 1911 and 1912 curves during the periods concerned.

An increase in the intensity of the Atlantic influx into the Northern North Sea, however, would probably not of itself be sufficient to account for the above-mentioned stranding of drifters on the Schleswig-Holstein coast, for, as a rule, a similar influx through the Straits of Dover would tend to direct the courses of drifters from the south-west Dogger area, at least to somewhat higher latitudes on the west coast of Denmark. Carruthers, however, has pointed out (**3***b*) that these two forces, one from the north and the other from the south, probably bear a complementary relationship towards each other, an accession to the one being associated with a corresponding diminution in the other. The above results, if their interpretation with reference to the northerly Atlantic inflow is correct, afford some confirmation of Carruthers's suggestion.

After April 1912, then, the intensity of the oceanic incursion into the Northern North Sea apparently diminished steadily to a minimum in September, to be followed, according to the above argument, by a marked reaccession to the strength of this impulse, whether by an increase in the amount of oceanic water transported into the region, or by an acceleration of the current bearing such water. The following observations, drawn from the foregoing cartographical analysis, support these deductions from the 1912 velocity-curve.

The Mid-East Scottish Coast Eddy has already been cited as having altered its

shape, and to some extent its position, under the influence of increased pressure from the northward, when the intensity of the oceanic inflow was about its maximum. Just at the time when, according to the velocity-curve, minimum intensity was registered, namely, in September, the analysis of certain drift-bottle records shows that the Mid-East Scottish Coast Eddy reverted to its earlier form and position.

Secondly, there is evidence that the northern limit of the Great Eddy remained at about the same latitude from May to September inclusive, but that, after September, this limit was gradually pushed southwards into the Northern North Sea, an effect which was evidently experienced also by the East Shetland Eddy in its complete form.

Again, the North-East Dogger Bank Swirl, in order to merge with the Lindesnaes Eddy, almost certainly travelled northwards during the months of May, June and July. After coalescence and " adjustment " of the resultant system, there is evidence that its translation southwards again quickened, as from September to the beginning of November, when it took up a comparatively stable position over the north-east end of the Dogger Bank.

Further evidence of a similar kind is to be gleaned from a study of the curves representing the tracks of drifters across the Middle North Sea, pointing to the actuality of the above-mentioned fluctuation in regard to the oceanic influence in the Northern and Middle Areas during 1912.

In view of the events which appear to have marked the close of this year, the analysis of the drift-bottle records for 1913 should prove interesting. Already, from a perusal of the records, it is evident that at least a part of the year was characterised by conditions which have not so far been encountered in these investigations.

LIST OF REFERENCES.

1. Böhnecke, G., " Salzgehalt und Strömungen der Nordsee." *Veröff. d. Inst. f. Meereskunde*, N.F., A, Heft 10, Berlin, 1922.
2. Bowman, A., " The Distribution of Plaice Eggs in the Northern North Sea." *Fisheries, Scotland, Sci. Invest.*, 1914, II, Edinburgh, 1914.
3. Carruthers, J. N. (*a*) " The Water Movements in the Southern North Sea, Part I. The Surface Drift." *Min. Agric. and Fish., Fish. Invest.*, II, Vol. III, 2, 1925.
   (*b*) " Certain Fishery Applications of the Results of Researches on Marine Currents carried out from the Lowestoft Fisheries Laboratory." *British Association for the Advancement of Science*, Report, 1934, p. 325.
4. Fulton T. W., " The Currents of the North Sea and their Relation to Fisheries." *Fishery Board for Scotland*, 15th Report (1896), Edinburgh, 1897.
5. Gilson, G., " Exploration de la Mer sur les Côtes de Belgique. Recherches sur la dérive dans le Mer du Nord." *Mem. du Musée Royal d'Hist. Nat. de Belgique.*, Tome VIII, No. 35, Brussels, 1924.
6. Helland-Hansen, B., " Report on Hydrographical Investigations in the Faroe-Shetland Channel and the Northern Part of the North Sea in 1902." *North Sea Fish. Invest. Comm., 1st Report (Northern Area), Hydrography*, 1905.
7. Helland-Hansen, B., and Nansen, F., " The Norwegian Sea. Its Physical Oceanography." *Report on Norweg. Fish. and Mar. Invest.*, Vol. II, 1909, No. 2.
8. Le Danois, Ed., " Les Transgressions Océaniques." *Revue des Travaux de l'Office des Pêches Maritimes*, Tome VII, Fasc. 4, Paris, 1934.
9. Liebert, F., " Proefnemingen met Drijfflesschen in de zuidelijke Noordzee." *Jaarb. van het Rijksinst. voor het onderzoek der See*, Helder, 1911.
10. Tait, J. B. (*a*) " The Surface Water Drift in the Northern and Middle North Sea, etc., Part I." *Fisheries, Scotland, Sci. Invest.*, 1930, No. II., Edinburgh, 1930.
    (*b*) " The Surface Water Drift in the Northern and Middle North Sea, etc., Part II, Section 1." *Fisheries, Scotland, Sci. Invest.*, 1930, No. IV, Edinburgh, 1930.
    (*c*) " The Surface Water Drift in the Northern and Middle North Sea, etc., Part II, Section 2." *Fisheries, Scotland, Sci. Invest.*, 1931, No. III, Edinburgh, 1932.

(*d*) " Surface Drift-Bottle Results in Relation to Temperature, Salinity and Density Distributions in the Northern North Sea." *Cons. Intern. pour l'Explor. de la Mer, Rapp. et Proc. Verb.*, LXXIX, III, 8, 1934.

(*e*) " Hydrographical Survey of the Moray Firth." *Ibid.*, LII, 1928.

11. WENDICKE, F., " Hydrographische und biologische Untersuchungen auf den deutschen Feuerschiffen der Nordsee, 1910–11." *Veröff. d. Inst. f. Meereskunde*, N.F., A, Heft 3, Berlin, 1913.

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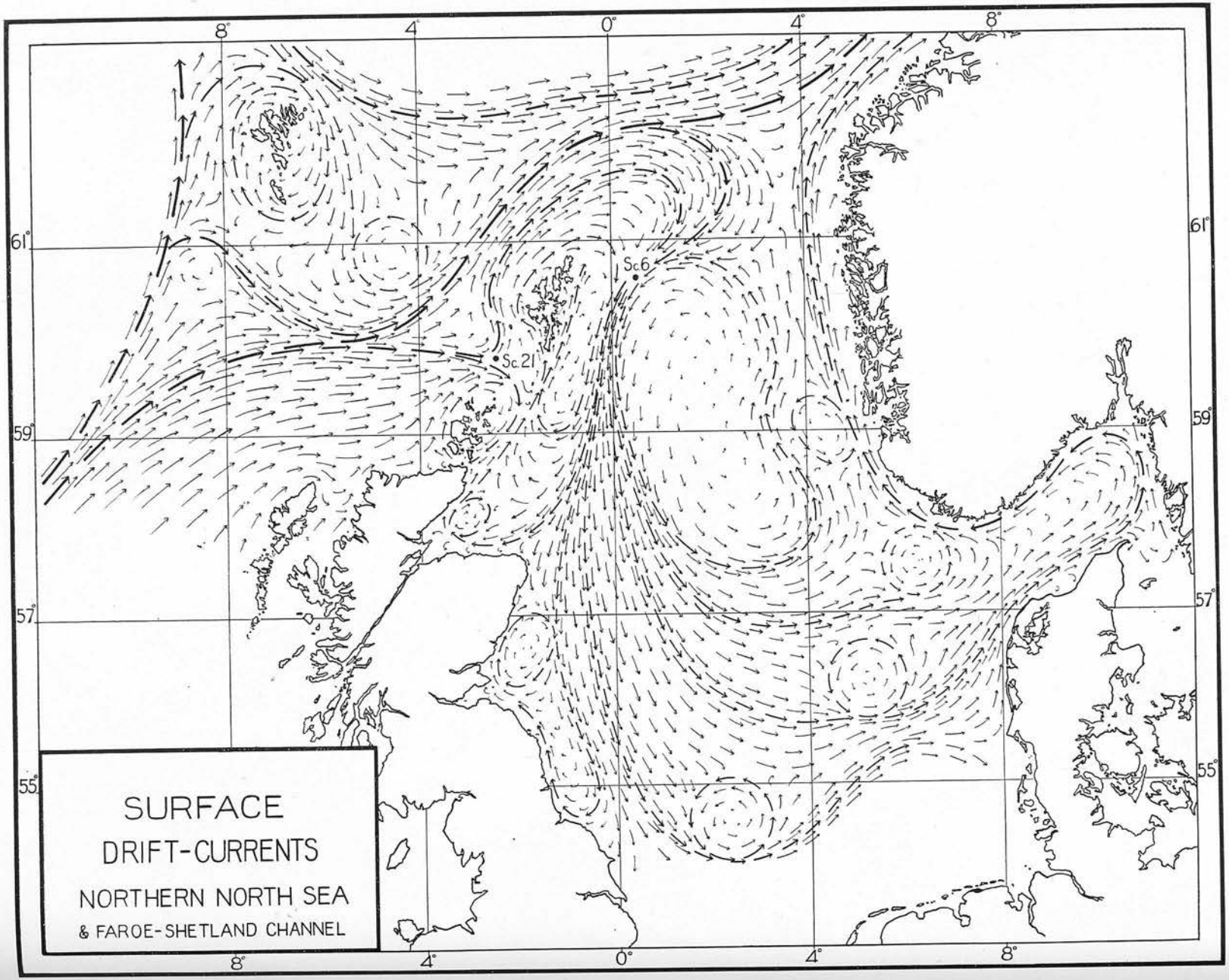

8°
4°
0°
4°
8°
61°
59°
57°
55°
Sc.6
Sc.21
SURFACE
DRIFT-CURRENTS
NORTHERN NORTH SEA
& FAROE-SHETLAND CHANNEL

Fig. 1.

8.

Surface Drift-Bottle Results in Relation to Temperature, Salinity and Density Distributions in the Northern North Sea.

By

JOHN B. TAIT, Aberdeen.

Recent analyses of the records of extensive surface drift-bottle experiments in the Northern North Sea and adjacent waters[1]) have produced some striking results in relation to the surface current system of these regions. Moreover, evidence is not wanting that, with reasonable modifications, at least the major findings are applicable also to sub-surface currents.

The above-mentioned results are the outcome of a close study of drift-bottle records on their own merits. In other words, their cartographical interpretations, which form the subject matter of the two latter papers quoted above and the basis also of the present discussion, were accomplished without the aid of information upon currents obtained by other means. The question, then, arises as to how these drift-bottle results compare with the indications as to currents afforded by independent investigation, notably, as the most prolific source of such knowledge hitherto in regard to the Northern North Sea, by computation and deduction from temperature and salinity observations.

The present paper is restricted mainly to a comparison of results bearing upon one of the principal issues of hydrographical investigation in the regions concerned, a more comprehensive survey with reference to the Northern North Sea as a whole requiring fuller treatment than can be given here.

Figure 1 provides an illustration of the currents which surface drift-bottle experiments indicate to be more or less characteristic of the regions involved. It is emphasised, however, that modifications of the scheme here depicted are not infrequently met with in parts, at least, of the area embraced by the diagram. Sometimes, indeed, the currents obtaining within a region bear little resemblance for the time being to those charted.

[1]) J. B. TAIT: The Surface Water Drift in the Northern and Middle Areas of the North Sea and in the Faroe-Shetland Channel. Fisheries, Scotland, Sci. Invest., 1930, Nos. II and IV, and 1931, No. III.

The arrows on the figure are intended primarily to convey the idea of direction only. The heavier arrows have a somewhat distinctive meaning which involves the idea of velocity. They are further explained below. All are entered on the chart with due regard to drift-bottle interpretations.

Mainly in regions south of about latitude 58° N. a close correspondence between drift-bottle results and the current indications of salinity distributions is at once evident from a comparison of Figure 1 with the current diagrams constructed by BÖHNECKE[1]). In particular, certain of the eddies ("Wirbel") established by this authority are again deduced — it might be claimed, in some cases, independently — from drift-bottle studies. Indeed, as regards information concerning eddies, as in other respects, drift-bottle work in the North Sea has advanced beyond what it has so far been found practicable to ascertain from physical data alone. It has been possible, for instance, to define some of these gyratory systems with greater precision as regards their surface area and in respect of certain changes in form and position to which they are liable. Again, especially in more northerly waters, new eddies have been discovered and larger systems of circulation, apparently nucleated in eddies and themselves subject to bounding or limiting influences, have been deduced from drift-bottle results, but have not yet answered, as it were, to temperature and salinity investigations. The essential reason for this lies in the general inadequacy, from the standpoint of current estimation, of the physical material.

The almost necessary minimum of the observations in question, from the point of view of their distribution along the lines of hydrographic sections laid normal to current directions, is suggested by a feature of the writer's cartographical analyses of drift-bottle records. This is to the effect that there are in operation in the

[1]) G. BÖHNECKE: Salzgehalt und Strömungen der Nordsee. Veröff. Inst. Meereskunde, (N. F.), A, 10. Berlin 1922.

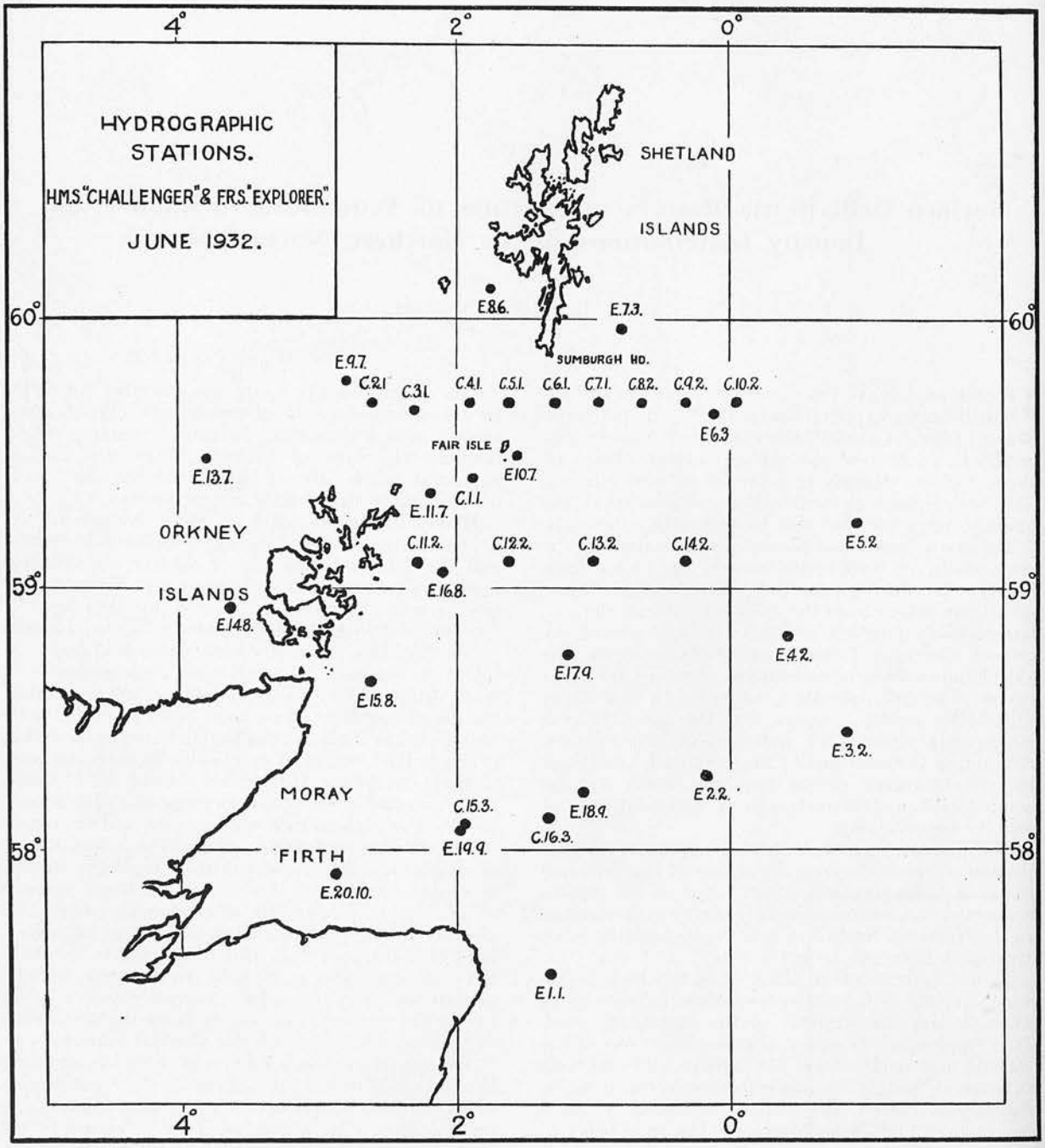

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JUNE 1932.
SHETLAND
ISLANDS
ORKNEY
ISLANDS
MORAY
FIRTH
FAIR ISLE
SUMBURGH HD.
4°
2°
0°
60°
59°
58°
E.8.6.
E.7.3.
E.9.7.
C.2.1
C.3.1.
C.4.1.
C.5.1.
C.6.1.
C.7.1.
C.8.2.
C.9.2.
C.10.2.
E.6.3
E.13.7.
E.10.7.
C.1.1.
E.11.7.
C.11.2.
C.12.2.
C.13.2.
C.14.2.
E.5.2.
E.16.8.
E.14.8.
E.17.9.
E.4.2.
E.15.8.
E.3.2.
E.2.2.
C.15.3.
E.18.9.
C.16.3.
E.19.9.
E.20.10.
E.1.1.

Fig. 2.

North Sea fairly definite stream-currents, which apparently flow within narrow limits, narrower on the whole than the distances generally allowed between consecutive stations on a hydrographic section. This is the meaning underlying the heavier arrows on Figure 1, although these, by their thickness, are not intended to represent, even approximately, the actual widths of stream-currents — merely their central axes, or cores.

It is to be expected that the waters comprising stream-currents may possess different chemical as well as physical properties from those of the adjacent medium on either side. Evidence, in fact, which supports this conception of stream-currents in the North Sea is contained in the different (sometimes markedly different) salinities frequently observed in the open sea at neighbouring stations on a hydrographic section, and many diagrammatic representations, in the usual way, of the properties of sections, enhance the concept from this point of view. The idea, moreover, offers an alternative explanation to that generally advanced, of the great variations occasionally noted within a short interval of time at one and the same hydrographic station. These variations may be due almost entirely to a slight alteration in the direction — part of an oscillation perhaps — of a nearby stream-current and not, as is usually implied, to such radical hydrographical changes as bespeak large and rapid hydrodynamical variations, for, as the writer has elsewhere pointed out, it can be taken as a general rule that modifications in the physical phenomena of the sea in which time is an essential factor do not take place with a marked suddenness approaching instantaneity.

Given, however, a sufficient number of approximately synchronous observations within a given area, close agreement, as regards directions, can be established between surface drift-bottle courses and the currents estimated from temperature and salinity data. This is most effectively demonstrated by a recent investigation in the north-western part of the North Sea, designed to substantiate, if possible, by reference to routine observations of temperature and salinity, a deduction arising from certain drift-bottle analyses pertaining to the summer of 1910 and repeatedly obtained from similar data in respect of various periods since.

According to drift-bottle interpretations (see Fig. 1) the sea area eastward from Orkney and Shetland to about the prime meridian, may, for considerable periods of the year, constitute practically a self-contained region, bounded on the east by a southerly-flowing current from the southern reaches of the Norwegian Sea (i. e. between latitudes 61° and 62° N.) and on the west by a narrow stream issuing from the north-west corner of the Moray Firth and flowing north-eastwards off the eastern shores of Orkney and Shetland. These two currents are connected in the north about latitude 61° N. and in the south approximately along the parallel of 58° N., thus forming a closed anticyclonic system of circulation.

This is at variance with what has until now been accepted, from temperature and salinity distributions, as the normal current régime of the region concerned, the southern half of which has hitherto been thought to maintain a direct current-connection, essentially of Atlantic water, between the Faroe-Shetland Channel and the Northern North Sea[1]). Hydrographical confirmation of a circulation such as that described above was obtained only in June 1932, when, at the same time as the Scottish research vessel "Explorer" was engaged in a survey of the region, the writer, by permission of the Hydrographer of the Navy, was afforded an opportunity, on board His Majesty's Survey Ship "Challenger", of intensifying observations within the area, particularly in the neighbourhood of the Fair Isle — Sumburgh Head passage. "Explorer" and "Challenger" hydrographic stations are differentiated on Figure 2 by the letters "E" and "C" respectively and each series of stations is numbered, first in the order of their performance and second, according to the day of the month upon which observations were taken.

The period embraced by the survey was about ten days. Even so the observations taken within six days of each other at the near-neighbouring stations C.15.3 and E.19.9 showed appreciable differences in the uppermost ten metres. The stations, however, were evidently situated, as can be seen from Figures 3 and 4, on the border of the circulation characteristic of the north-western area at the time. Under these circumstances the differences noted are capable of an explanation on the lines already suggested.

The curves on Figures 3 and 4 are not entered with strict accuracy as regards the interpolation of required values of σ_t. In the present case it is believed that a truer representation of the actual conditions is obtained by the exercise of a legitimate amount of freedom in this respect, firstly on account of the irregular and, for the most part, widely-scattered nature of the original observations and secondly, because of the known hydrographical complexity of the region, which embraces water of at least three, if not four different origins, namely, Atlantic water, west Scottish coast water, eastern North Sea water and probably, to a small extent, inner Moray Firth water. Due cognisance of the latter circumstance has been taken in the construction of the curves of equal density.

Confirmation of the circulation represented on Figure 3 is contained in the cartographical analysis of a number of drift-bottle results embracing the period and area under review. Figure 5 shows the courses estimated in respect of certain drift-bottles liberated in April 1932 and recovered, mainly upon Shetland, in the weeks prior to, identical with and following those of the above survey. The larger figure

[1]) A. J. Robertson: Hydrographical Investigations in the North Sea and Faroe-Shetland Channel during the years 1903 to 1910 inclusive. North Sea Fish. Invest. Comm. (Northern Area), 2nd, 4th and 5th Reports, 1907, 1909 and 1913.

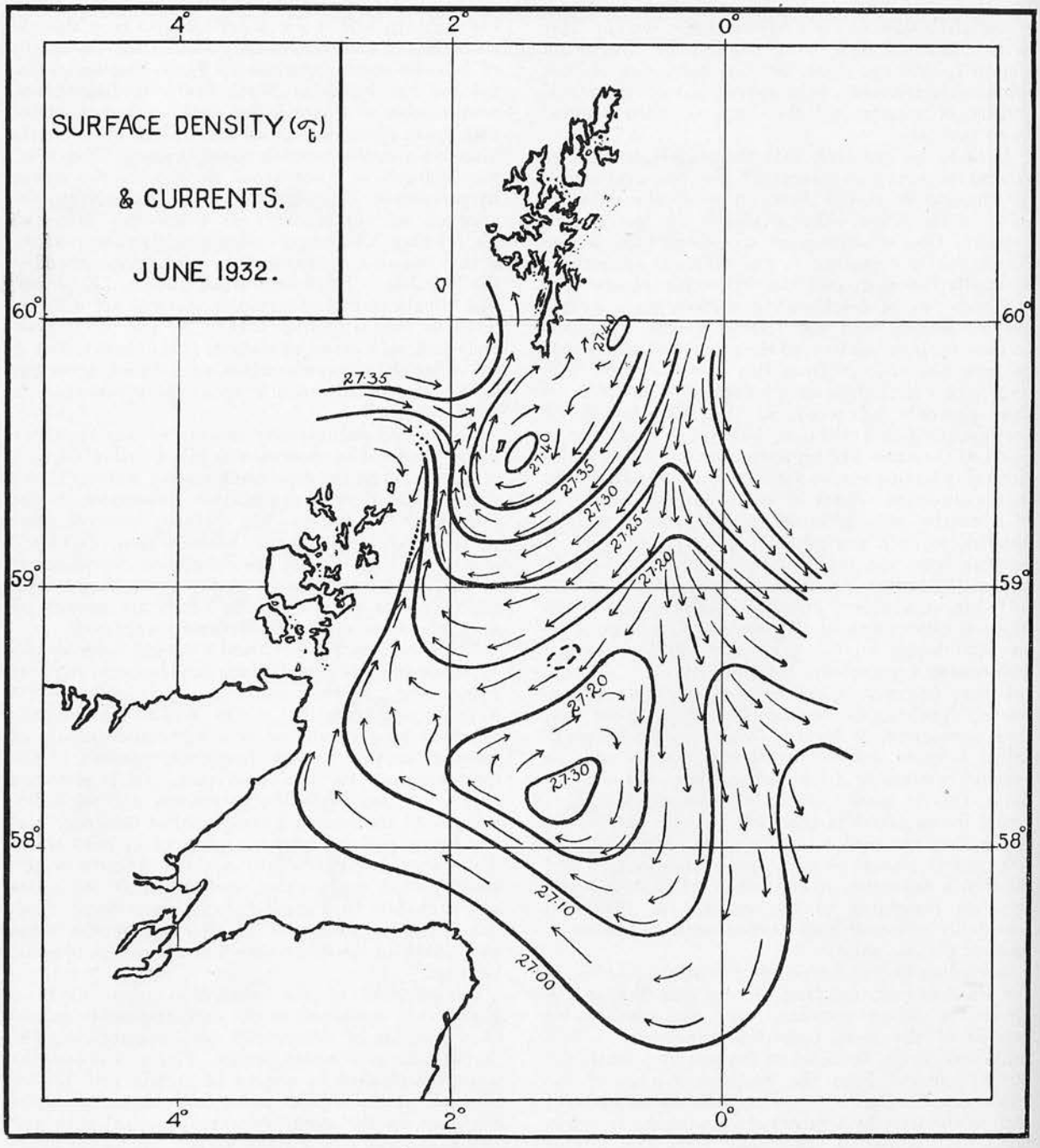

SURFACE DENSITY (σ_t)
& CURRENTS.
JUNE 1932.
4°
2°
0°
60°
59°
58°
27·35
27·40
27·35
27·30
27·25
27·20
27·20
27·30
27·10
27·00

Fig. 3.

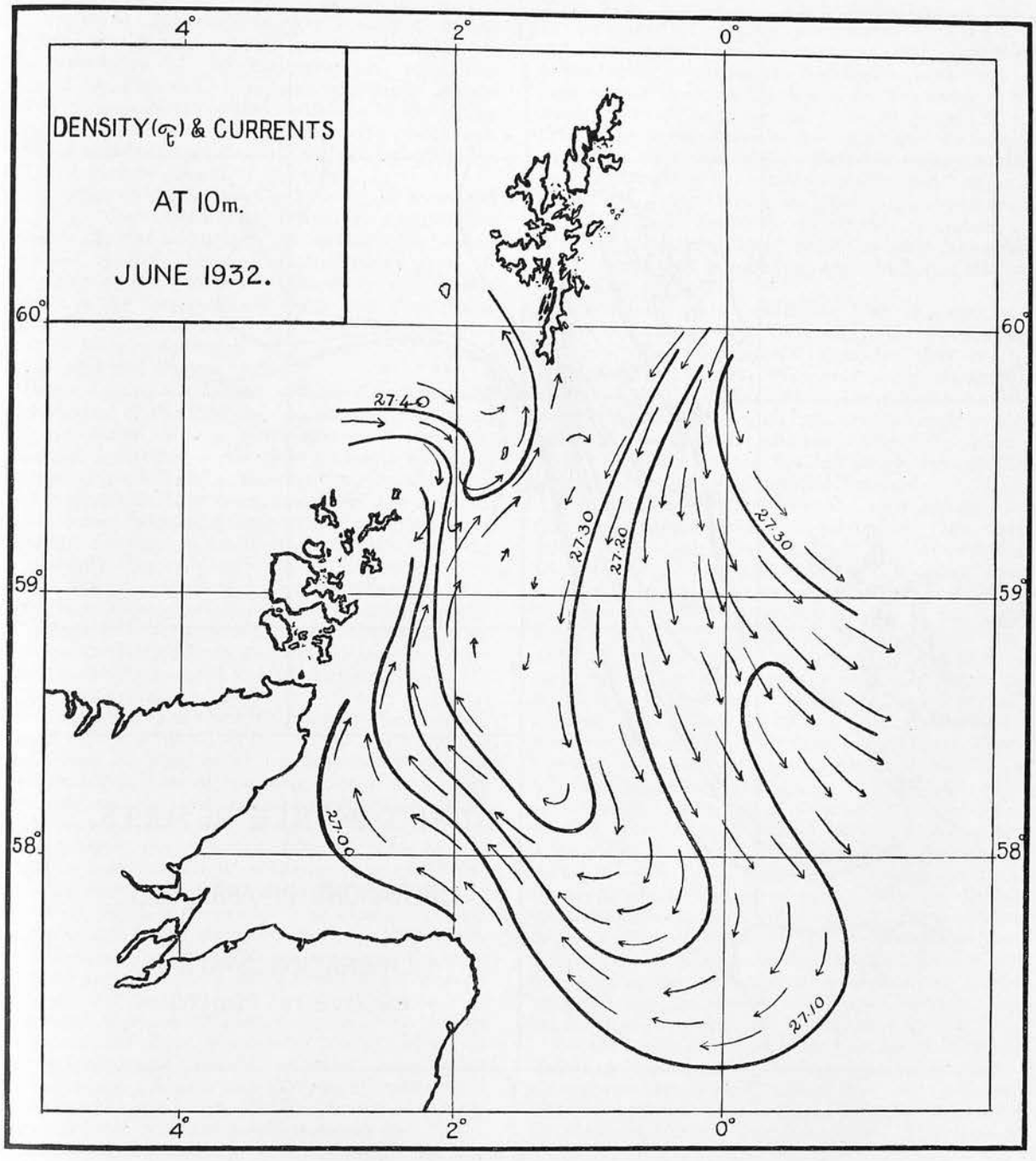

DENSITY (σt) & CURRENTS
AT 10m.
JUNE 1932.
4°
2°
0°
60°
59°
58°
27.40
27.30
27.20
27.30
27.00
27.10

Fig. 4.

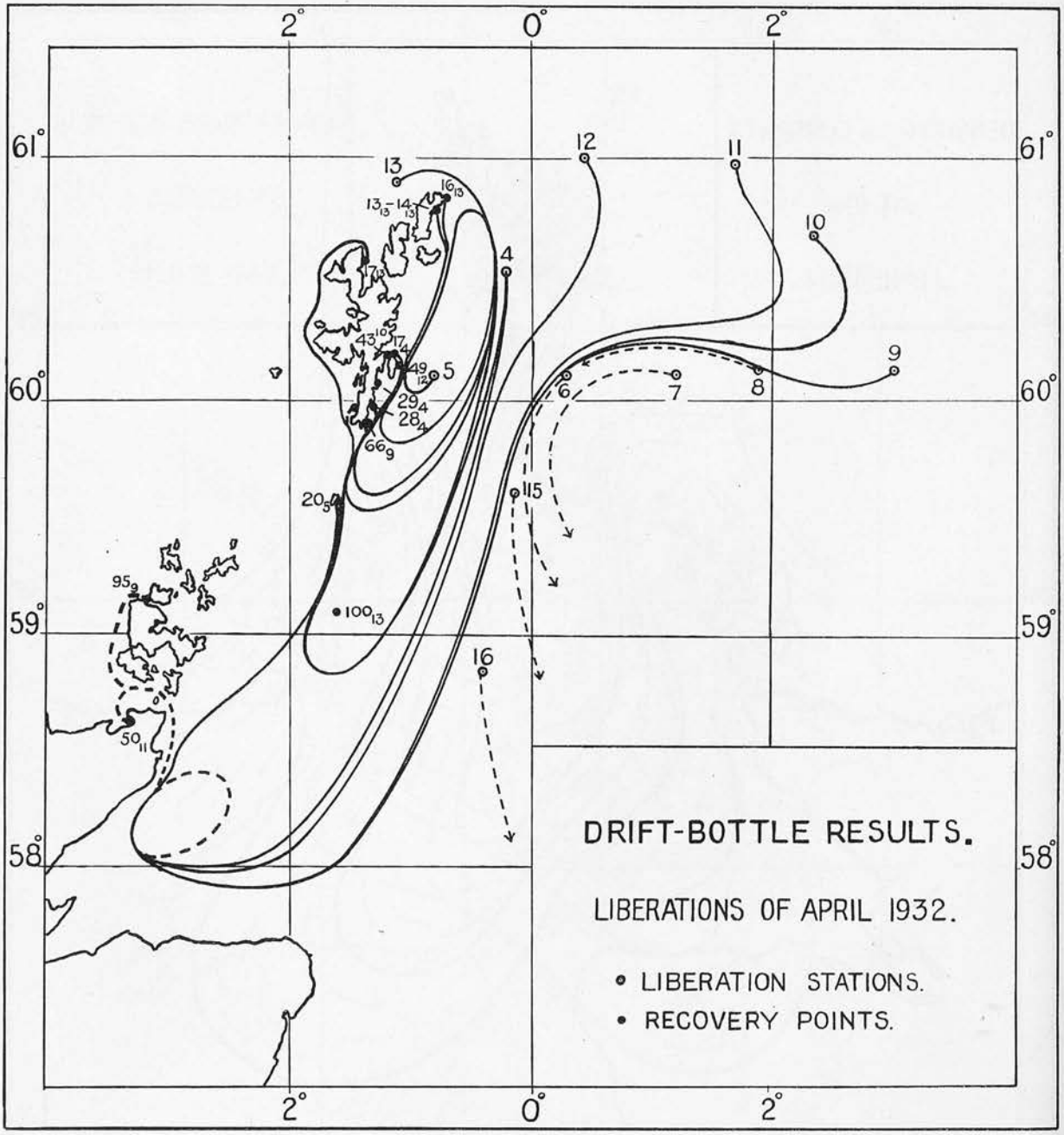

2°
0°
2°
61°
60°
59°
58°
12
11
13
10
4
9
5
6
7
8
115
16
DRIFT-BOTTLE RESULTS.
LIBERATIONS OF APRIL 1932.
LIBERATION STATIONS.
RECOVERY POINTS.

Fig. 5.

beside a recovery point denotes the number of days between liberation and recovery, the smaller, index figure referring to the liberation-station bearing the same number. This chart is given exactly as it was derived, that is, independently and in fact without full knowledge of the hydrographical conditions implied by Figure 3. Comparatively slight adjustments to some of the routes, especially in the Moray Firth region, will clearly bring about the coincidence of these drift-bottle courses with the hydrographically-deduced current system of the area.

The drifter which is shown as having been recovered at sea, 100 days after liberation from the April station number 13, was taken from the surface by herring drift-net on 27th July, 1932. This result gives an indication of the duration of the above anticyclonic system in the north-western North Sea. From these and later drift-bottle results this system can be shown to have been in operation from about the middle of April until mid-August 1932.

Before passing to the consideration of an important consequence of the foregoing conclusions relative to the circulation of the north-western North Sea, attention is directed to the close similarity obtaining between Figures 3 and 4, showing the currents at ten metres depth to have been essentially the same as at the surface. Existing hydrographical records contain sufficient evidence to justify the inference that this is generally true of the Northern North Sea as a whole. Hence, following a demonstration such as that given above, greater confidence may be placed in surface drift-bottle analyses as a source of intelligence regarding currents which do, in fact, lie deeper than the most superficial stratum of water to a depth of only a few inches.

The current system which may therefore be accepted, if not as the normal régime of the north-western North Sea, at least as of frequent occurrence for considerable periods of the year, reacts, as already indicated, upon a fundamental conception in regard to the water economy of the entire Northern North Sea. Hitherto, the influx of Atlantic water to this area has been conceived as taking place chiefly to the southward of Shetland and only secondarily by way of the north of these islands and thence through the opening between them and Norway. Drift-bottle results strongly suggest that the reverse is the case, if indeed any appreciable influx occurs at all between Scotland and Shetland.

In short, it is not difficult to associate the heavier arrows in the Faroe-Shetland Channel region of Figure 1 with the powerful Atlantic stream which passes through this area and, carrying the association a step farther, it appears that the essential current-connection (of Atlantic water) between the Faroe-Shetland Channel and the Northern North Sea lies by way of the north of Shetland and the Shetland-Norway opening.

The following hydrographical facts support this deduction from bottle-drifts.

The positions of the early Scottish hydrographic stations Sc. 6 and Sc. 21 are given on Figure 1. On five of the six occasions, representing the months of May, June, August and November in one or more of the years 1902 to 1904, when almost synchronous observations were taken at these two stations, salinities at the former position were, at all depths, considerably higher than those at the latter. In the exceptional instance, which refers to the month of August 1902, the fresher water found in the uppermost 20 metres at station Sc. 6 was almost certainly carried round to that position on the outskirts of the Great Northern North Sea Eddy[1]) from the North Sea Norwegian coastal region, probably from the off-region of Stavanger, or Utsire Island. Salinities below 20 metres were, at the time in question, again higher at station Sc. 6 than at Sc. 21.

Incidentally, it is remarkable that this anomaly should occur in the year 1902, for, in his report upon the Scottish hydrographical data for that year[2]), HELLAND-HANSEN gives the only other statement apart from the above, of which the writer is aware, concerning the greater significance, as regards the inflow of Atlantic water into the Northern North Sea, of the Shetland-Norway opening as opposed to the passages between Shetland and Scotland.

Hydrographically, however, the case against the Shetland-Scotland passages, particularly the Fair Isle — Sumburgh Head Channel, as entrances for Atlantic water from the west, can be more convincingly illustrated by appropriate sections. Several of these, representing various months of the year, can be taken from Scottish hydrographical records. They are, almost without exception from the present point of view, characteristically similar to Figure 6, which is the "Challenger" section of nine closely-set stations on latitude 59°42′ N. running practically midway through the Fair Isle — Sumburgh Head Channel, as shown on Figure 2. It is at once clear from the dispositions of isotherms and isohalines that there was not a free flow of Atlantic water from west to east through this channel in the beginning of June 1932. The isotherms particularly, which, for values below 8.5° C. to 8.0° C., are entered at 0.1° C. intervals, are indicative of a section more or less across the main current directions rather than parallel to them. This, of course, we now know to have been the case from Figure 3. Relative to the matter under discussion at the moment there was clearly an hiatus between east and west conditions between the longitude of Sumburgh Head and that of Fair Isle.

For the openings between Fair Isle and the Scottish mainland, the numerous salinity values scattered throughout the records contain the best evidence available against the incursion of Atlantic water into the Northern North Sea by these routes. These values

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[1]) See the writer's drift-bottle papers already quoted.

[2]) B. HELLAND-HANSEN: Hydrographical Investigations in the North Sea and Faroe-Shetland Channel in the Year 1902. North Sea Fish. Invest. Comm. (Northern Area), 1st Report, 1905.

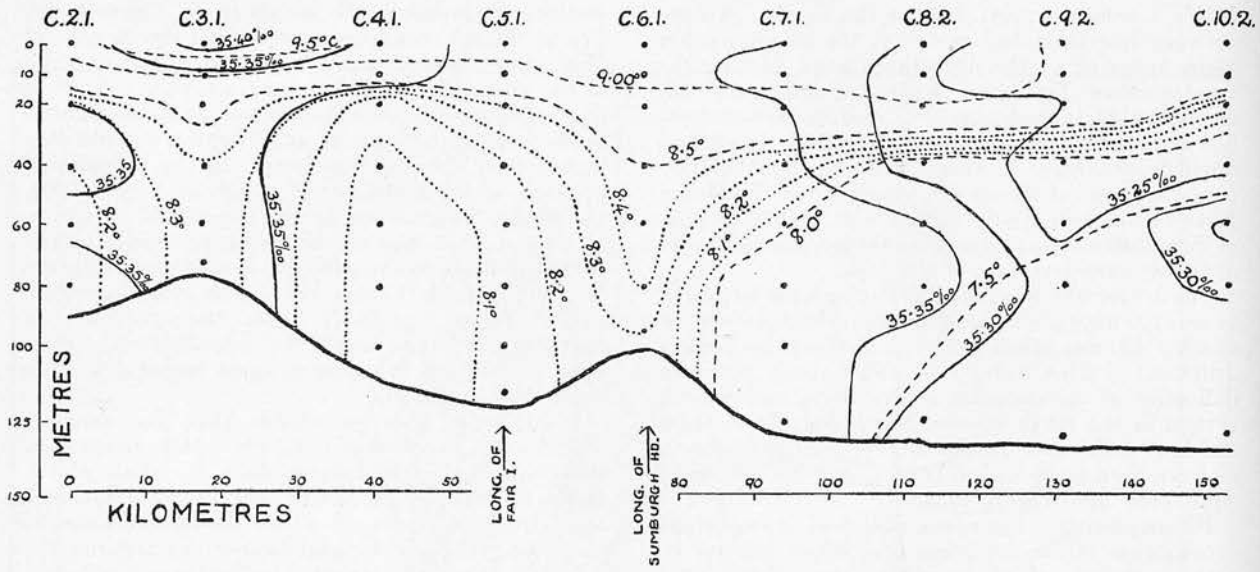


Fig. 6. Hydrographic Section: Fair Isle — Sumburgh Head Channel. H.M.S. "Challenger". June, 1932.

as a rule bear witness to the envelopment of Orkney in water of west Scottish coast origin, which, as is clear from Figure 1, is in agreement with the indications of drift-bottle results.

Not only, however, do drift-bottle investigations suggest the Shetland-Norway opening as the principal, if not practically the only way by which Atlantic water finds access to the Northern North Sea, but they carry the further implication that entry is effected by this route essentially in the form of a stream-current of fairly definite and limited width. Moreover, this stream-current appears generally to be centred considerably to the eastward of Shetland and not, as hitherto believed, in close proximity to the eastern shores of these islands.

Appropriate hydrographical sections across the northern entrance to the North Sea, from which to obtain, if possible, corroboration of this deduction, are unfortunately scarce and the stations on those sections which are available are usually few and far apart. Nevertheless, in a section such as that of Figure 7, there is evidence, which is supported by a close study of the scattered data referring to the area concerned, that the foregoing inference from drift-bottle work is substantially correct.

In like manner, isolated hydrographical material can be found to yield strong support to the current indications of drift-bottle results in other parts of the Northern North Sea and contiguous areas.

So far we have dealt only with the directions of currents. Further relationships between hydrographical and drift-bottle results are arguable in respect of velocity, the second of the two chief characteristics of currents from the point of view of the original purpose of surface drift-bottle experiments in the Northern North Sea, namely, to gain insight into questions of the transport of plankton organisms, especially of fish eggs and larvae.

The absence of a certain condition in regard to the North Sea itself precludes the calculation of absolute current velocities from temperature and salinity data by means of BJERKNES' well-known circulation theory, such as have been obtained in respect of the Faroe-Shetland Channel. It is established beyond question, however, that there is an intimate connection between the principal currents in the Northern North Sea area and those of the Faroe-Shetland Channel, so that current velocities in the former region probably do not differ very markedly on the whole from those found to obtain in the latter, certainly not so much as, previous to the writer's drift-bottle investigations, might be inferred from the figures available.

In the Faroe-Shetland Channel the surface current velocity of the Atlantic stream has repeatedly been computed from hydrographical data[1]) and found to vary between a maximum of 12 to 16 nautical miles per day in spring or early summer and a minimum of 6 to 8 miles per day in autumn or winter. Hitherto, the only figure for the Northern North Sea was that given by FULTON as a result of his drift-bottle studies[2]), namely, an "average" value of between two and three miles per day, although his records do contain evidence of much higher velocities. These, however, were

[1]) See papers by B. HELLAND-HANSEN and A. J. ROBERTSON previously noted.

[2]) T. W. FULTON: The Currents of the North Sea and their Relation to Fisheries. Fishery Board for Scotland, 15th Annual Report, 1897, Part III, p. 334.

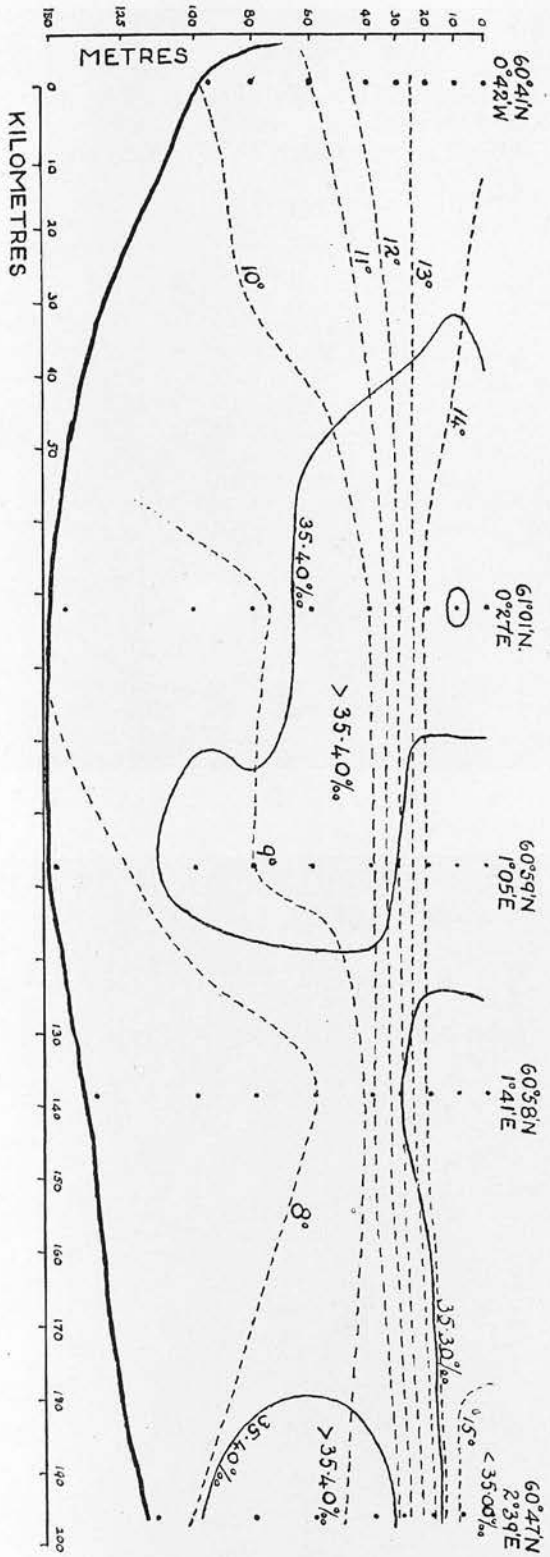


Fig. 7. Hydrographic Section: NE.—E.-ward from Unst, Shetland. F.R.S. "Explorer". July 1933.

treated as anomalies as also were extremely low velocities of a mere fraction of one mile in 24 hours.

That a closer relationship exists between current velocities in the Northern North Sea and those which have been calculated in respect of what may be termed, in relation to this area, the "parent" region of the Faroe-Shetland Channel, is clear from Figures 8 and 9 which show the time-velocity curves derived, on the basis of certain assumptions[1]), from surface drift-bottle analyses referring to the years 1910 and 1911 respectively. The velocities there represented vary seasonally between about five and almost thirteen miles per day, the seasonal variation corresponding with that of the Faroe-Shetland Channel. This circumstance effectively disposes of the "average" idea in regard to the Northern North Sea.

There is still a sense, however, in which the above velocity curves represent only mean conditions. Referring again to the matter of stream-currents, it is more than likely that, in the centre of such a current, the velocity will be slightly greater than to right and left. The following quotation from FULTON supports this argument.

"It also appears that the speed is, as a rule, greatest at some distance from the coast of Scotland and the north of England; that it diminishes quite near the coast and likewise at a considerable distance, say 50 or 60 miles, from it."

It is still more probable, if not practically certain that, contemporaneously, the surface current velocity varies somewhat from place to place over the Northern North Sea. Neither of these variations, however, appears to be so significant as to affect, materially, the cartographical analysis of drift-bottle records on the lines adopted, as evidenced by the fact that a smooth curve results from the assumption that the velocity estimated in respect of a small but essential part of the entire area may be taken as representative of conditions in any similar part, or, in effect, in the whole area.

Besides the above apparently close connection between hydrodynamically-computed surface velocities in the Faroe-Shetland Channel and those estimated from bottle-drifts in the Northern North Sea, there is another inference of a hydrographical character which may be drawn from the velocity-curves of 1910 and 1911. In the first place, by their similarity of form, these curves bespeak a more general applicability of the conditions they represent than as pertaining exclusively to the two years in question. Both exhibit a maximum of practically the same magnitude and, although the 1911 curve stops short of a minimum, there is evidence from the cartographical analysis of drift-bottle data for the following year that probably the same minimum velocity was

[1]) Fisheries, Scotland, Sci. Invest., 1931, No. III, p. 12.

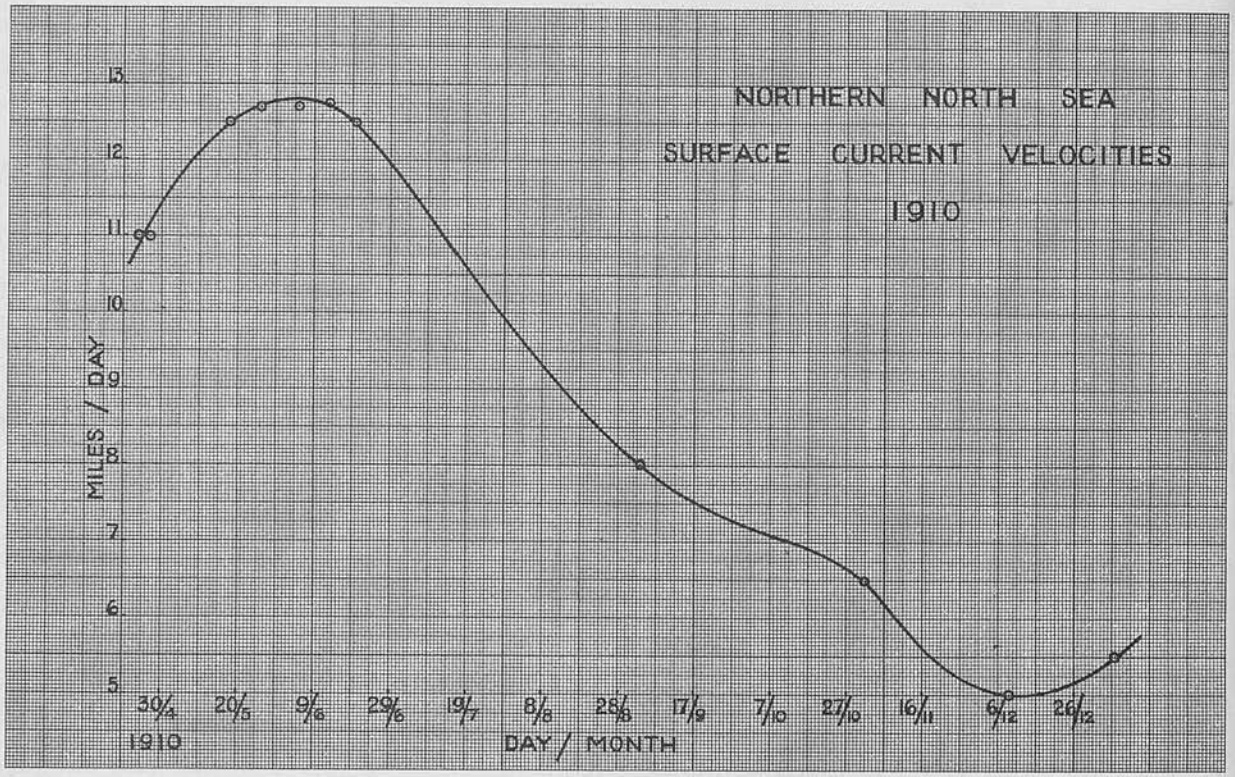

NORTHERN NORTH SEA
SURFACE CURRENT VELOCITIES
1910
MILES / DAY
13
12
11
10
9
8
7
6
5
30/4
20/5
9/6
29/6
19/7
8/8
28/8
17/9
7/10
27/10
16/11
6/12
26/12
1910
DAY / MONTH

Fig. 8.

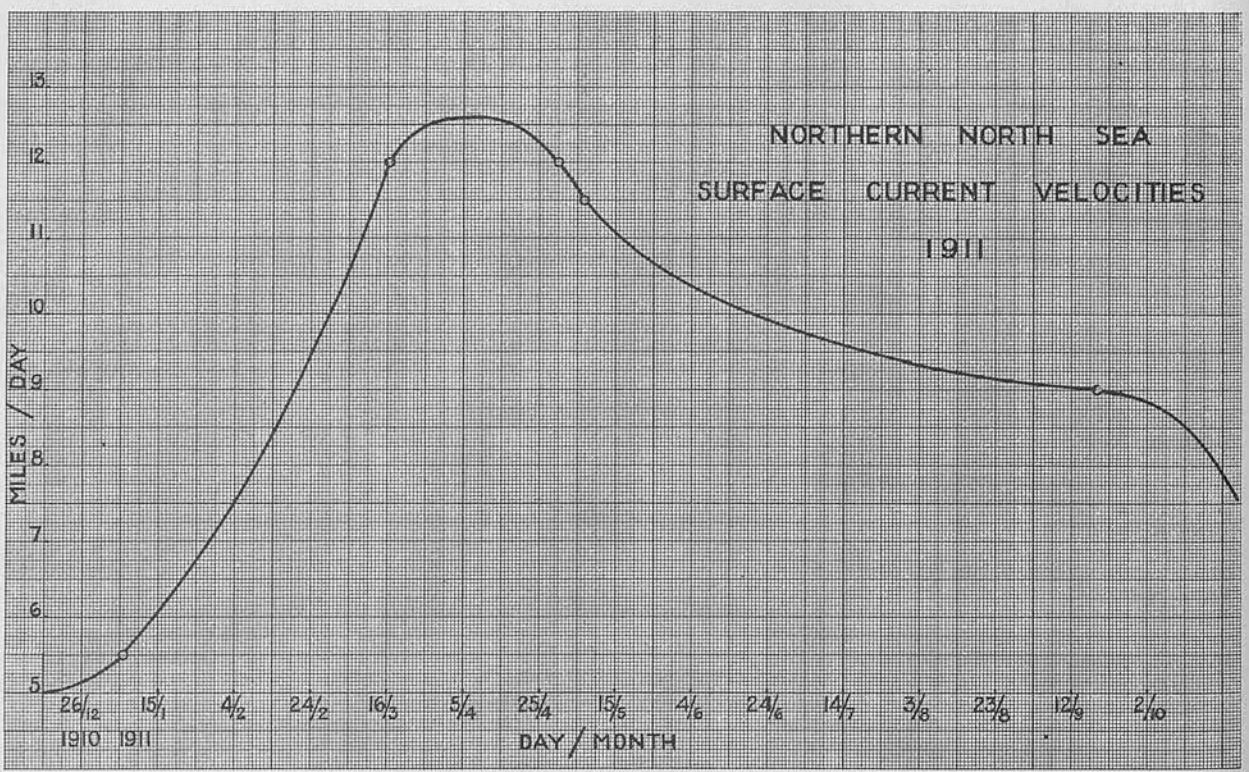

NORTHERN NORTH SEA
SURFACE CURRENT VELOCITIES
1911
MILES / DAY
13
12
11
10
9
8
7
6
5
26/12
15/1
4/2
24/2
16/3
5/4
25/4
15/5
4/6
24/6
14/7
3/8
23/8
12/9
2/10
1910 1911
DAY / MONTH

Fig. 9.

registered towards the end of 1911 as at the corresponding period of the previous year. Maximum velocity, however, shows a difference of about two months in its incidence in one year as compared with the other. The association of this difference with a corresponding difference in the incidence of maximum intensity of the Atlantic influx in these two years is prompted by an examination of hydrographical observations extending over a long period and on this matter of the differences in physical conditions to be met with in the Northern North Sea at corresponding times from year to year, the present paper is concluded.

As probably the most far-reaching deduction made from a series of yet incomplete and therefore unpublished drift-bottle and other hydrographical studies, it is clear that, while the principal, broad features of Northern North Sea hydrography, in which the oceanic influence certainly predominates, may be expected to reappear annually and to undergo similar transformations at approximately the same times every year, there are undoubtedly some years in which conditions differ markedly in one respect or another from those which may be said to be generally experienced. The year 1933 in fact would appear to have been such a year, as evidenced by the extraordinarily high temperatures and salinities recorded throughout the summer in the Northern North Sea area.

In other words, variations in the hydrographical and hydrodynamical aspects of this region, not only from one year to another, but even during a particular year, may be so considerable, that it is impracticable meantime, either to argue a general case in any detail, or to submit so-called "normal" or "average" diagrammatic representations, either of hydrographical distributions or of currents, which would be of more than limited practical service from the point of view of the fishery hydrographer, to whom the above-mentioned anomalies would appear to be of greater significance than what, for the present, can best be imagined are standard conditions.

CONSEIL PERMANENT INTERNATIONAL POUR
L'EXPLORATION DE LA MER

EXTRAIT

DU

RAPPORTS ET PROCÈS-VERBAUX, VOL. XCIV, 1935



8.

Recent High Salinity Records from the Northern North Sea.

By

JOHN. B. TAIT, Aberdeen.

In the penultimate paragraph of the paper noted below[1]), the writer remarks upon the apparent singularity of the year 1933 as regards the hydrography of the Northern North Sea; this on account of the extraordinarily high temperatures and salinities recorded for that year and region. As a matter of fact, Scottish hydrographic records for the past four years are remarkable for the numbers of high salinities cited in respect of the Northern Area. This is shown by the following table, which comprises the material from that region where Scottish operations are most consistently carried on, year after year, omitting only the data from proximately coastal stations where water of 35.00 ‰ salinity and over is seldom, if ever, found. The limits of the region, otherwise, are latitudes 57°30′ N. and 61°01′ N., the Shetland-Orkney Islands and longitude 2°30′ W. to the west, and on the east, longitude 3°30′ E., or approximately the 100-fathom bathymetric contour.

Table 1. Frequency-Distribution of Scottish Salinities greater than 34.99 ‰ in the Northern North Sea from 1930 to 1934.

Year	Total No. of Salinities	Frequency-Distribution of Salinities > 34.99‰								
		35.00/.24	.25/.39	.40/.49	.50/.59	.60/.69	.70/.79	.80/.89	.90/.99	> 36.00
1930	705	311	215	2	—	—	—	—	—	—
1931	842	335	319	9	2	1	—	—	—	—
1932	947	369	388	34	9	2	2	—	—	—
1933	728	318	192	41	—	5	3	—	—	1
1934	693	137	399	79	20	5	2	2	—	1

The above table contains salinities of an order which has never before been acknowledged in the Northern North Sea. Moreover, such high values as do occur in the records for this region, appear almost exclusively as isolated surface observations collected by ships *en route*, while a feature of the recent records is that, in the great majority, they apply, not to the surface, but to intermediate and bottom depths. Furthermore, even as surface observations, high salinities have previously been recorded in significant numbers only in reference to a certain few years — 1903 and 1906, for instance, when maximum values of 35.57 ‰ and 35.66 ‰ respectively were obtained. These figures provide a fair index of the highest salinities hitherto recorded in respect of the waters of the Northern North Sea. At the same time, it is probably true to say that their acceptance with any degree of confidence is still not general.

In consequence, therefore, the question of the validity of these later results assumes an added importance, for already, from Table 1, besides the obvious significance of their numbers in terms of oceanic influence in each of the years concerned, there is clearly a further meaning to be attached to the increase in these numbers which has taken place, annually, since 1930.

The numbers themselves, of course, provide an argument in favour of validity, but first of all comes the question of the accuracy of the salinity determinations by the usual chemical method. The accuracy of the method itself is well-known and needs no comment.

It is the custom of the Government Chemist, in whose Laboratory the Scottish salinities are worked out along with others, not only to verify many of the determinations by duplicate titrations performed by independent workers, but also to give notice of adverse circumstances, either in regard to the water-sample or its container, which might have an effect upon the actual salinity of the sample as at the time of its collection. For example, a sample may be advised as having contained sediment, or its volume as having been considerably less than the capacity of the container; or again, the container itself is frequently noted as having been insecurely sealed. All these are obviously factors of possible

[1]) J. B. TAIT: Surface Drift-Bottle Results in Relation to Temperature, Salinity and Density Distributions in the Northern North Sea. Cons. Intern. pour l'Explor. de la Mer. Rapp. et Proc.-Verb., LXXXIX, III, 8, 1934.

consequence to the original salinity of a sample when the interval and conditions of storage are taken into account.

A scrunity of the Scottish Northern North Sea records for the past five years, that is, of the actual figures returned by the Government Chemist, elicits, in regard to the higher salinities recorded — those in excess of 35.39 ‰ are meantime so designated — the information which is summarised in the following table. The significance of the two sections into which Table 2 is divided is explained later.

Chemist definitely states that there was no apparent cause for the extraordinary value recorded. Another fact of importance in this connection is that, according to the "Bulletin Hydrographique" for 1933, Scotland was not alone in obtaining unusually high salinities in the Northern North Sea in that year.

More convincing answers, however, to the question of the validity of some and therefore, by inference, of most if not all of these latest records, appear to be given by certain circumstances in regard to their

Table 2. Concerning the Determination of Scottish Northern North Sea Salinities greater than 35.39 ‰ in the years 1930 to 1934.

Year	Salinities > 35.39 ‰				Salinities > 35.49 ‰			
	Total No.	No of results verified	No. with adverse comment	No. of results not verified	Total No.	No. of results verified	No. with adverse comment	No. of results not verified
1930	2	1	—	1	0	—	—	—
1931	12	6	—	6	3	3	—	—
1932	47	18	1	28	13	9	1	3
1933	50	49[1])	1	—	9	8	1	—
1934	109	68	6	40	30	24	5	6

[1]) All 1933 results and those for the first four months of 1934 were verified as explained above. Thereafter, recourse was had again to the practice of duplicating only a selection of the determinations.

The figures of Table 2 allay any doubt which, on account of the large number of samples handled[1]), might reasonably be entertained as to the accuracy of some, at least, of the higher determinations. Their acceptance, however, as true salinities, as at the time of the collection of water-samples at sea, is still another matter, for although remarkably few determinations appear specifically to have been attended by more or less adverse conditions, it so happens that several more are covered by a general statement as to the imperfect sealing of a number of the containers. To this must be added the known fact that a considerable interval sometimes elapsed between the actual collection of the water samples and their chemical treatment.

By an examination of several hundred containers, which, it should perhaps be mentioned, were practically all "old" bottles in the sense that they had been used repeatedly for the storage of sea-water, the writer was satisfied that any error to be attributed to faulty sealing, in association with lengthy storage-periods during which evaporation from the sea-water samples concerned might be appreciable, was, on the whole, negligible. The fact of the numbers of the high results, particularly those which have occurred during the past two years, cannot thus be fully explained. It is to be remembered also that, still the majority of these high values were not adversely commented upon. Indeed, with reference to one particularly high salinity of 1934, the Government

[1]) Scotland, in the above five years, contributed an average of about 1,800 samples yearly.

occurrence and for which an explanation in terms of coincidence seems hardly adequate.

The following figures refer to practically the same hydrographic station situated off Balta Island, Shetland, and operated on two occasions with an interval of exactly six weeks between them.

Salinities obtained near Balta Island, Shetland, in June and July 1933.

Depths m.	60°43′ N. 0°39′ W. 7:VI:33 Salinities ‰	60°41′ N. 0°42′ W. 19:VII:33 Salinities ‰
0	35.36	35.35
10	.37	.37
20	.36	.35
30	.37	.34
40	**.66**	**.67**
60	.33	.35
80	.33	.36
96	—	.36
100	.32	—

It will be observed that, not only were the singularly high salinities at 40 metres practically identical on these two occasions, but the entire water column appears to have retained its salinity-distribution almost unaltered during the six weeks' interval, and this despite the fact that, on the first occasion, the vertical equilibrium around the 40-metre level was unstable.

Another condition of somewhat similar nature, from which it would appear legitimate to draw the obvious inference in regard to the validity of the figures mentioned, is taken from the records of 1932. At the points A, B and C on Figure 1b practically the same salinity — outstanding among the other simultaneous observations at each station — was registered, in all three instances, at the 100-metre level, the values being 35.50, 35.53 and 35.50 $^0/_{00}$, and the dates of the stations, 14th, 19th and 20th July respectively. Other instances of a like description may be observed from Figure 1.

So far, however, we have not dealt with the highest salinities denoted in Table 1. These, being singular in number as in magnitude, in the geographical positions at which they were obtained, and, in the case of the 1933 result of 36.02 $^0/_{00}$, in the date of its alleged occurrence, can receive only indirect and partial confirmation such as may accrue from the circumstances attending their determination, or from their share of the arguments led in favour of the validity of less exalted records.

36.57 $^0/_{00}$, registered, as on July 29, 1934, at the surface, at a position just outside the northern part of the Moray Firth, is a verified result by titration, and the highest among the Scottish records for the year. It is, in fact, that result for which the Government Chemist could find "no apparent cause" offering a possible explanation of its singularity. Next in order of magnitude is a record of 36.02 $^0/_{00}$ obtained, early in April, at a depth of 20 metres at the position 60°07′ N. 1°45′ W., which is in fairly close proximity to the western shore of southern Shetland. Relatively high salinities have not infrequently been registered in this same region. Indeed, two more of the high results for 1934, both verified determinations, belong here: — (a) 35.82 $^0/_{00}$ at 60 metres on June 5, and (b) 35.68 $^0/_{00}$ at 20 metres on June 8. In general, the salinities found in this quarter bear a closer identity with contemporaneous records from the North-Western North Sea — in the line of the main southerly current — than they do to records from the region a little to the south and west of the above positions. By way of explanation, the current chart published along with the paper already quoted is of service.

Further in support of all but the highest salinity found within the Northern North Sea during 1934, the following data from the west of Orkney and Shetland, and of Scotland, are submitted: —

Date	Position	Depth	Salinity
3:IV:34	59°54′ N. 2°37′ W.	60 m.	35.66 $^0/_{00}$
4:IV:34	59°06′ N. 5°37′ W.	0 -	35.89 -
15:IV:34	58°36′ N. 5°16′ W.	0 -	35.59 -

All three values are verified results without adverse comment and it will be observed that the last refers to a position in the neighbourhood of Cape Wrath, where it is almost the invariable rule to find only west Scottish coast water of much lower salinity than that indicated by any observations taken in the region of the North Minch in April 1934, when Atlantic water of not less than 35.00 $^0/_{00}$ salinity was found at all depths, even at the entrance to Broad Bay, Lewis.

Similar indications of a most powerful Atlantic flow towards and into the Northern North Sea in the early part of 1934 are afforded by the material relevant to the Middle North Sea between about latitude 57°30′ N. and the Dogger Bank. It is clear from the entire salinity data for this region that, until the month of August, the Atlantic influence was unusually strong, penetrating apparently to places where it is seldom in evidence. This is also true of the Northern Area. One of the higher Scottish salinities for the year belongs to the Middle North Sea. As on May 3, a value of 35.71 $^0/_{00}$ was recorded at a depth of 80 metres at the position 56°41′ N. 0°28′ E (see Figure 1 d).

More copious material and, from it, more cogent reasons can be found in support of the high salinities of 1933 in the Northern Area, again, all but the highest values. Hence, to sum the foregoing considerations, there would appear to be reasonable grounds for accepting, at their face value, the majority of the high and extraordinarily high salinities recorded during the past four years, which means that, in each of those years, particularly strong oceanic influences permeated the Northern North Sea.

It is pertinent now to enquire further into the yearly increase in the numbers of these values occurring in the records. The obvious suggestion of Table 1, to the effect of there having been an underlying natural process to account for this increase, is more clearly conveyed by considering the relative abundance of the higher results.

A perusal of the data for the Northern North Sea, which is contained in the "Bulletins Hydrographiques" suggests the definition of high salinities as those in excess of 35.39 $^0/_{00}$ and of extraordinarily high records, those greater than 35.49 $^0/_{00}$. The following table is constructed on the basis of these definitions and reveals the proportional nature of the increase in the frequency of high and extraordinarily high salinities among the Scottish records of the past five years.

Table 3.

Relative Frequency of high and extraordinarily high Salinities in the Northern North Sea from 1930 to 1934.

Year	1930	1931	1932	1933	1934
Percentage of total salinities $>$ 35.39 $^0/_{00}$....	0.3	1.4	5.0	6.9	15.7
Percentage of total salinities $>$ 35.49 $^0/_{00}$....	0.0	0.4	1.4	1.3	4.3

The question as to whether these ratios are truly significant is, of course, bound up with the question of whether or not the same, or approximately the same opportunities were present, in each of the years concerned, of recording high salinities, provided these

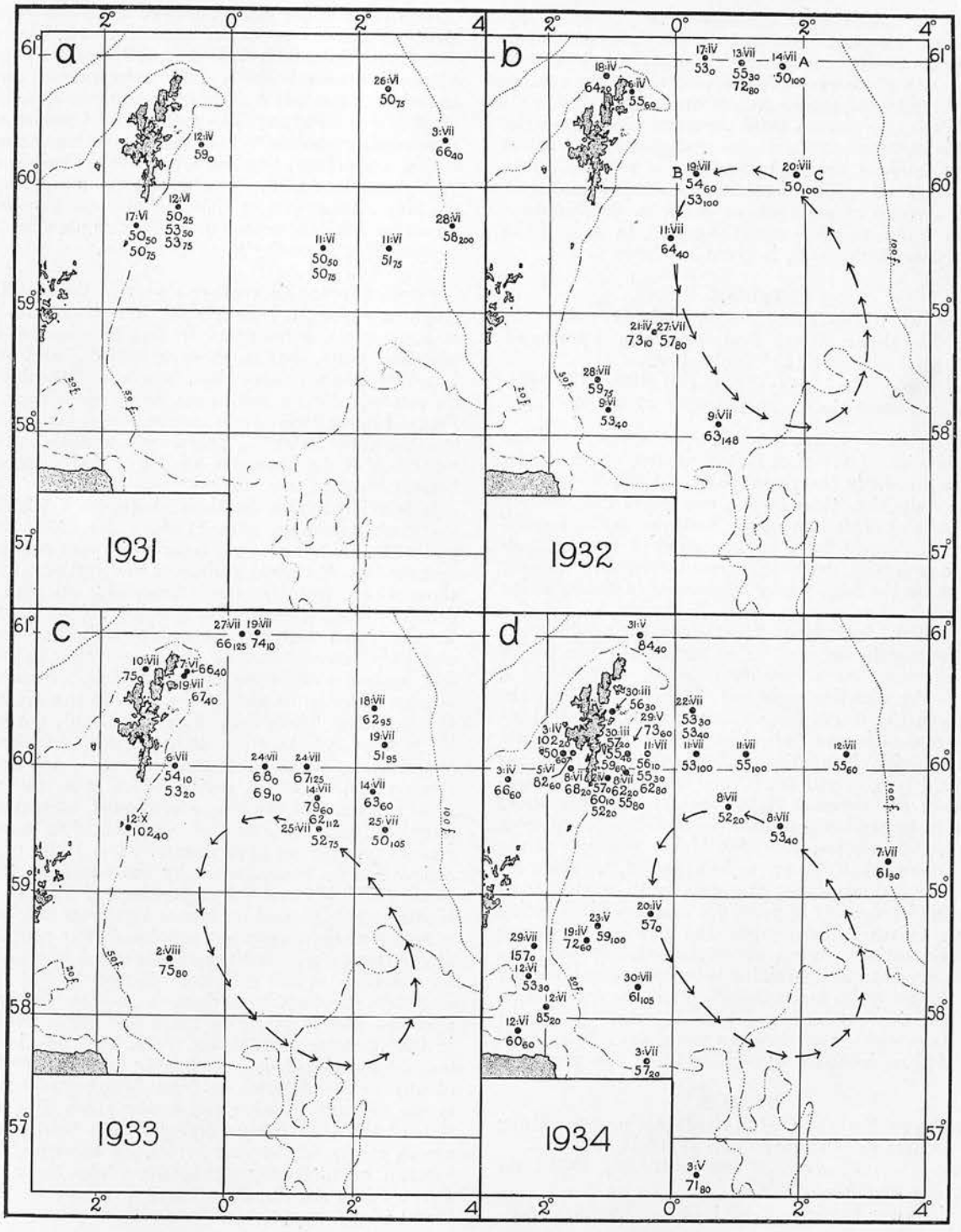


Figure 1.
Extraordinarily High Salinities in the Northern North Sea; 1931—1934
$100\ (S. - 35.00‰)_m$.

were by natural circumstances to be obtained. This involves the two factors of time and region and in respect of both, irregularities have to be acknowledged, as between one year and another, in the distribution of the Scottish hydrographic stations.

In the four years in which they were most numerous, however, (that is, in 1931, 1932, 1933, and 1934) practically all the high values were recorded in at least three of the five months April to August inclusive. The number of observations taken in the Northern Area within this five-monthly period, in each of the five years from 1930, is given in Table 4.

Table 4.

Number of Salinity Observations taken in the Northern North Sea, between April and August inclusive.

Year	1930	1931	1932	1933	1934
No. of observations	440	681	729	595	541

From these figures it would appear that, from the standpoint of the time-factor, greater opportunities were present in the years 1931 and 1932, of recording high salinities, than in the two years immediately succeeding. This impression, however, is "corrected" to some extent by a consideration of the regional- in conjunction with the time-factor. For present purposes the former may be assessed in the following way.

Scottish hydrographic stations, generally, are systematically worked in so far as the number of observations at a station depends, within limits, upon the sounding registered. This is particularly the case in the North Sea, where a sounding of about 100 metres means that eight combined temperature and salinity observations will be taken at the depths of 0, 10, 20, 30, 40, 60, 80 and ca. 100 metres. Nine depths are recorded if the sounding exceeds about 110 metres and only seven if the total depth is between 70 and 90 metres. Now, the higher salinities of the Northern North Sea are to be expected, for the most part, in regions of over 90 metres depth, so that, from the regional point of view, the chances of recording high values depends upon the number of deeper water stations. As we are concerned only with the relative chances obtaining between one and another of the five years under consideration, the information sought is contained in Table 5, which gives the average number of salinities per station from April to August inclusive in each of these five years.

Table 5.

Average Number of Salinities per Station; April to August; 1930 to 1934.

Year	1930	1931	1932	1933	1934
Average Number of Salinities per Station	8.1	8.1	7.8	8.0	8.3

Despite the circumstance that a difference of even 0.1 in the above figures is of some significance, it can undoubtedly be argued that reasonably equal opportunities obtained during the above five years of striking high salinities, if and when these were present.

By the foregoing considerations, then, the implications of Table 1 appear to be established. There is little room for doubt that the past five years have witnessed perhaps the most outstanding manifestation of the last decade in regard to the hydrography of the Northern North Sea. Not only has the usual spring oceanic influx been more than usually strong, since 1931, but there has also taken place a yearly accession to the intensity of this spring force, reaching a maximum in 1934, for already, the indications for 1935 are to the effect that this phenomenon of increasing intensity is on the wane.

Before alluding to another aspect of these hydrographical events, it is instructive to consider the loci of at least the extraordinarily high salinities of the past four years, that is, those of 35.50 $^0/_{00}$ and over. Together with the dates (day: month) and the depths (in metres) of their occurrence, these are set out on Figure 1 in the form of one hundred times their excess over the value 35.00 $^0/_{00}$. This avoids decimals and the repetition of the character 35. All available records, besides Scottish, are entered.

It is evident from the three charts on which they are most numerous, namely, those for 1932, 1933, and 1934, that the values considered were confined, more or less, to certain regions of the Northern Area; those which, from the latest knowledge afforded by drift-bottle experiments, are generally, if not always, in the most direct relationship with the main southerly current entering the Area from the north and bearing with it the purest (that is, the saltest) oceanic water to be found, as a rule, in the whole of the Northern North Sea. More significant, perhaps, in relation to another finding from drift-bottle experiments, is the circumstance that, in the above three years, a certain region which was traversed in at least one of the above-mentioned "auspicious" months, from the point of view of high salinity records, yielded no such datum. This is the region believed to be encompassed by the Great Northern North Sea Eddy and the dispositions of some of the higher records plotted on Figure 1 support this belief in regard to the three years concerned. The periphery of the Great Eddy is given on Figures 1 b, c and d, on the basis of the guidance afforded by the high records in question. From these charts it would appear that the system occupied much the same position in the summers of 1933 and 1934. This position, it may be mentioned, is considerably to the southward of any so far determined from drift-bottle experiments referring to other and earlier years. The position of the 1932 Eddy (Figure 1 b) is reminiscent, among others, of the year 1911[1]). All three positions betoken an unusually strong force from the north, directed into the Northern North Sea between Shetland and Norway.

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[1]) J. B. TAIT: The Surface Water Drift in the Northern and Middle Areas of the North Sea ..... in the year 1911. Fisheries, Scotland, Sci. Invest., 1931 III, Figure 35, p. 88.

The final aspect of these results, which it is desired merely to touch upon, is that of their bearing upon the general question of hydrological anomaly. It is obvious, granting the truth of the above records and of the inferences therefrom, that, not only in some years, but for a succession of years, physical conditions in the North Sea may be very different from those usually represented by so-called "average" or "mean" charts, thus greatly modifying the utility of the latter as standards for the assessment of the conditions of a particular year in relation to others. And since the interpretation of many of the biological phenomena of the sea necessarily depends, in greater or less degree, upon a close knowledge of the physical medium, or environment, there seems here to be presented a strong case for the intensification and continuity, over a long period of years, of hydrographical work in and about the Northern North Sea.

JOHN B. TAIT

SALIENT FEATURES OF THE HYDROGRAPHY OF THE NORTHERN NORTH SEA AND THE FAROE-SHETLAND CHANNEL IN 1935

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Salient Features of the Hydrography of the Northern North Sea and the Faroe-Shetland Channel in 1935.

By

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THE hydrography of the northern North Sea and the Faroe-Shetland Channel in 1935 presented some peculiar features which are the subject of this preliminary notice.

The most significant factor in northern North Sea hydrography is always the oceanic influence which proceeds from the north-eastern Atlantic Ocean by way of the Faroe-Shetland Channel. At all events the major hydrographic variations in the northern North Sea are more or less concomitant with the seasonal and annual variations in the strength and volume of this oceanic impulse. Estimation of the intensity of the Atlantic incursion is therefore of prime importance to northern North Sea hydrography. On account of the general insufficiency of data, this estimation is usually made by inference from the actual temperatures and especially the salinities recorded, and from their vertical and horizontal distributions.

The most reliable cross-section of the Atlantic current, from which to gauge its strength, is that which is to be obtained in the Faroe-Shetland Channel, between Shetland and Faroe. Following upon the close connexion which, early in the history of the hydrographical investigation of these regions, was shown to exist between the Faroe-Shetland Channel and the northern North Sea, the apparent intensity of the oceanic stream in the former region has in the past been taken as evidence of the intensity of its influx into the North Sea. Based on a misconception, however, the connexion between the two regions has formerly been believed to be more direct than is actually the case.

A special study of temperature and salinity distributions in the regions concerned[1]) has established the indications of certain drift-bottle results to the effect that the invasion of the northern North Sea by Atlantic water takes place almost entirely through the uninterrupted

[1]) J. B. Tait: Surface Drift-Bottle Results in relation to Temperature, Salinity and Density distributions in the northern North Sea. Cons. Int. pour l'Explor. de la Mer., Rapp. et Proc.-Verb., LXXXIX, 1934, III, No. 8.

opening between Shetland and Norway, and not to any appreciable extent, if at all, through the passages between Shetland and the mainland of Scotland, as has hitherto been supposed. This is an important finding, for it means that, before reaching the North Sea from the Faroe-Shetland Channel, the Atlantic current encroaches upon another hydrographical region, namely, the southern Norwegian Sea where, as seems to have occurred in 1935, it may be subject to modifying influences. Hence, an estimate of its strength in the Faroe-Shetland Channel may not always be a safe guide to its effect upon the North Sea, although in relation to events in the latter region it will always be an advantage to know something of conditions in the former.

At the end of 1934, in summarizing the Scottish hydrographical work for that year, the prognostication was made that, in the following year, the incidence of spring conditions in the northern North Sea would in all probability be delayed. By this was meant that the oceanic influence, which usually from December onwards increases rapidly towards maximum intensity in March or April, would, in 1935, not attain this maximum until later in the year. Despite an indication from salinities observed in March in the neighbourhood of Shetland that the Atlantic stream was then flowing fairly strongly, the results of surface drift-bottle liberations carried out between March and May 1935 tend to the conclusion that, so far as concerns the northern North Sea, it was not until June that the maximum intensity of the Atlantic impulse for the year was registered.

The above anticipation of the early events of 1935 was also based upon the results of surface drift-bottle liberations carried out in the months of November and December 1934. These results showed that a strong northward drift was then running along the entire length of the Scottish east coast, embracing the waters out at least to the prime meridian. The evidence is that this northward drift endured until the end of January 1935, if not longer, that is, well into the period when the southward urge, due to oceanic influence, ought to have been increasing in strength. The oceanic incursion of 1935 had obviously first to overcome this reverse movement on the western side of the North Sea.

By the month of April, the northmost reaches of the North Sea and the waters for some distance southward a little to the west of zero meridian, were distinctly oceanic in character. Temperatures and salinities were, in fact, above the average values in these regions during this month. But, on the other hand, the intensity of the incursion cannot have been so strong as these observations suggest, for in the following month, the effect had not yet reached the middle North Sea area south of about latitude 58° N, where the chief physical characteristics of the upper waters especially were appreciably below normal for the time of the year.

Towards June, when increased oceanic activity was evident in the northern area, a further indication of the drift-bottle results already referred to was that the pulsation was not a particularly strong one,

less so than the actual salinities recorded would lead one to deduce. Its influence continued to be confined very largely to the north-western part of the North Sea. Even two months later, when it was anticipated that Atlantic water would be found to have extended its influence considerably southwards, very little of it appeared below latitude 58° N.

These circumstances are the more surprising when it is known that, in June, water of very high salinity — up to 35.50 ‰ — indicating a powerful Atlantic current directed towards the Faroe-Shetland Channel, was found in the region of the Wyville Thomson Ridge. On a hydrographic section between the Butt of Lewis and Faroe Bank, water of scarcely less than 35.35 ‰ salinity occupied all depths along the entire section, while the cross-sectional area of 35.40 ‰ water, and over, was almost equal to that found on the same section at practically the same period of 1933 which was a "peak" year as regards the intensity of the Atlantic current in the Faroe-Shetland Channel and also in respect of its influence upon the northern North Sea[1]).

A most fortunate drift-bottle result gave the first indication of the reason for this influence being so much less in 1935. A bottle set adrift on 26th May 1935 near the island of North Rona, which lies some 40 miles in a north-easterly direction from the Butt of Lewis and 25 miles within the 100-fathom line, was most surprisingly recovered on the Island of Fuglö in the Faroe group, 43 days later, having apparently cut rectangularly across the Atlantic stream, if we assume this to have been heading as usual north-eastwards through the Faroe-Shetland Channel. The true explanation of this and certain other drift-bottle results, especially from the June liberations along the line of stations from Butt of Lewis to Faroe Bank, seems to be that a very large part of the Atlantic stream itself was diverted in a north to north-westerly direction soon after it reached the Wyville Thomson Ridge, passing thence towards Faroe Bank and the west side of Faroe.

This deduction is not discounted by the fact that, in the same month of June 1935, the whole region between Faroe and Shetland, in the uppermost 250 metres at least, was flooded with Atlantic water of scarcely less salinity than 35.30 ‰. There is reason to believe that this flooding was caused by a strong resistance to the further progress northwards of the great Atlantic drift, and here again, the apparent histories of certain drift-bottles, or rather drift-buoys, in conjunction with other factors, probably furnish the explanation of this phenomenon which affected the flow of oceanic water from the Faroe-Shetland Channel into the northern North Sea by way of the north of Shetland.

In Bulletins Nos. 7 and 9 (1935) of the Arctic Institute, accounts are given of the extraordinarily rapid transport of no less than eleven drift-buoys from the northmost part of the Kara Sea, where they were liberated during August 1934, to the north-west coast of Norway,

[1]) J. B. Tait: Recent High Salinity Records from the Northern North Sea. Cons. Int. pour l'Explor. de la Mer. Rapp. et Proc.-Verb., XCIV, 1935, III, No. 3.

where they were recovered between the end of April and the middle of July 1935. The buoys are assumed to have "rounded Franz Joseph Land and Spitzbergen from the north and to have got into the East Greenland current, from where they were carried by the Jan Mayen current to the Lofoten Islands." The rapidity of their passages over this route is taken to denote "an intensified clearing of the Polar Basin from ice, towards the end of 1934 and the beginning of 1935, through the gate between Greenland and Spitzbergen." It is mentioned also that "the atmospheric conditions observed in the winter of 1934 and spring of 1935 in the sub-Atlantic portion of the Arctic were such as to increase the activity of the East Greenland current."The same no doubt held in regard to the East Icelandic Polar current, with the result that its influence was felt much nearer to Faroe and perhaps Shetland than is usually the case. In these conditions, commencing with an increased Polar activity in the summer of 1934, appears to lie the reason for the evident stemming of the Atlantic current in the Faroe-Shetland Channel during the summer of 1935, allowing only a restricted portion of it to pass round the north of Shetland into the North Sea.

Not only did conditions in the southern Norwegian Sea during 1935 retard the advance of the Atlantic stream beyond the Faroe-Shetland Channel, but they appear also to have hindered the usual strong outflow from the North Sea along the Norwegian coast. Of the large numbers of surface drift-bottles liberated annually in the northern and middle areas of the North Sea, by far the greatest proportion of returns comes as a rule from northerly Norwegian latitudes, and there seems generally to be no particular period of the year when such strandings may not be expected. In 1935, only isolated drifters among those liberated during the months of March, April and May, attained to the higher latitudes of Norway and the few which did so were not recovered until after the middle of October. From the later North Sea liberations of the year — August to November — the Norwegian coast recoveries north of latitude 62° N. took place mostly in the early months of 1936.

Another circumstance pointing to the "closure" of the North Sea in the north was the extraordinary concentration of recoveries which took place in the months of September, October and November 1935 on the North Sea section of the Norwegian coast, between about latitudes 59° N. and 61° N. These belonged to the liberations of every month from March to August inclusive. This particular coastline is not one from which many Scottish bottles are normally returned. Moreover, in a hydrographic year such as 1935 appears to have been, when the southward urge in the North Sea due to oceanic influences is distinctly weak, the expectation in regard to drift-bottle recoveries towards the end of the year, when this oceanic force is approaching a minimum, is that these will mostly occur without the North Sea.

Thus we have in the hydrography of the Faroe-Shetland Channel and the northern North Sea during 1935 a number of apparently

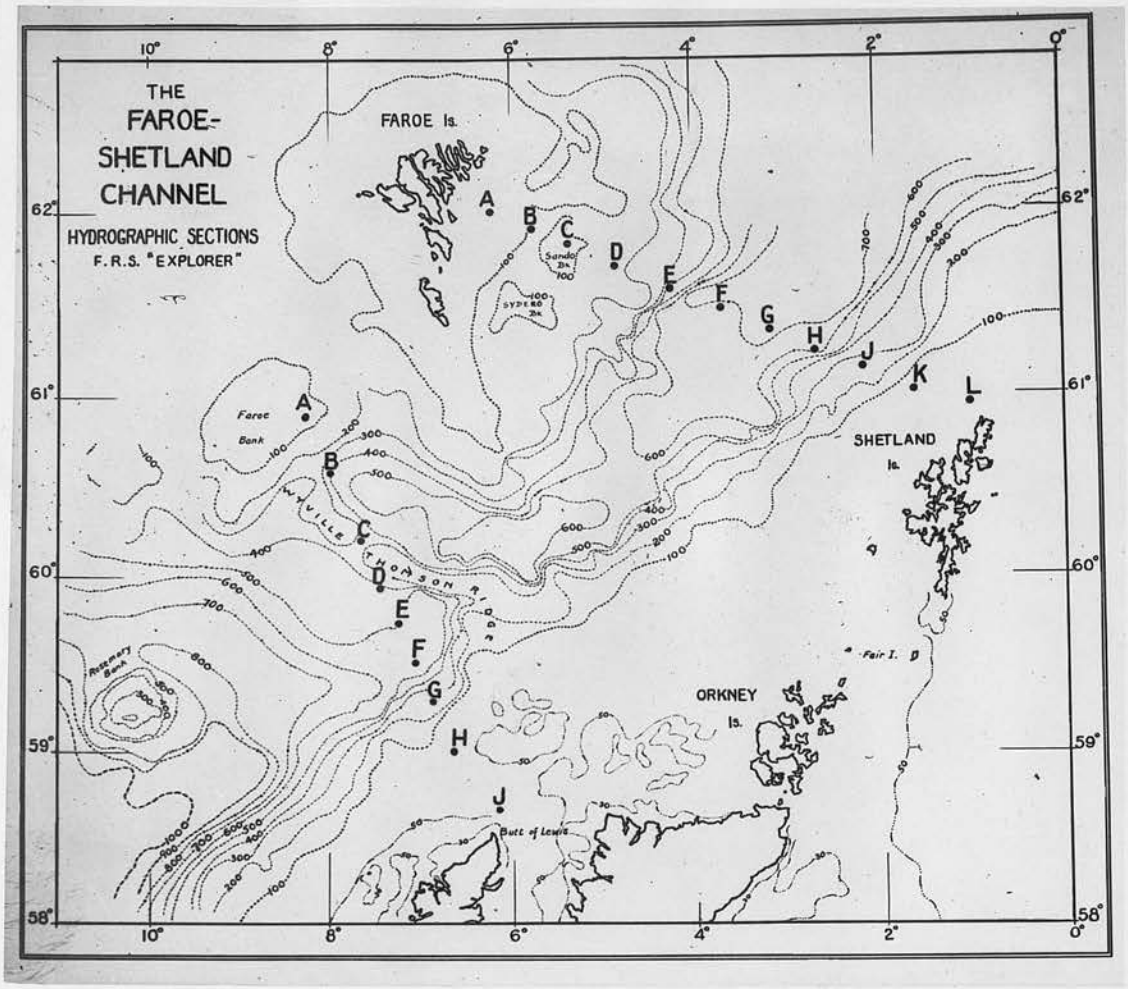
contradictory features, illustrating the complexity of the hydrographic problem in these regions. It is obvious that, in the study of the physical conditions of the northern North Sea, one must take into account not only the great oceanic stream coursing through the Faroe-Shetland Channel and the lesser influence proceeding from Baltic regions (which has not been dealt with specifically in this report), but also the trend of contemporary hydrographic events in the far north, in so far as these may affect conditions in the southern Norwegian Sea adjacent both to the Faroe-Shetland Channel and the North Sea. A point, moreover, which is to be noted in conclusion is the value, towards hydrographic interpretations, of surface drift-bottle results, either in extension or in modification of the inferences which may be drawn from temperature and salinity distributions.

HYDROGRAPHICAL SIGNIFICANCE OF THE RESULTS OF SURFACE DRIFT-BOTTLE EXPERIMENTS IN THE FAROE-SHETLAND CHANNEL.

By

JOHN B. TAIT, B.Sc., Ph.D., F.R.S.E.

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This chart of the Faroe-Shetland Channel is inserted here for reference. The points marked A. B. C., etc., relate to Paper No. 6, "Fluctuations in the Intensity of the Oceanic Incursion into the Faroe-Shetland Channel."

HYDROGRAPHICAL SIGNIFICANCE OF THE RESULTS OF SURFACE DRIFT-BOTTLE EXPERIMENTS IN THE FAROE-SHETLAND CHANNEL.

~~Confirmed for the most part by temperature and salinity distributions,+~~

It can ~~nevertheless~~ be accepted on the evidence of drift-bottle results alone that, at least normally, the only considerable inflow of Atlantic water to the northern North Sea takes place between Shetland and Norway, although the finding is confirmed, for the most part, by temperature and salinity distributions.+ On the same basis, Atlantic water seldom, if ever, enters properly into the North Sea, as some investigators have assumed, through the passages between Shetland and the Scottish mainland. It is true that, as evidenced by the occurrence of oceanic plankton, as well as by salinities, Atlantic water, mixed with west Scottish coast water, may occasionally penetrate eastwards south of Fair Isle, but here again, drift-bottle results, once more supported by salinity data, clearly show that this very small influx usually remains in the immediate neighbourhood of Orkney. At the farthest it may reach into the north-west corner of the Moray Firth.

It/

+ (a) HELLAND-HANSEN, B. "Hydrographical Investigations in the North Sea and Faroe-Shetland Channel in the year 1902." North Sea Fish. Invest.Comm. (Northern Area) 1st Report, 1905.

(b) HELLAND HANSEN, B. and NANSEN, F. "The Norwegian Sea, Its Physical Oceanography." Rept.Norweg.Fish. & Mar.Invest., Vol.II, No.2, 1909.

(c) TAIT, J.B. "Surface Drift-Bottle Results in relation to Temperature, Salinity and Density Distributions in the Northern North Sea." Cons.Intern.l'Explor. de la Mer. Rapp. et Proc.Verb., LXXXIX, 1934, III, 8.

It can further be said that such modifications of statement as appear above in relation to the main facts are only necessary, or rather precaution-:ary, because experience tells that the annual cycle of events, for long recognised to underlie the ever-changing hydrographical conditions of the northern North Sea, is subject, on closer examination, to greater or less aberration annually. The respects in which, severally or conjointly, such aberration may manifest itself, fall under three main heads, namely, time, place, and incident.

It is not, however, the purpose of this paper to discuss further this most important matter, the significance of which, in relation to the problem of fisheries' fluctuations, is coming more and more to be appreciated as an almost fundamental issue. Much yet remains to be more definitely established in regard to the general hydrography of the northern North Sea, and in this, surface drift-bottle experiments, by the light they throw on the fundamental question of currents, are proving a valuable aid.

The dominating hydrographical feature of the northern North Sea is the oceanic influence, entering, as above-mentioned, between Shetland and Norway. Hitherto, the conception which has been formed of this incursion is that it originates as an offshoot, or branch, from the greater flow of Atlantic water through the Faroe-Shetland Channel, the bulk of which, from the region north of Shetland, passes on towards, and finally along, the Norwegian coast, although at some distance from it. Certain drift-bottle results, from liberations carried out across the Faroe-Shetland Channel, would seem to demand modification

of/

of this conception, at least as regards certain periods or seasons.

The first indication of this comes from the results of liberations made in the latter half of May 1910. In Figure I[+] these results are summarily represented.[++] The points of liberation on this and subsequent figures are numbered in chronological order, not always commencing with unity, nor in consecutive numerical sequence, since the records have been excerpted from the monthly chronological lists which it is the custom to compile as a basis for all work and reference. On the left of each point is given the number of drifters liberated, and on the right, the number subsequently recovered. The number of arrow-heads represents the number of recoveries in the directions indicated, the contraction Sh. standing for Shetland, Ork. for Orkney, Sc. for Scotland, Skag. for Skagerak, Sw. for Sweden, Dk. for Danmark, Ny. for Norway and F. for Faroe. The capitals N., W. and E have each their usual significance. Since, in relation to the subject of this paper, the higher-latitude Norwegian recoveries are of primary interest, particulars of these are given along the appropriate arrows, namely, the number of days apparently taken to reach the latitude cited, on the Norwegian coast. Norwegian recoveries south of latitude 62°N. are designated North Sea Norwegian (N.S.Ny.) or Skagerak Norwegian (Skag.Ny.) as the case may be.

Reverting to Figure 1, the evidence is incontrovertible that the drifters which ultimately stranded on the Norwegian coast north of latitude 62°N. must first/

[+] Figures are collected at the end of the paper.

[++] Conclusive cartographical interpretations of these results are to be found in the writer's papers on Surface Water Drift in the series of "Scientific Investigations" published by the Fishery Board for Scotland.

first of all have passed from the Faroe-Shetland Channel into the northern North Sea by the north of Shetland. There is no evidence that even a single drifter made a direct passage from the Faroe-Shetland Channel region to the Norwegian coast outwith the North Sea. To begin with, as will the better be appreciated from what follows, the drift-periods of all 19 recoveries are fairly long, ranging from 168 to 462 days. Only one bottle was found within 200 days, and 15 in from 200 to 400 days. With 12 of the 19 recoveries is directly associated a North Sea or Skagerak recovery belonging to the same group of simultaneous liberations. As regards the remaining 7, a study of Figure 1 reveals that indirect association with such returns is, in fact, so close that it can confidently be assumed that all the drifters subsequently recovered, with the exception of one which was picked up at sea to the west of Faroe, passed into the northern North Sea relatively soon after their liberation. The significance of this inference, since liberations were carried out practically from seaboard to seaboard between Shetland and Faroe, is that, on the surface at all events, the entire flow of Atlantic water through the Channel, and not merely a part of it, passed southwards into the northern North Sea on rounding the Shetland Islands.

The next series of Faroe-Shetland Channel liberations was made from most of the same points during August 1910. The results are set out in Figure 2. In regard to the higher Norwegian recoveries, there are obvious differences from the corresponding records accruing from the liberations of the previous May. No fewer than five of the 18 August bottles registered drift-periods of between 45 and 71 days. Six more were found in under 200 days. None of these is directly/

directly associated with a North Sea or Skagerak recovery. Such association, in fact, applies to only two records. Almost certainly, therefore, despite the North Sea recoveries noted from the liberations at points 10 and 11,+ the five shortest-period bottles at least, passed directly from the Faroe-Shetland Channel to their respective stranding-places on the Norwegian coast north of latitude 63°N. This carries the implication that, from August 1910, for at least two months, the northward flow of Atlantic water parallel to the Norwegian coast was continuous with that which passed through the Faroe-Shetland Channel, and that any Atlantic water deviating into the northern North Sea at this period was an offshoot from this, as it were, parent stream.

In the month of May 1911, similar series of liberations were carried out on a double line across the Faroe-Shetland Channel (Figure 3). In this case, the association of higher Norwegian with North Sea (or Skagerak) recoveries is practically non-existent. The lengths of the drift-periods, however, notwithstanding that three out of the 23 fall between 75 and 86 days, in relation to the mean velocity of the Atlantic drift-current at the time, argue in favour of northern North Sea routes in respect of the drifters involved, which interpretation is borne out by a rigorous cartographical analysis of these, in conjunction with all the other records for the year.++

A few groups of scattered liberations were carried out in August 1911 (Figure/

+ For explanation of these returns see Fisheries, Scotland, Sci.Invest., 1930, No. IV, p.42.

++ TAIT. J.B. Fisheries, Scotland, Sci.Invest., 1931, No.III.

Figure 4), and here again, as in the case of the August 1910 experiments, occurs a higher Norwegian recovery showing a drift-period of only 51 days, and that from a point (No. 19) well down in the Channel. A direct passage in this instance is in conformity, as regards the average speed entailed, with other contemporary results.+

For the third time, at practically the same period of the year, two almost parallel lines of liberations were made across the Channel between 25th May and 2nd June 1912 (Figure 5), and once more, in the results, occurs the evidence from which it may be deduced that all bottles later found in the upper latitudes of Norway, representing liberations all the way from Shetland to Faroe, passed into the northern North Sea in course of their drifting. As before, the deduction is substantiated by rigorous cartographical treatment of the results.++

The next extensive series of liberations from which confident deduction can be made, were carried out towards the end of April 1923. The results are indicated in Figure 6. Nine higher Norwegian coast recoveries are equally distributed, as regards their origin, among three of the four points of liberation, and the drift-periods of all but two of these, in conjunction with the fact of direct association, in each case, with no less than two North Sea (including Skagerak) recoveries, argues strongly in favour of North Sea routes having been followed. Nor, in face of the evidence, can the doubt

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+ Fisheries, Scotland, Sci.Invest., 1931, No.III.

++ Fisheries, Scotland, Sci.Invest., 1937, No.I.

occasioned by a 48-day record in respect of the second, and a 59-day return from the third group of liberations, be seriously entertained. There is, first of all, the possibility of an abnormally high rate of drift thus early in the season to be considered, whereby much longer routes would be overtaken in a given time than under normal circumstances. Two Orkney records pertaining to the liberation-series 1 and 2 respectively, afford unmistakable evidence of an unusually high rate of drift. Both bottles, in fact, along with others, are estimated, by cartographical methods, to have passed into the northern North Sea by the north of Shetland at an average rate exceeding 14 miles per day, which is at least two miles per day greater than the normal rate of drift for the time of year involved. Moreover, the actual courses determined for these two drifters at once preclude the assumption of direct passages in respect of the above-mentioned short-period recoveries between latitudes 62°50'N. and 63°50'N. on the Norwegian coast.

Apart from the evidence of the drift-periods of the higher Norwegian recoveries - which were almost the only results obtained from the few scattered liberations of May 1924 - as indicative of North Sea routes for the drifters concerned, reference may be made, on Figure 7, to the Faroe recovery resulting from the sixth series of liberations near the intersection of latitude 60°N. with longitude 7°W. Jacobsen and Jensen, in 1926, published a surface current chart of the Faroe Shetland Channel,+ based on hydrodynamical/

+ JACOBSEN, J.P. and JENSEN, Aage J.C. "Examination of Hydrographical Measurements from the Research Vessels "Explorer" and "Dana" during the summer of 1924." Report of the Northern-Western Area Committee for 1924 and 1925. Cons.Intern.l'Explor. de la Mer, Rapp. et Proc. Verb., XXXIX, p.67.

hydrodynamical data, and referring particularly to the first half of May 1924. A possible explanation of the above drift-bottle record cannot be got from this chart, which, indeed, would appear to demonstrate the impossibility of such a record. That it was not, however, fortuitous, may be gauged from the fact that similar results accrued from liberations in the same neighbourhood in August 1928 (from 59°56'N. 7°27'W.) and in June 1935 (from 60°12'N. 7°40'W.) Still more surprising, in view of the generally accepted idea concerning the passage of Atlantic water from the Wyville Thomson Ridge through the Faroe-Shetland Channel, implying the existence of a current barrier between the southern part of the Channel to the north-west of Scotland and the northern part near Faroe, are the records of Faroe recoveries from liberations at (a) 58°14'N. 8°24'W. in May 1927 and (b) 59°06'N. 5°41'W. in May 1935. These results may be taken to show that such a barrier does not at all times exist.

This, however, is by way of parenthesis and is only cited in illustration of ~~how very variable may be the current conditions~~ the great variations to which currents are liable, even in a region of such reputed constancy as the Faroe-Shetland Channel.

From the point of view of the matter under discussion, namely, the nature of the connection at various times between the Atlantic water flowing through the Faroe-Shetland Channel and that which invades the northern North Sea from the north, the next drift-bottle results which are of interest are those pertaining to the liberations of August 1927. These took place in the neighbourhood of Faroe and between Faroe Bank and the Butt of Lewis, i.e. over the Wyville Thomson Ridge (Figure 8). From the first series of liberations over against Faroe, only two recoveries ensued, one on east Shetland and the other on the east coast of Scotland near Aberdeen. The second series yielded

only/

only a high Norwegian return after considerably more than a year, and from point 3, to the north of Faroe, besides a similar record, we have, in addition to a Faroe one, two from east Shetland and east Orkney respectively. Two similar returns were the only result of the sixth group of liberations to the south-west of Faroe, and from point 8, on the edge of the Faroe Bank, there resulted again a Shetland recovery and another near Aberdeen. In view of these results, there can be little doubt that the higher Norwegian coast recoveries from all liberations - and only the first and the sixth series are not thus represented - took place some time after the bottles in question had issued from the northern North Sea. In this respect, the results of these August liberations of 1927 differ from the results of the same month's liberations of 1910 and 1911, when there was evidence of at least some drifters having made direct passages from the Faroe-Shetlnd Channel to the higher latitudes of Norway. Thus we have another illustration of how conditions may not always be the same, or even similar, at corresponding periods of different years.

During May 1929, liberations were intensified on the Butt of Lewis-Faroe Bank line, and further liberations carried out (a) between Faroe Bank and Sudero, the southmost island of the Faroe group, (b) in the waters around Faroe, and (c) between Faroe and Shetland (Figure 9). Higher Norwegian recoveries, after periods ranging from 111 to 372 days, bulk largest among the results. Most of the 29 series of liberations are represented by at least one such record. There were, however, nine Shetland recoveries, the origins of which are interesting from the point of view of their distribution. They belong, one to each of the following series of liberations:- No. 8 immediately to the west/

west of Shetland; to No. 12 in mid-Channel; No. 17 over against Faroe, on the east side; No. 21 in the north-western vicinity of Faroe; Nos. 23 and 24 between Faroe and Faroe Bank; No. 29 on top of the Wyville Thomson Ridge and midway between Faroe Bank and the edge of the Continental Shelf; No. 31 to the southward of the Ridge and just beyond the Continental Shelf edge (this the remarkably short-period record, in comparison with the others, of only 35 days): and, lastly, No. 33 within about 30 miles of the Butt of Lewis. This remarkable concentration on Shetland from so many widely-scattered points affords some indication of the restriction to which the oceanic current is subjected as it forces its way northward through the Faroe-Shetland Channel.

The conclusion in regard to the higher Norwegian recoveries from these May 1929 liberations is, in this case also, that, without exception, they took place only after shorter or longer passages within the northern North Sea.

With few exceptions, the same liberation-points were visited in the latter half of May 1931. The results are given in Figure 10. They invite little in the way of detailed comment, being for the most part similar to results which have already been described. In all respects, save perhaps in the lack of North Sea recoveries from all but one, and that the westmost, of the Shetland-Faroe line of liberations, the evidence points to North Sea routes in respect of the Norwegian coast recoveries outwith the North Sea. Detailed cartographical treatment confirms the estimate.

The data entered on Figure 11, referring to the liberations of the month of June 1933, would appear, at first sight, to present a more difficult problem. While the majority of the drift-periods of the 79 higher Norwegian recoveries/

recoveries suggest northern North Sea routes in all cases, the complete absance of Shetland, or other North Sea returns, from the Shetland-Faroe, Faroe-Faroe Bank lines of liberations, except from the first three series set out in proximity to west Shetland, appears to weigh against the assumption , as does the fact of a 58-day Norwegian recovery in latitude 63°50'N. from a point between Faroe and Faroe Bank.

On the other hand, 1933 was a year in which, on the evidence afforded by temperature and salinity distributions, as well as by actual values of these characters, the North Atlantic drift through the Faroe-Shetland Channel was extraordinarily strong.+ This means, usually, an abnormally high rate of drift, and certain results++ from subsequent North Sea liberations are so outstanding among records embracing a long period of years that they may be taken unequivocally to signify an abnormally powerful inflow of Atlantic water into the northern North Sea during the summer of 1933.

In the case of the 58-day bottle above-mentioned, a direct route to its stranding-place would entail a mean rate of drift of only about 9 miles per day which is by no means extraordinary.

In short, the above considerations, supported by a preliminary cartographical examination of the entire records for the year, make it almost obligatory to accept northern North Sea routes for all the higher Norwegian coast recoveries from the Faroe-Shetland Channel liberations of June 1933. The same applies to the/

+ Vide, "Fishery Board for Scotland. 52nd Annual Report. Edinburgh, 1934, p.65.

++ These are the returns mentioned in the foregoing reference as having come from the coasts of Lincolnshire, Norfolk and Suffolk, England.

the results of the following month's liberations (Figure 12). Here, however, we do have at least a Shetland recovery from the most westerly series of liberations on the Faroe side of the Channel, and none of the Norwegian recoveries, all of which took place north of latitude 62°N. is of such short-drift-period as, with the rate of drift no doubt prevailing at the time, precludes at least a short sojourn within the northern North Sea.

Similar arguments apply also to the records of the June 1935 experiments (Figure 13), as well as to those of the liberations of June 1936 (Figure 14) and May 1937 (Figure 15), notwithstanding that several relatively short-period Norwegian returns occur among each set of records. As a basis for comparison with these, however, may be cited the following singular record of 1935, about which there is no doubt that a direct passage from liberation-point to stranding-point was entailed. This is the record of a recovery in latitude 63°40'N., 29 days after the bottle in question had been liberated (on 24th September 1935) at the position 61°08'N. 2°10'W.

It is unfortunate that, in the more recent years which have been considered no extensive Faroe-Shetland Channel liberations were carried out in the late summer or in autumn, for, evidently, it is from liberations at this time of the year that direct passages from the Faroe-Shetland Channel to northern Norway are most likely to result.

Ample evidence, however, has been adduced to warrant a general statement to the effect that drifters liberated within the Faroe-Shetland Channel area in spring or early summer, normally and without exception pass into the nothern North Sea by way of the north of Shetland, such as are eventually recovered on the Norwegian coast beyond latitude 62°N. coming immediately

from/

from that region. No drifter, at this time of the year, passes directly from the Faroe-Shetland Channel to the higher latitudes of Norway. Later in summer, or in the early autumn, on the other hand, such passages may be said to be the rule, although entry into the North Sea may take place in some instances.

The hydrographical implications of these findings are somewhat striking. In interpretation of the drift-bottle results, it would appear that, in spring or early summer, not merely an offshoot from, but the entire Atlantic stream through the Faroe-Shetland Channel, in its uppermost layer or layers at all events, passes into the northern North Sea, and that only later in the year, from about August onwards, is the oceanic influx to the North Sea but a branch of the main Faroe-Shetland current which, at this time, proceeds at once towards Norway from the region north of Shetland.

Already, the former part of this interpretation enables a reasonable account to be given of a marine biological phenomenon which has hitherto lacked satisfactory explanation, namely, the occurrence of Sub-Arctic or boreal species among the plankton in the Viking Bank region in spring; for it is clear that if there does not at all seasons exist, as has hitherto been supposed, a continuous and deep barrier of Atlantic water all the way from the Faroe-Shetland Channel to the Norwegian coast, thus completely shutting-off, as it were, the northern North Sea from sub-Arctic influence, this influence, emanating from the East Icelandic Arctic Current, will have opportunity in the circumstances recounted above, to find access to the northern/

northern North Sea in spring along the northern border of the oceanic current as it turns southward almost midway between Shetland and Norway. In support of this argument and as reference to the writer's current chart of the North Sea[+] will show, the Viking Bank region is precisely where one would expect such influence first to manifest itself within North Sea limits.

Finally, towards the end of March 1937, the distribution of temperature and salinity about the Viking Bank region clearly demonstrated the presence of water which almost certainly derived from the last Icelandic Arctic Current.[++]

[+] TAIT, J.B. Fisheries, Scotland, Sci. Invest., 1937, No.1, p.53.

[++] Vide Fishery Board for Scotland, 56th Annual Report, Edinburgh, 1938, p.50.

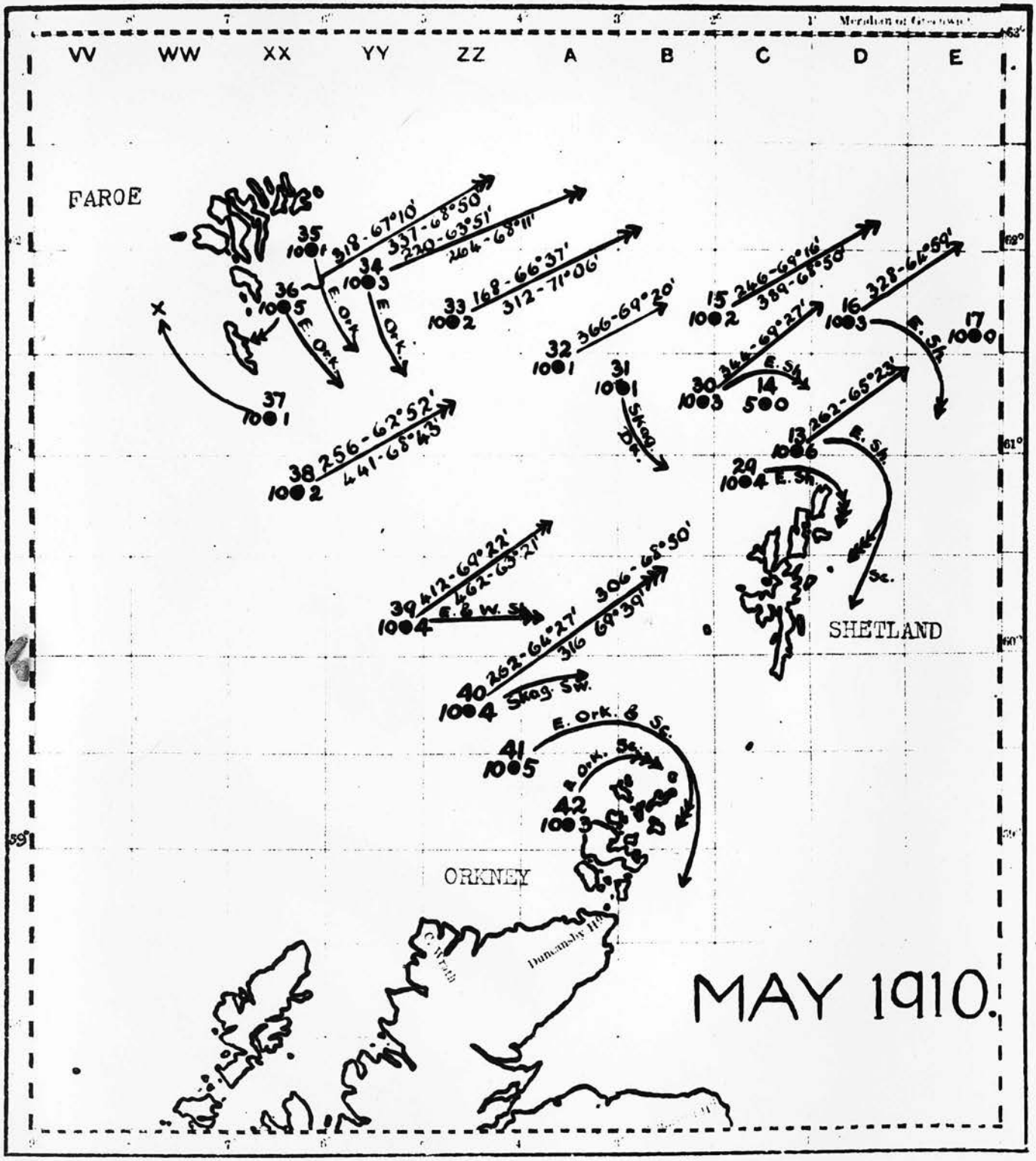

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FAROE
SHETLAND
ORKNEY
MAY 1910.
35 1001 318-67°10' 337-68°50'
34 1003 220-63°51' 204-68°11'
36 1005 E. Ork.
E. Ork.
E. Ork.
33 1002 168-66°37' 312-71°06'
X
37 1001
38 1002 256-62°52' 441-68°45'
32 1001 366-69°20'
31 1001 Skag. Dr.
15 1002 246-69°16' 389-68°50'
16 1003 328-66°59'
17 1000
30 1003 344-69°27' E. Sh.
14 500
13 1006 262-65°23' E. Sh.
29 1004 E. Sh.
Sc.
39 1004 412-69°22' 462-65°21' E. & W. Sh.
306-65°50'
316 69°39'
40 1004 262-64°27' Skag. SW.
41 1005 E. Ork. & Sc.
42 1003 E. Ork. Sc.
Dunnansby Hd.
59°
60°
61°
62°

Figure 1.

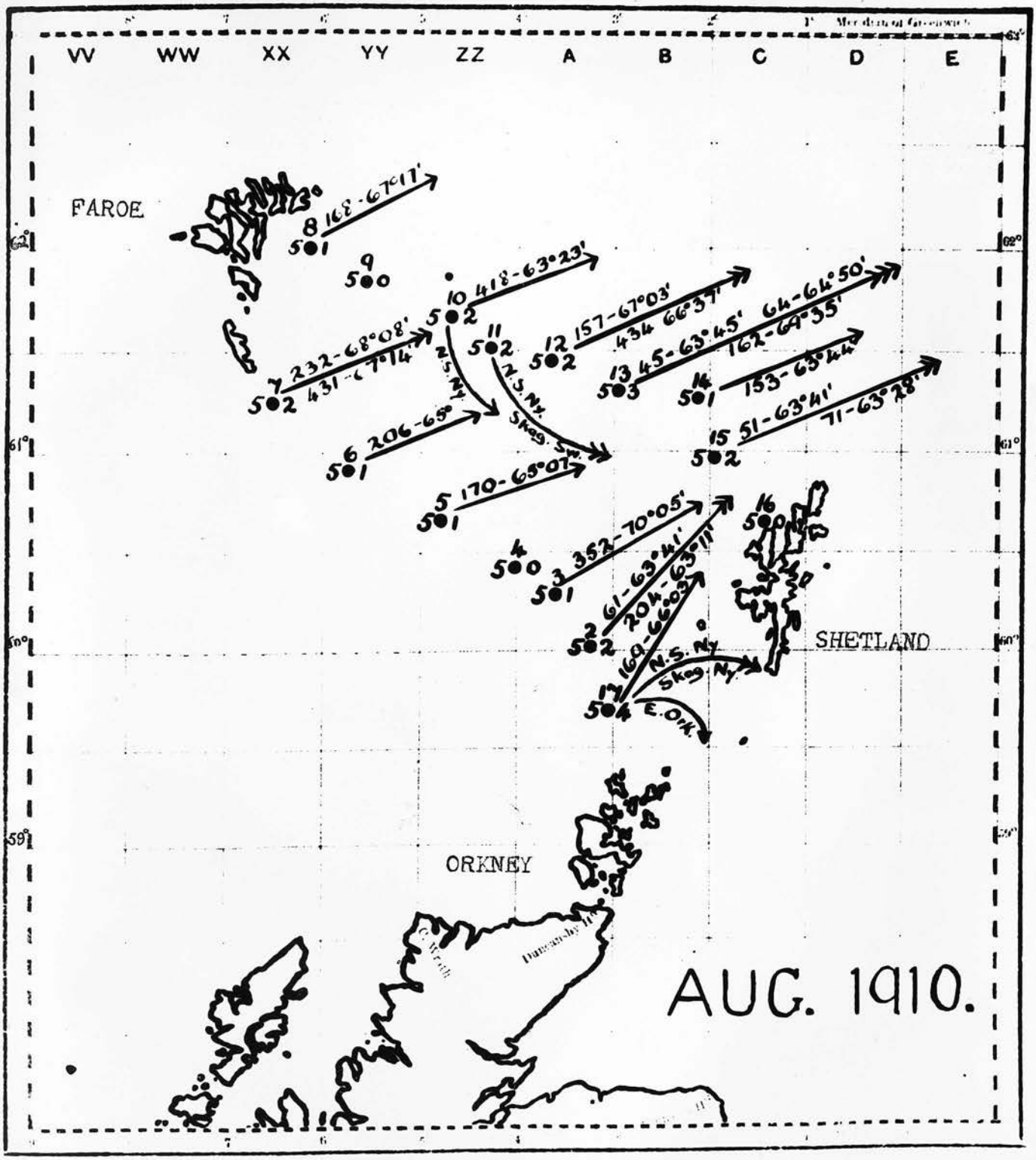


Figure 2.

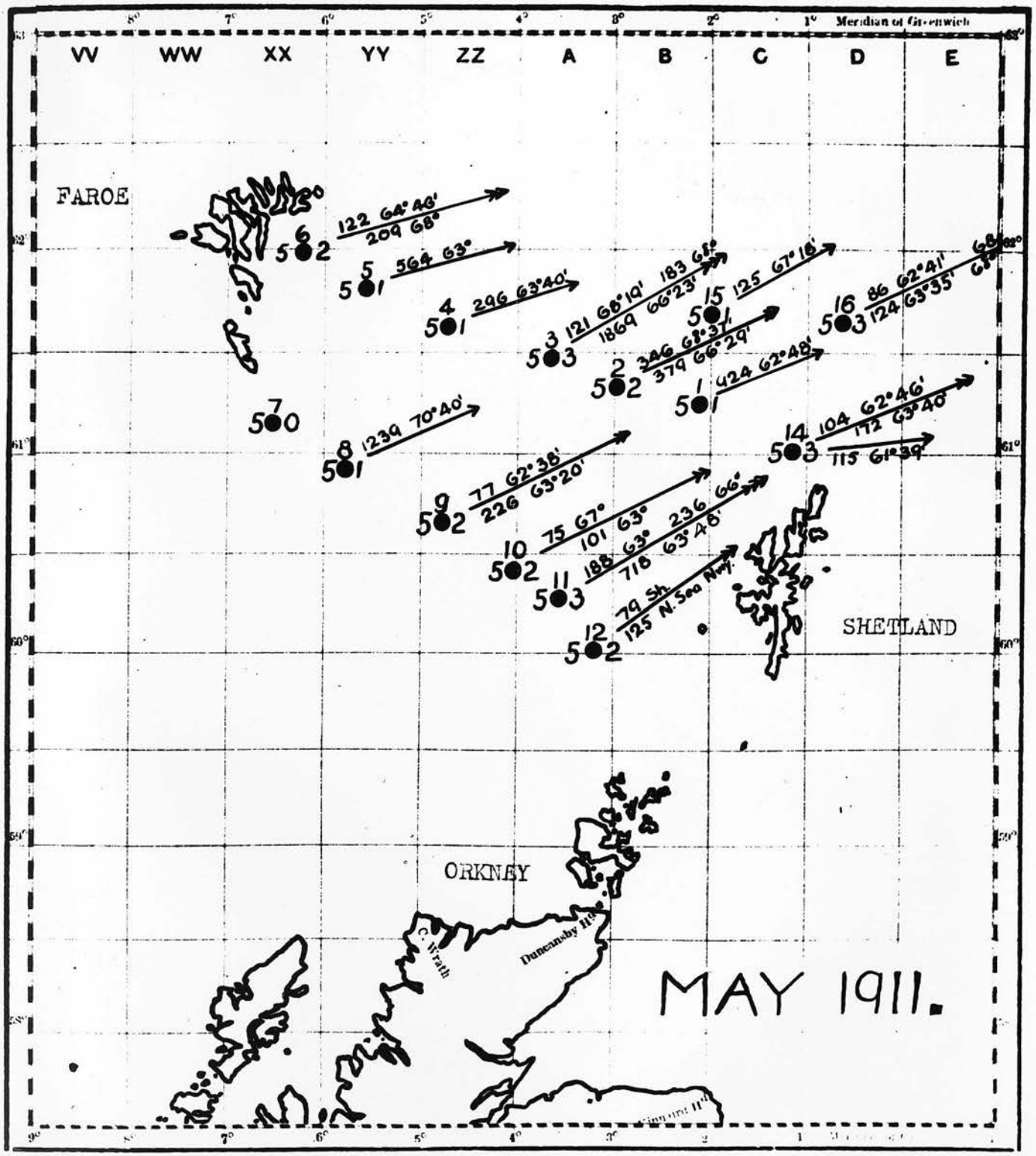

Meridian of Greenwich
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C. Wrath
Duncansby Hd.
MAY 1911.

Figure 3.

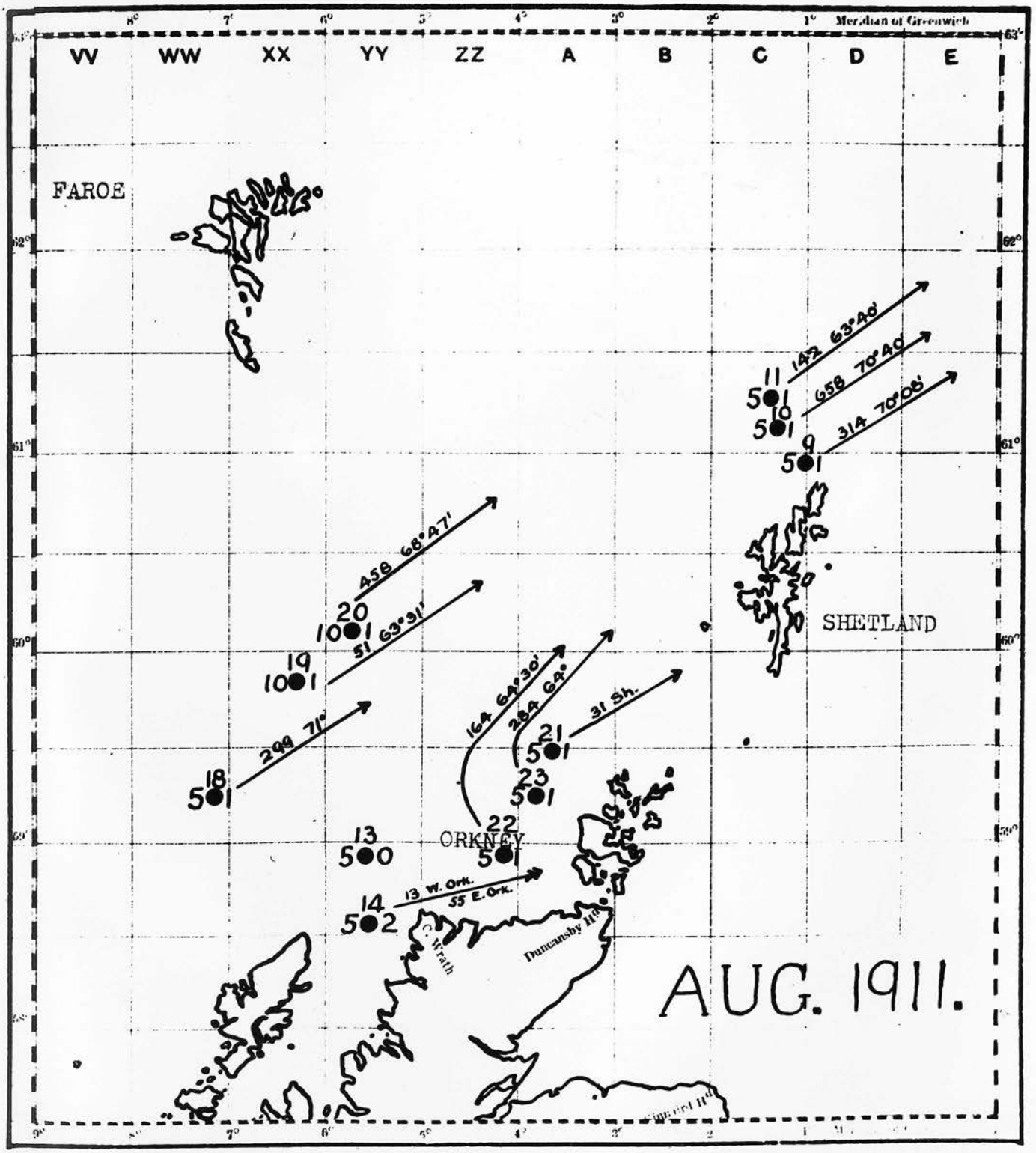

Meridian of Greenwich
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SHETLAND
ORKNEY
11
5●1
142 63°40'
10
5●1
658 70°40'
9
5●1
314 70°08'
20
10●1
458 68°47'
19
10●1
51 63°31'
18
5●1
299 71°
164 64°30'
284 64°
21
5●1
31 Sh.
23
5●1
22
5●1
13
5●0
14
5●2
13 W. Ork.
55 E. Ork.
C. Wrath
Duncansby Hd
AUG. 1911.

Figure 4.

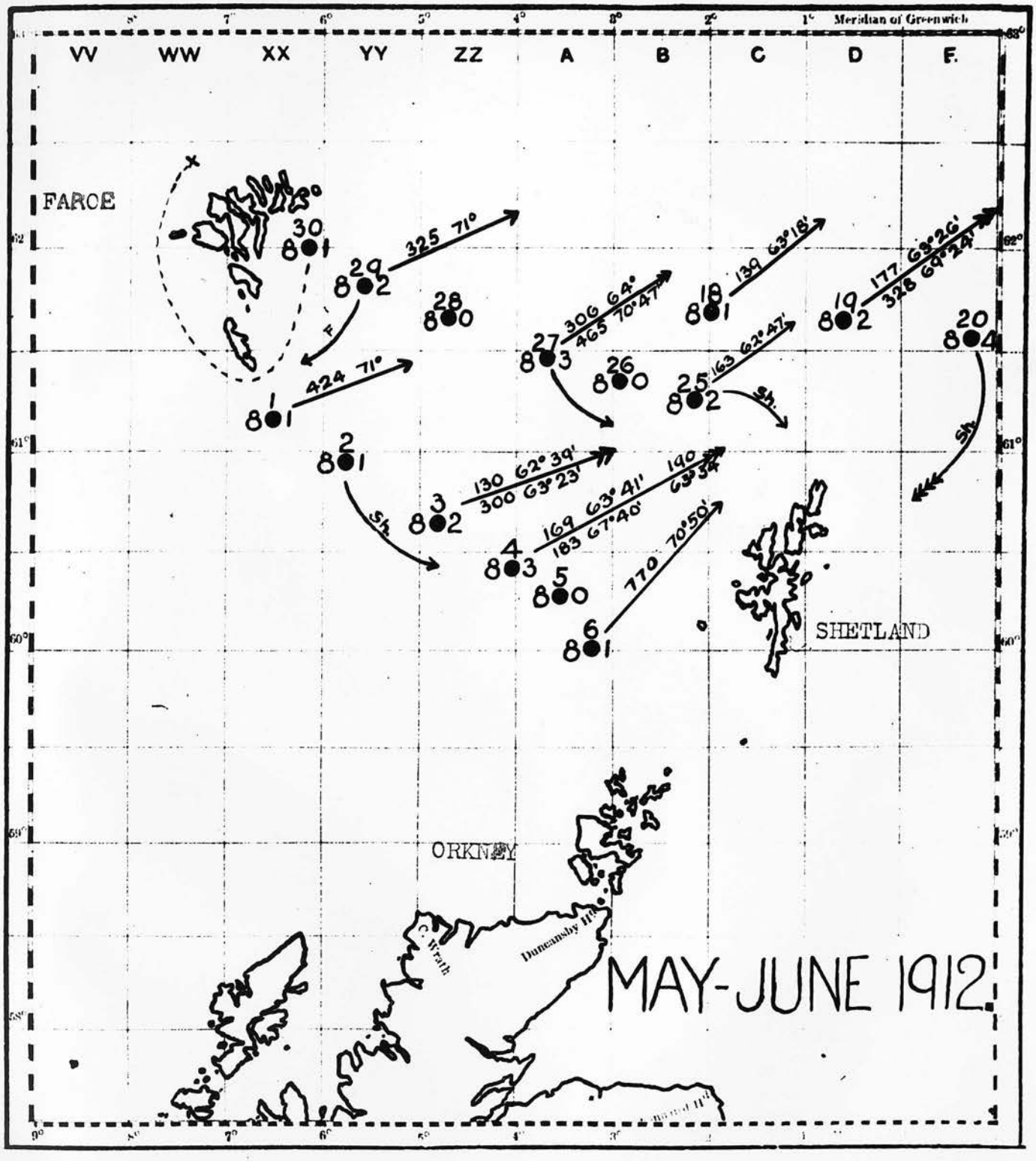

Meridian of Greenwich
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FAROE
SHETLAND
ORKNEY
C. Wrath
Dunnansby Hd
MAY-JUNE 1912
325 71°
424 71°
306 64°
465 70°47'
139 63°18'
177 63°26'
328 64°24'
163 62°47'
130 62° 39'
300 63° 23'
169 63° 41'
183 67°40'
190 63°34'
770 70°50'
Sh.
F.

Figure 5.

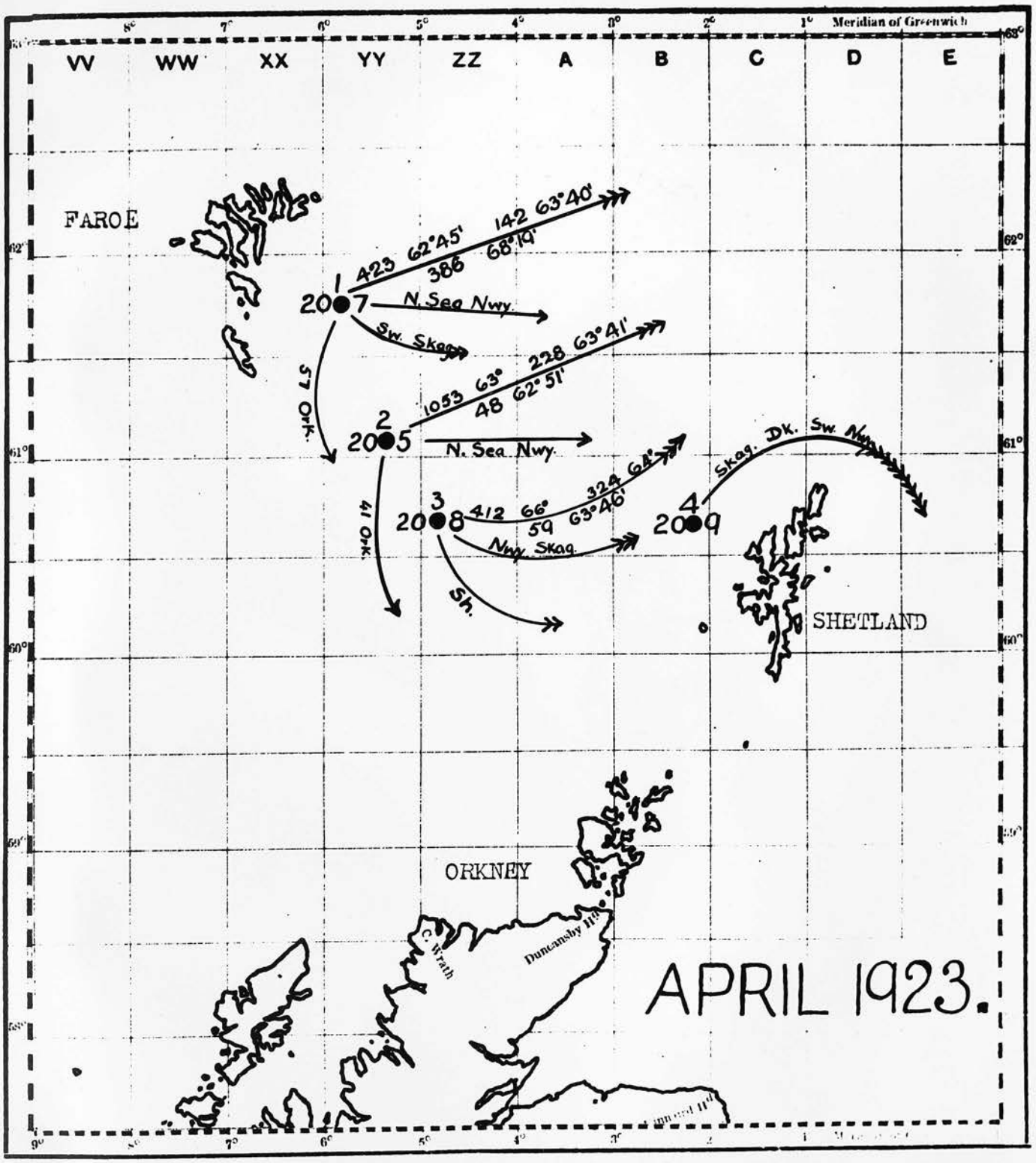

Meridian of Greenwich
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FAROE
SHETLAND
ORKNEY
1
207
423 62°45'
142 63°40'
386 68°19'
N. Sea Nwy.
Sw. Skag.
2
205
1053 63°
228 63°41'
48 62°51'
N. Sea Nwy.
St. Ork.
3
208
412 66°
324 64'
59 63°46'
Nwy. Skag.
Sh.
4
209
Skag. Dk. Sw. Nwy.
St. Ork.
C. Wrath
Duncansby Hd.
APRIL 1923.

Figure 6.

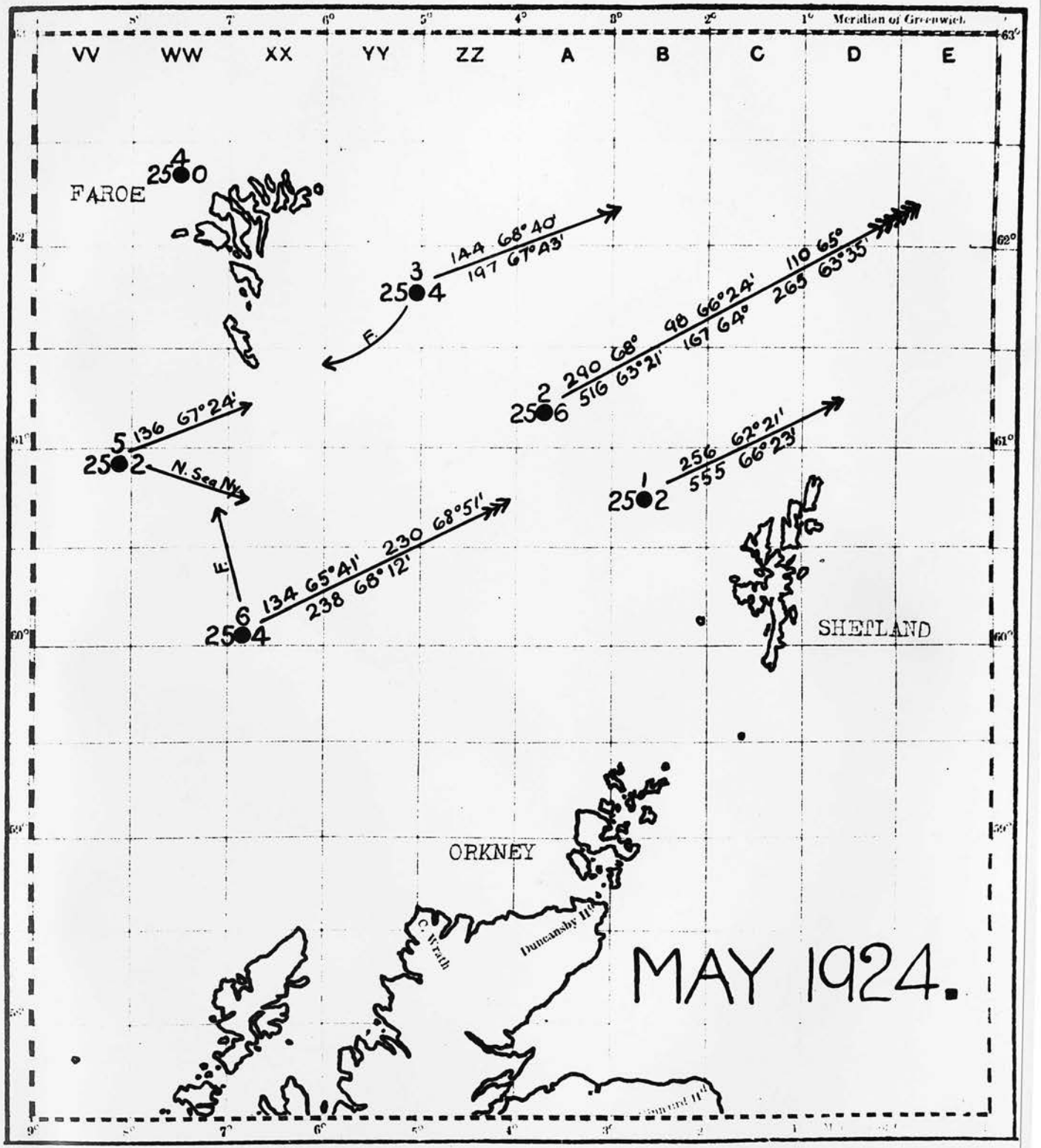

Meridian of Greenwich
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144 68° 40'
197 67° 43'
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290 68°
516 63° 21'
98 66° 24'
167 64°
110 65°
265 63° 35'
5
2502
136 67° 24'
N. Sea Ny
F.
6
2504
134 65° 41'
238 68° 12'
230 68° 51'
1
2512
256 62° 21'
555 66° 23'
SHETLAND
ORKNEY
C. Wrath
Duncansby Hd
MAY 1924.

Figure 7.

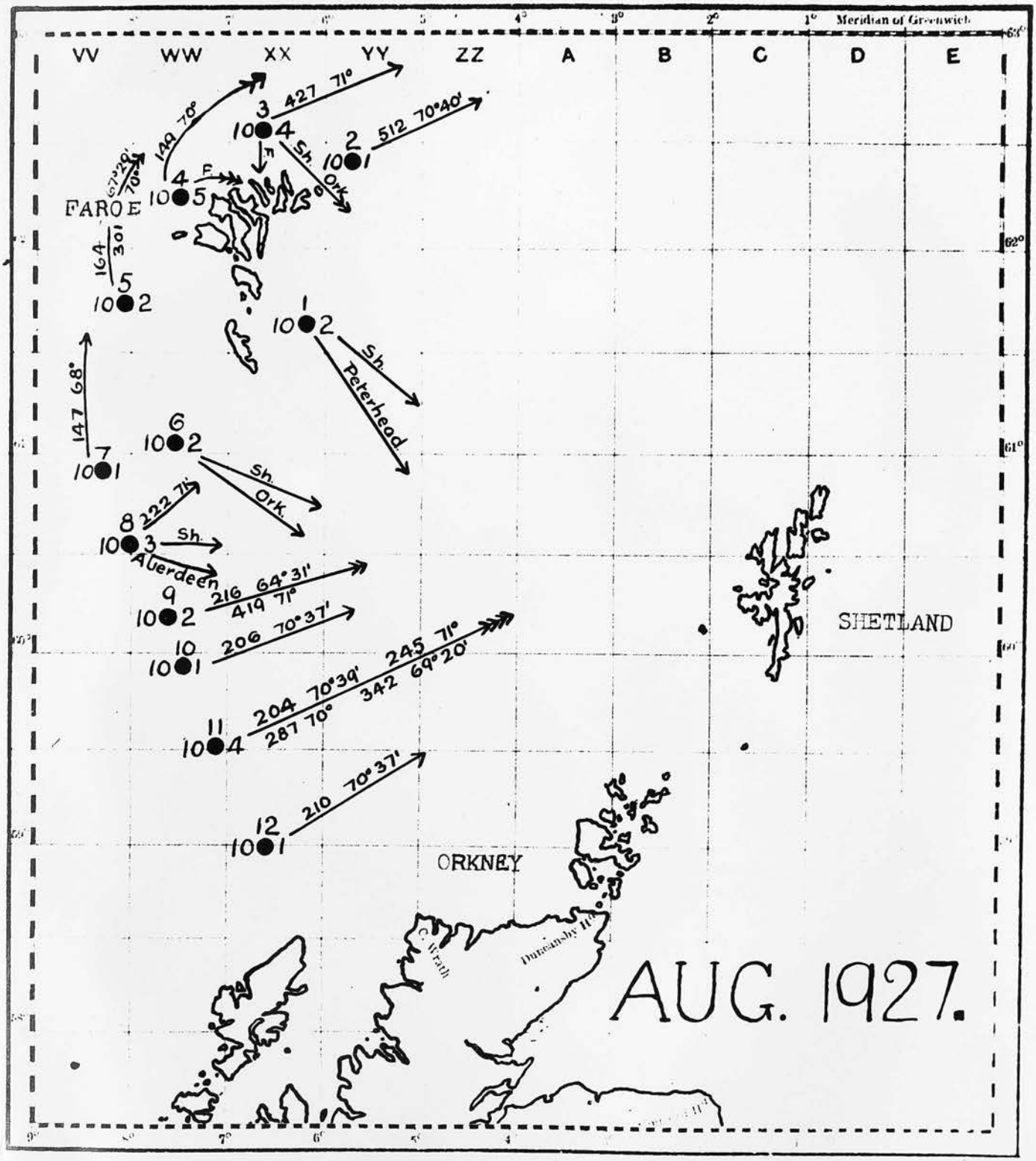

Meridian of Greenwich
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427 71°
512 70°40'
149 70°
147 68°
222 71°
216 64°31'
419 71°
206 70°37'
204 70°39'
245 71°
287 70°
342 69°20'
210 70°37'
C. Wrath
Duncansby H.
AUG. 1927.

Figure 8.


Meridian of Greenwi.
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SHETLAND
ORKNEY
Finland
Murmansk
N. Sea Ny
Ork
MAY 1929.

Figure 9.

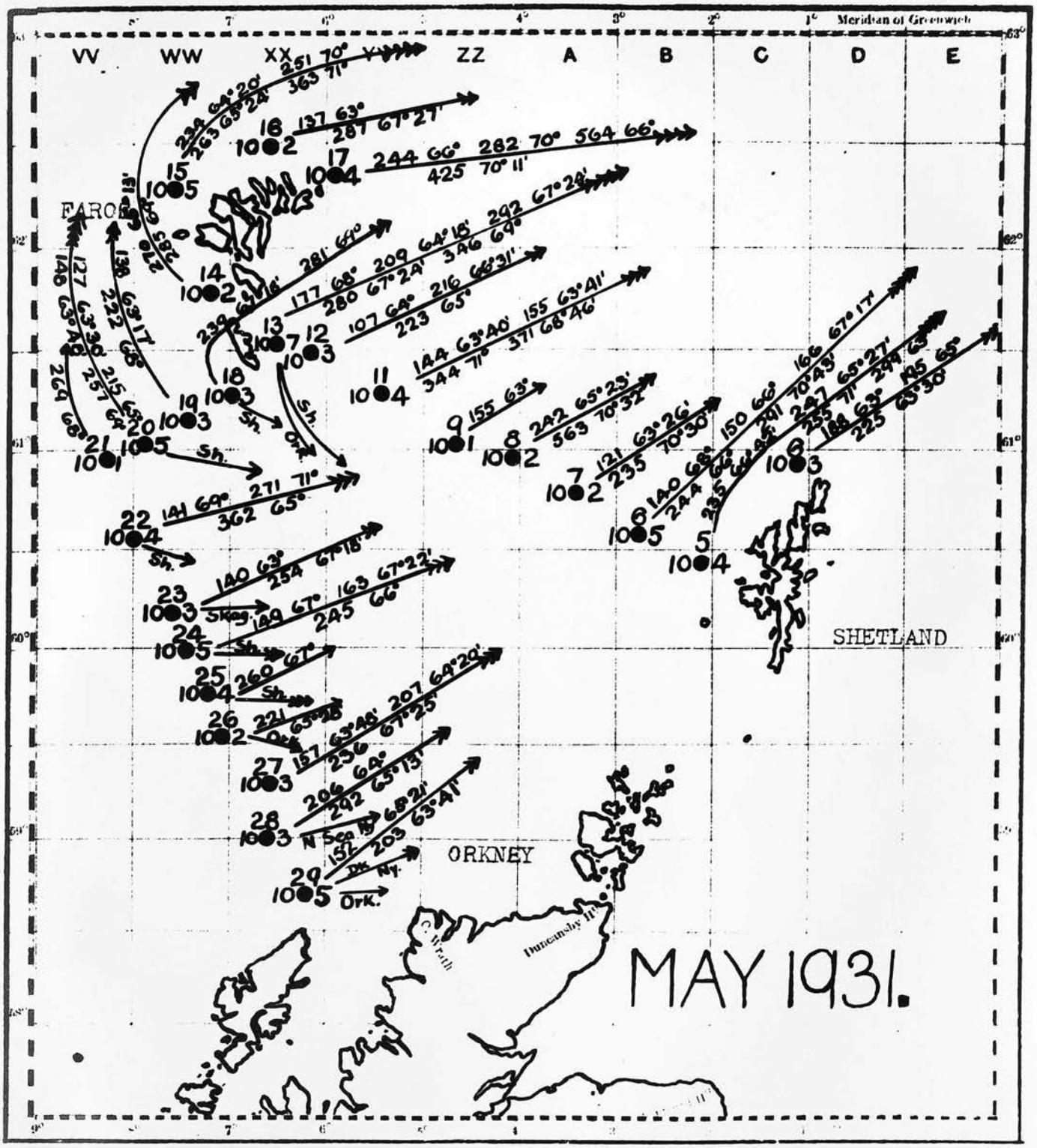

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Meridian of Greenwich
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SHETLAND
ORKNEY
MAY 1931.

Figure 10.

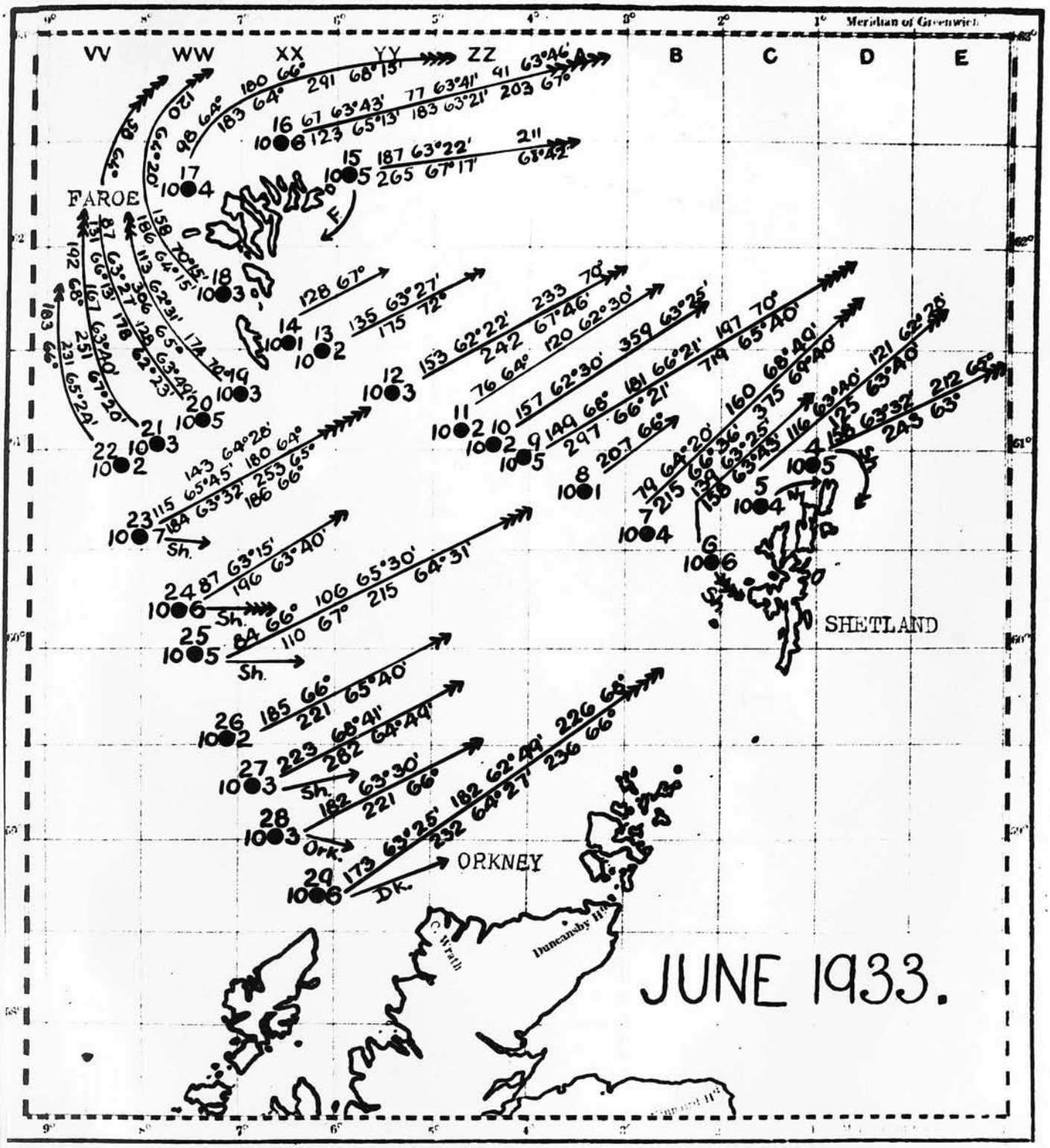

Meridian of Greenwich
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JUNE 1933.

Figure 11.

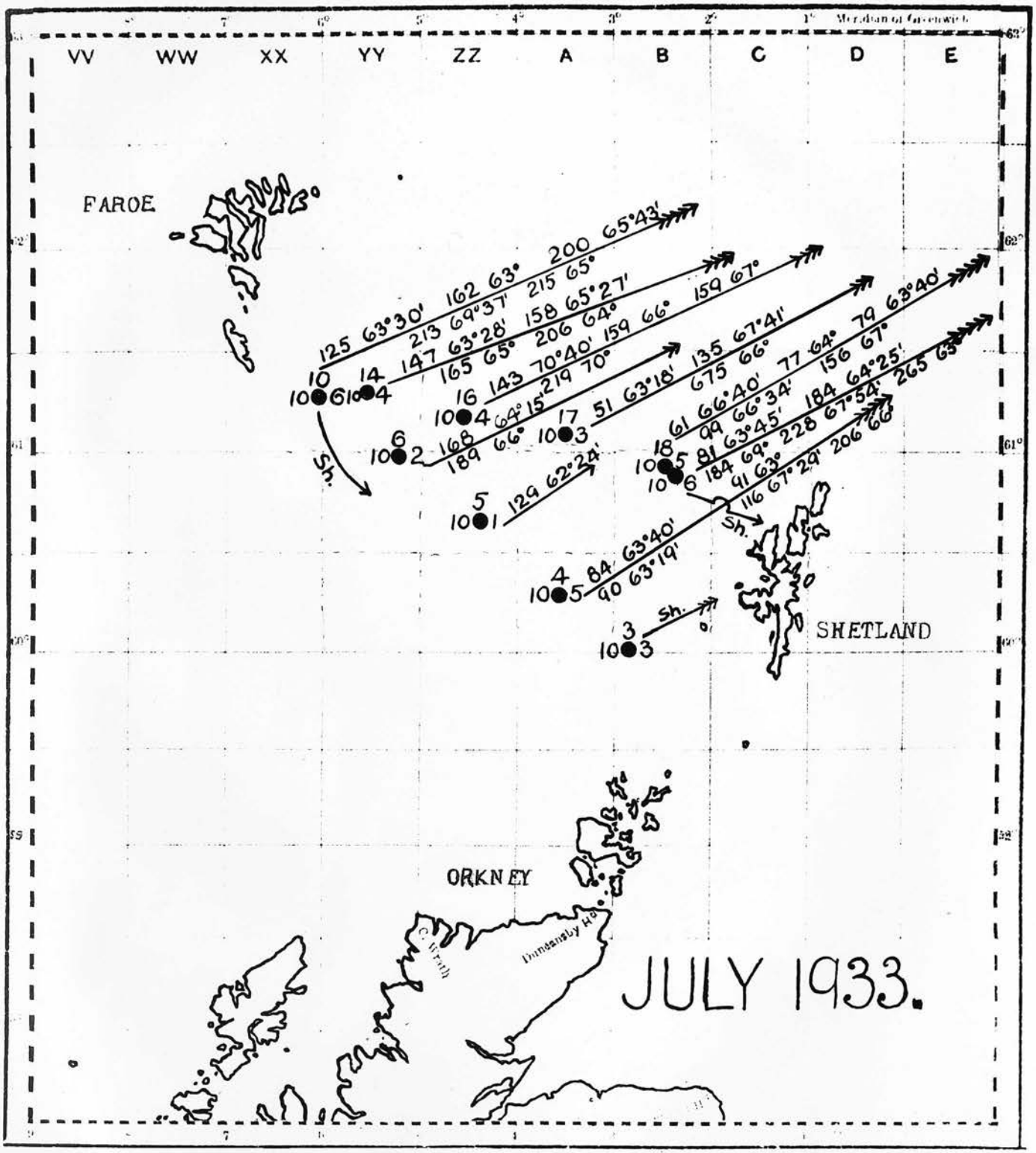

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JULY 1933.

Figure 12.

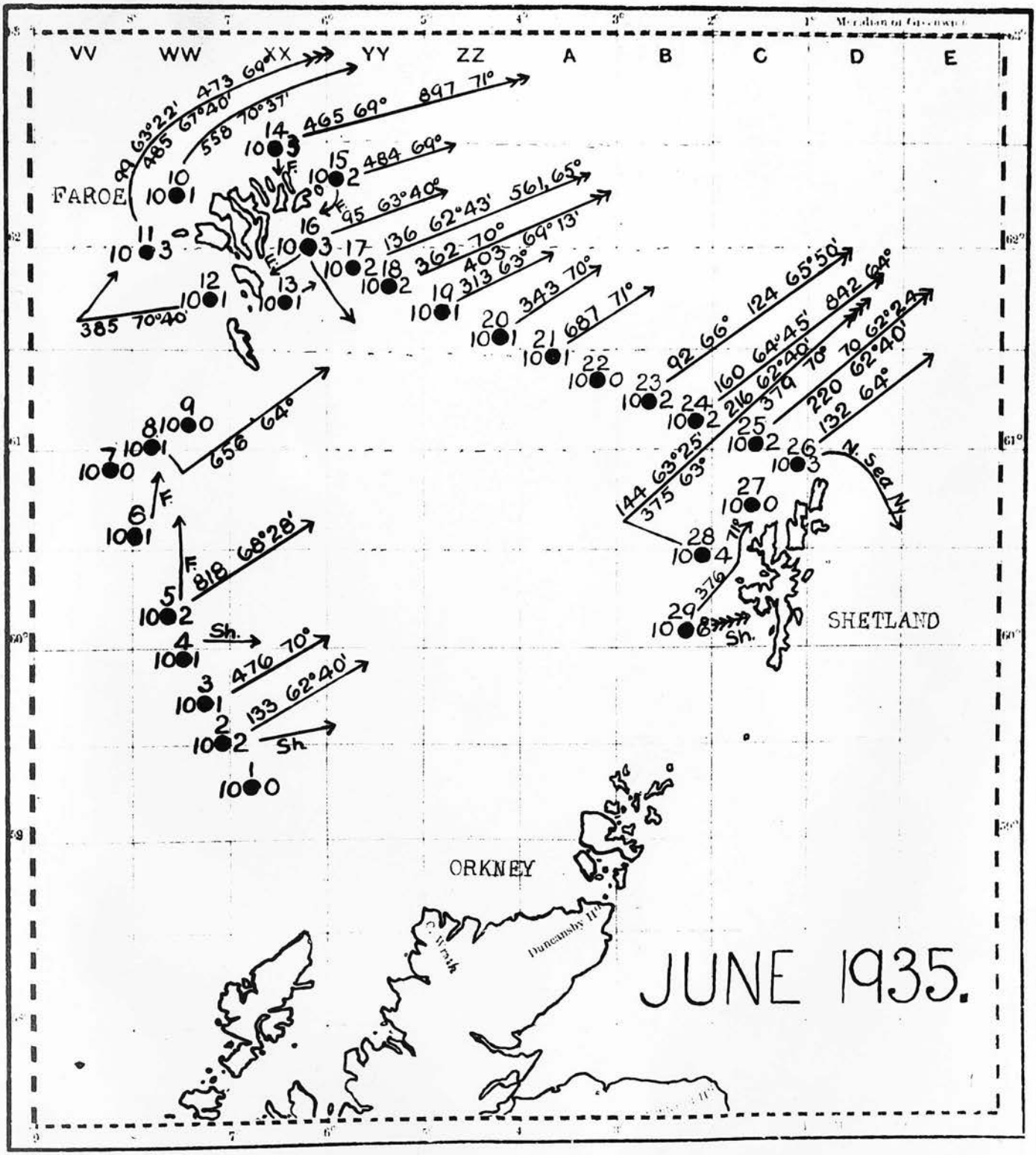


Figure 13.

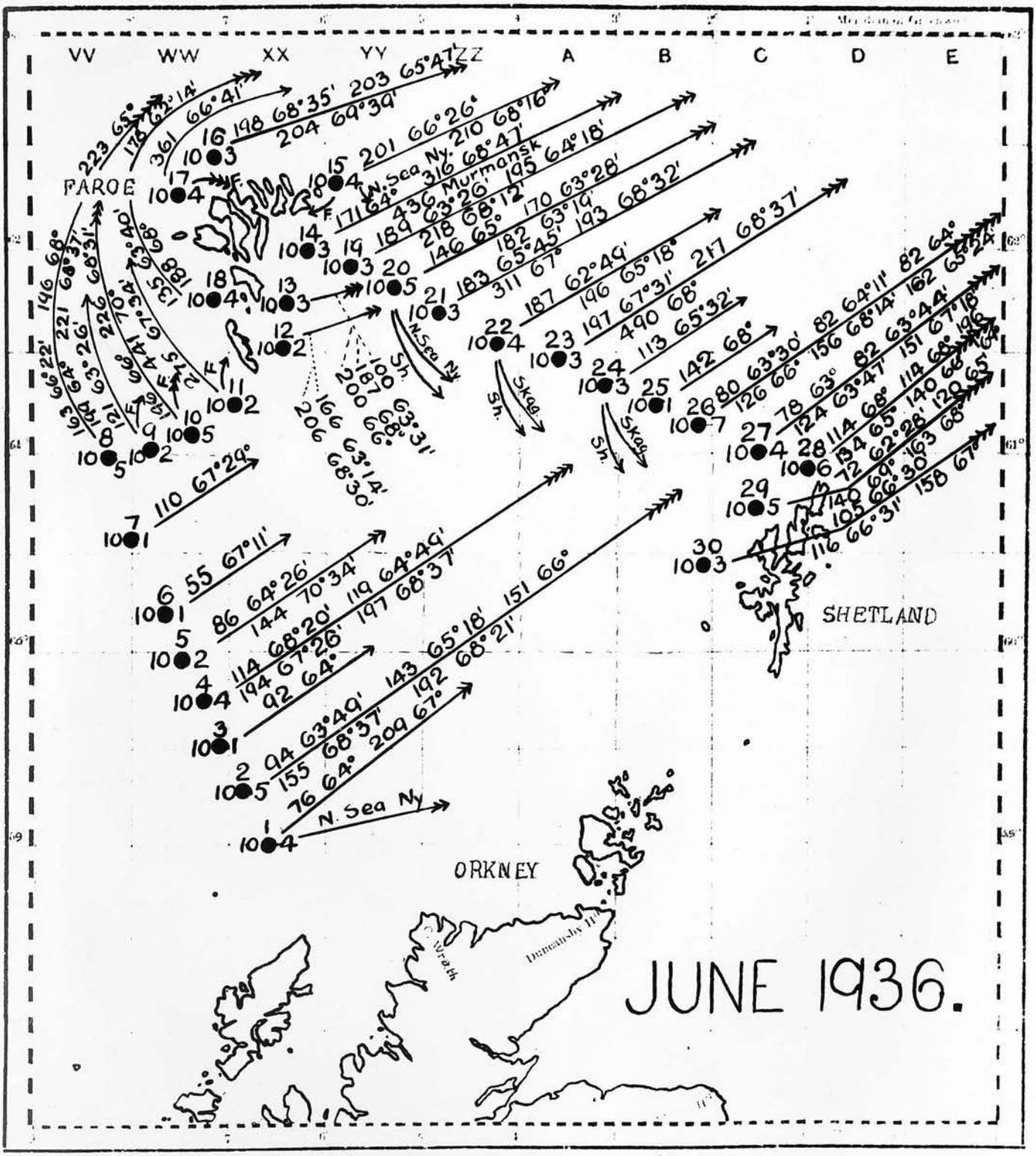

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JUNE 1936.

Figure 14.

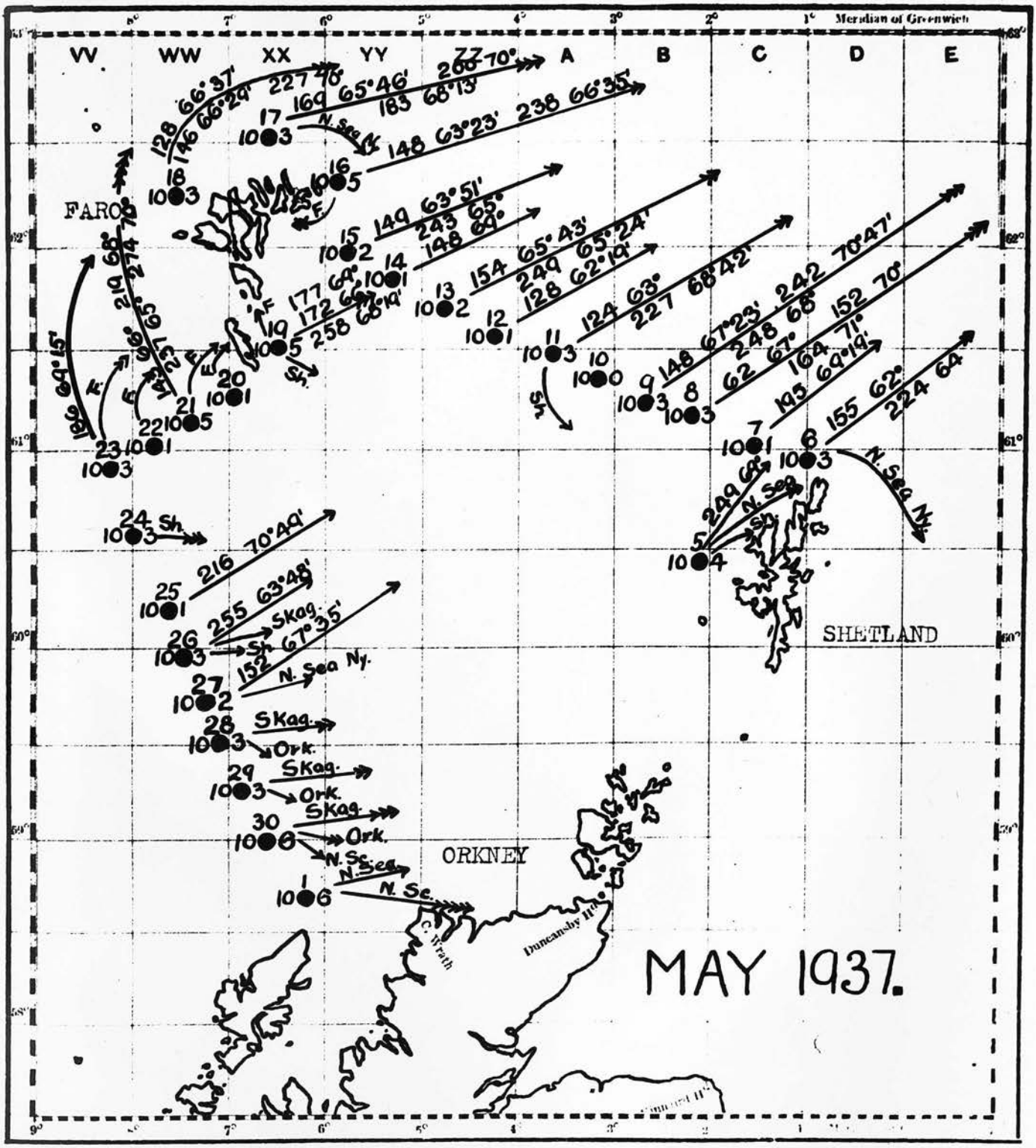

Meridian of Greenwich
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Ork.
N. Sea Ny.
Sh.
C. Wrath
Duncansby Hd.
MAY 1937.

Figure 15.

FLUCTUATIONS IN THE INTENSITY OF THE OCEANIC INCURSION INTO THE FAROE-SHETLAND CHANNEL.

By

JOHN B. TAIT, B.Sc.,Ph.D.,F.R.S.E.

NOTE.

For examination purposes, the original drawings of Figures 3, 4, and 5 in this paper are submitted, photographic reproduction to such a reduced scale as that in which they appear in the text having rendered much of the figuring illegible.

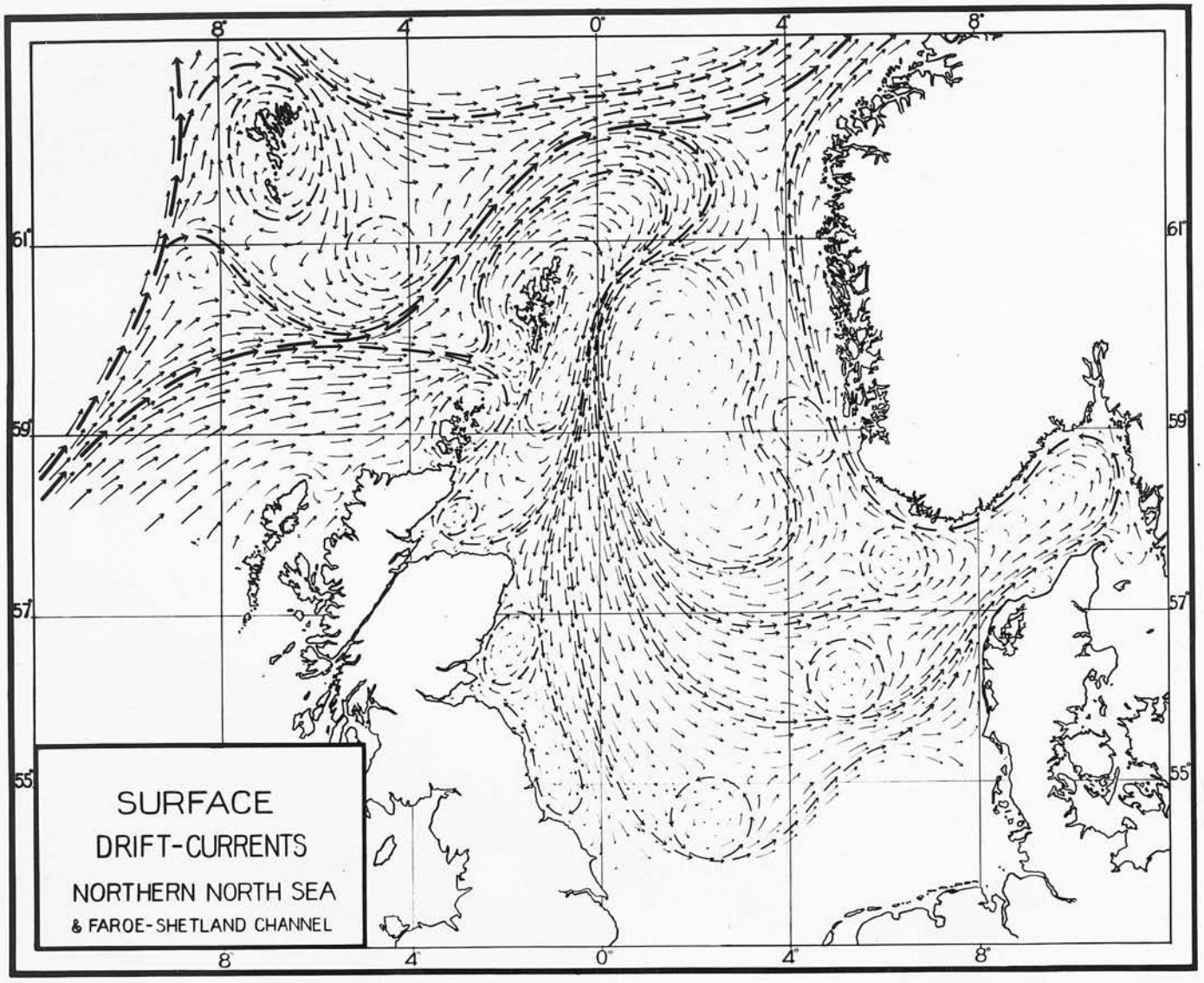
J.B.T.

FLUCTUATIONS IN THE INTENSITY OF THE OCEANIC INCURSION INTO THE FAROE-SHETLAND CHANNEL.

In its oceanographical work in connection with fisheries, the fisheries of the northern part of the North Sea, in particular, the Fishery Board for Scotland has always regarded as an essential part of its area of investigation, the region of the Faroe-Shetland Channel, through which the North Sea has wide and almost interrupted connection with the North Atlantic Ocean. The reason is twofold. Primarily, it rests in the much greater significance which, almost from the beginning, has been attached to the oceanic, or Atlantic water, influence in the northern North Sea, as opposed, more or less, to those of continental and other less characteristically distinct water-masses.

There is at least *prima facie* evidence, by no means negligible, or even scarce, in the aggregate, that the great natural fluctuations so characteristic of the commercial fisheries of the North Sea and adjacent regions, are intimately associated with those other fluctuations which are only now beginning to receive adequate quantitative expression, but which have long been known to occur in the amount, and which doubtless also affect the inherent properties, of the oceanic water flowing into these northern European seas. Indeed, it is at least arguable from existing data that the ultimate causes of fisheries fluctuations/

FIGURE I.


8°
4°
0°
4°
8°
61°
59°
57°
55°
SURFACE
DRIFT-CURRENTS
NORTHERN NORTH SEA
& FAROE-SHETLAND CHANNEL

fluctuations probably lie in the ever-changing physical, or physico-chemical oceanography of the regions involved. Towards solution of the problem, it has become obviously necessary to acquire a more exact understanding than now obtains, in regard to hydrographical phenomenona, particularly, in the first instance, in relation to the most fundamental, as well as the most universal characteristic of the sea, namely, its movement, or movements.

Already, by means of drift-bottles, there has been evolved a new and much more detailed conception of the current system of the northern North Sea and adjacent regions, in virtue of which many biological and hydrographical features receive more rational explanations than have hitherto been possible.

The currents depicted on Figure I have, moreover, been related satisfactorily, although more or less in qualitative fashion only, with the movements and relative dispositions of the typical water-masses (typical, that is, from the point of view of their origin and their inherent physico-chemical characteristics) which were early shown to occupy these regions.

Unquestionably, the water-mass of most far-reaching importance in the northern North Sea and neighbouring areas north and west, is that which emanates from the north-eastern part of the Atlantic Ocean, and the immediate desideratum is to give quantitative expression to the varying intensity of this/

this influence in the regions concerned.

The assessment of the oceanic influence in the northern North Sea, however, is extremely difficult, not only on account of the complexity of the current system, but because of the presence, in continuously varying proportions, of these other water-masses already-mentioned, in which the oceanic mass gradually loses, by admixture, its distinctive characteristics, and by which it is over-ridden, sometimes to a considerable extent, especially in summer months.

On the other hand, the first systematic observations of temperature and salinity in these regions revealed an apparently direct connection between the Atlantic water passing through the Faroe-Shetland Channel and that entering the northern North Sea, from which it was inferred that the so-called "intensity" of the oceanic influence in the one region was more or less proportional to its intensity in the other. The fact that, by more recent investigations, this may not always be true,* does not entirely discount the significance of a second observation from these earliest records, namely, that the Atlantic/

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* Vide J.B.TAIT. " Salient Features of the Hydrography of the Northern North Sea and the Faroe-Shetland Channel in 1935." Journ. du Cons.Intern.pour l'Explor. de la Mer. Vol. XI, No.2, 1936.

Atlantic water of the Faroe-Shetland Channel, more especially between Shetland and Faroe, evidently flows in an almost constant direction and within fairly definite and ascertainable limits, thus allowing some measure of its force or intensity to be obtained.

Accordingly, in the past thirty to forty years, and in conjunction with the biological work entailed in fisheries research, many hydrographic sections (for temperature and salinity) have been taken between Shetland and Faroe, approximately at right angles to the supposed mean direction of the Atlantic water drift-current, which here flows practically north-eastward as a rule. Then, either on the basis of the areal content of oceanic water on these sections, diagrammatically reproduced, or by the aid of Helland-Hansen's modification * of Bjerknes's well-known Circulation Theorem, computations have been made of the intensity of the oceanic influence at various times.

Such computations, especially those based on areal measurement, are liable to more or less serious error from various causes. On identical geographical sections, for instance, a greater areal dimension at one period than at another, ~~may mean quite the reverse of what it implies~~ does not necessarily denote correspondingly greater intensity. As a general rule indeed, the greater the/

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* B.HELLAND-HANSEN. "Report on Hydrographical Investigations in the Faroe-Shetland Channel etc." Fishery Board for Scotland. Fish. and Hydrogr.Invest.,North Sea and Adjacent Waters, 1902-1903. London 1905.

the speed of the Atlantic drift-current, unless this is accompanied by correspondingly greater masses of water, which is not always the case, the less will be the tendency for the water of the current to spread out over the section. Or, a comparatively weak flow, experiencing greater resistance to its progress, may, by its consequent extension on a section normal to its course, convey the impression of much greater intensity than an actually stronger flow subjected to relatively less impediment.

In hydrodynamical computations based on Bjerknes's Circulation Theorem, the liability to error is doubtless much less, on the whole, although, apart from the neglect of friction, there is the primary difficulty of determining exactly the "nought" or "zero-level" on which depends the accuracy of results when relative velocities are converted into absolute values. Again, on a single section, from which the actual direction of the current cannot be determined with certainty, error may arise also from this cause in estimating the volume- or mass-transport across the section.

The greatest and most frequent source of error, however, as Helland-Hansen points out, usually arises from an insufficiency of observation-stations, and in this respect the early Scottish sections laid across the Faroe-Shetland Channel, from Shetland to Faroe, undoubtedly are inadequate, although some useful information may still be gleaned from them. Over a lineal distance/

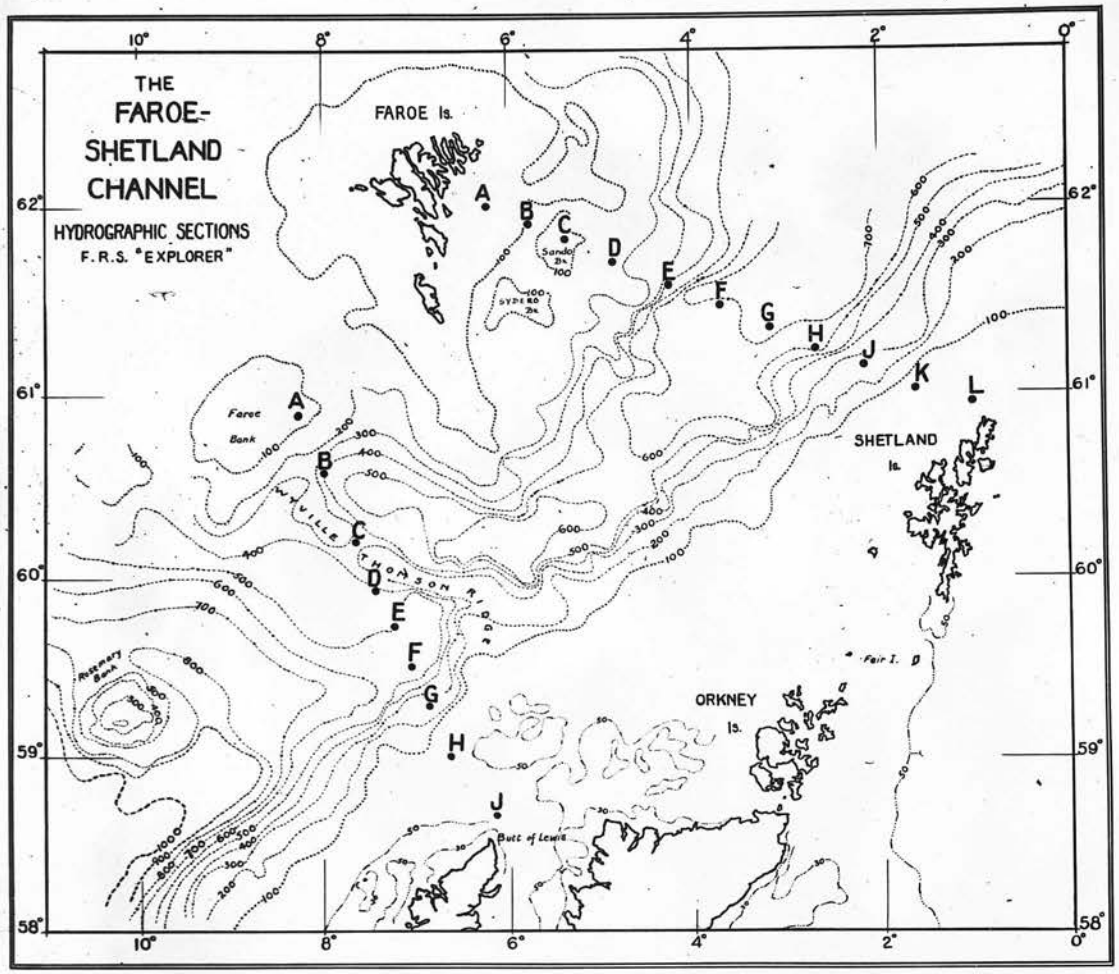

THE
FAROE-
SHETLAND
CHANNEL
HYDROGRAPHIC SECTIONS
F.R.S. "EXPLORER"
FAROE Is.
SHETLAND
Is.
ORKNEY
Is.
Faroe
Bank
WYVILLE
THOMSON RIDGE
Rosemary
Bank
Fair I.
Butt of Lewis
Sandoy
Bk.
Hyskeo
Bk.
10°
8°
6°
4°
2°
0°
62°
61°
60°
59°
58°

Figure 2.

distance of about 180 nautical miles between the northmost point of Shetland and the nearest land of the main Faroe group, originally only five stations were laid down at intervals of thirty miles or more, which is too great an interval to permit of sufficiently accurate representation of significant details of water movement such as stream-currents and vortices , these being the fundamental or constituent water-movements of which the large-scale mass-movements are comprised. Later, the number of stations was increased to seven, but it is only within the last twelve years that this particular section has included eleven stations, with, on the average, 17 nautical miles between each successive pair.

The section in question is shown on Figure 2. It lies across the deepest part of the Faroe-Shetland Channel before the latter opens out into the deep basin of the Norwegian Sea.

Prior consideration, however, ought logically to be given to the more southerly section shown on Figure 2. This one was introduced in 1927 and has been repeated almost every year since.

From the point of view of the oceanic incursion into the region, the "threshold" of the Faroe-Shetland Channel is undoubtedly the Wyville Thomson Ridge, over which, and occupying the entire depth from the surface of the sea to the summit of the Ridge, probably passes almost the whole volume of Atlantic water which subsequently finds access to northern European seas, including/

including the North Sea. Here, then, we have a first definite measure of the influx, namely, its depth, ~~and~~ This circumstance, coupled with the probability of less obstruction to, and consequently less dilution of, the oceanic current in this region than on the Faroe-Shetland section, adduced a practical reason to the logical one for re-commencing here the investigation of the Atlantic influence in the northern North Sea, on this scene of the earliest deep-sea scientific exploration under the leader whose name the Ridge has borne since its discovery seventy years ago.

Accordingly, and to meet biological as well as hydrographical needs, a section of nine stations was laid down in 1927 between the Butt of Lewis and the north-east corner of Faroe Bank. The section, as indicated on Figure 2, does not lie exactly over and along the summit of the Wyville Thomson Ridge. From the European continental shelf of less than 100 fathoms' depth, the section passes over deep water of between 500 and 600 fathoms on the Atlantic side of the Ridge, before obliquely crossing the same at about its highest part in 210 fathoms. The section then passes through a saddle-depth of 320 fathoms on the Ridge itself and thereafter into water of over 400 fathoms on its northward side, thence up on to Faroe Bank which sounds less than 100 fathoms. So disposed, this section probably lies very nearly at right angles to the mean direction of the Atlantic drift-current as it corsses the Wyville Thomson Ridge, having/

having regard to the forces which act on a gradient-current in the northern hemisphere, and which is passing also from a deeper into a shallower region.

Observations on this Butt of Lewis - Faroe Bank section ~~was~~ were inaugurated in August 1927, and ha~~s~~ve been ~~overtaken~~ carried out, in all, nine times. Since the object is the assessment of fluctuations in the Atlantic current, those sections are considered which involve practically the same calendar period of each year, in order to afford a reasonable basis for comparison. Of the nine sections completed to date, eight fall into two groups involving three and five years respectively, as revealed by the following table.

Table 1.

Butt of Lewis - Faroe Bank Section.

Inclusive Dates.

Year	Day / Month		
	I.	II	III
1927			18-19/8
1929	28-29/5		
1931	27-28/5		
1933		20-22/6	
1935	27/5-6/6		
1936	28/5-4/6		
1937	28/5-3/6		
1938		26/6-3/7	
1939		26-27/6	

Since/

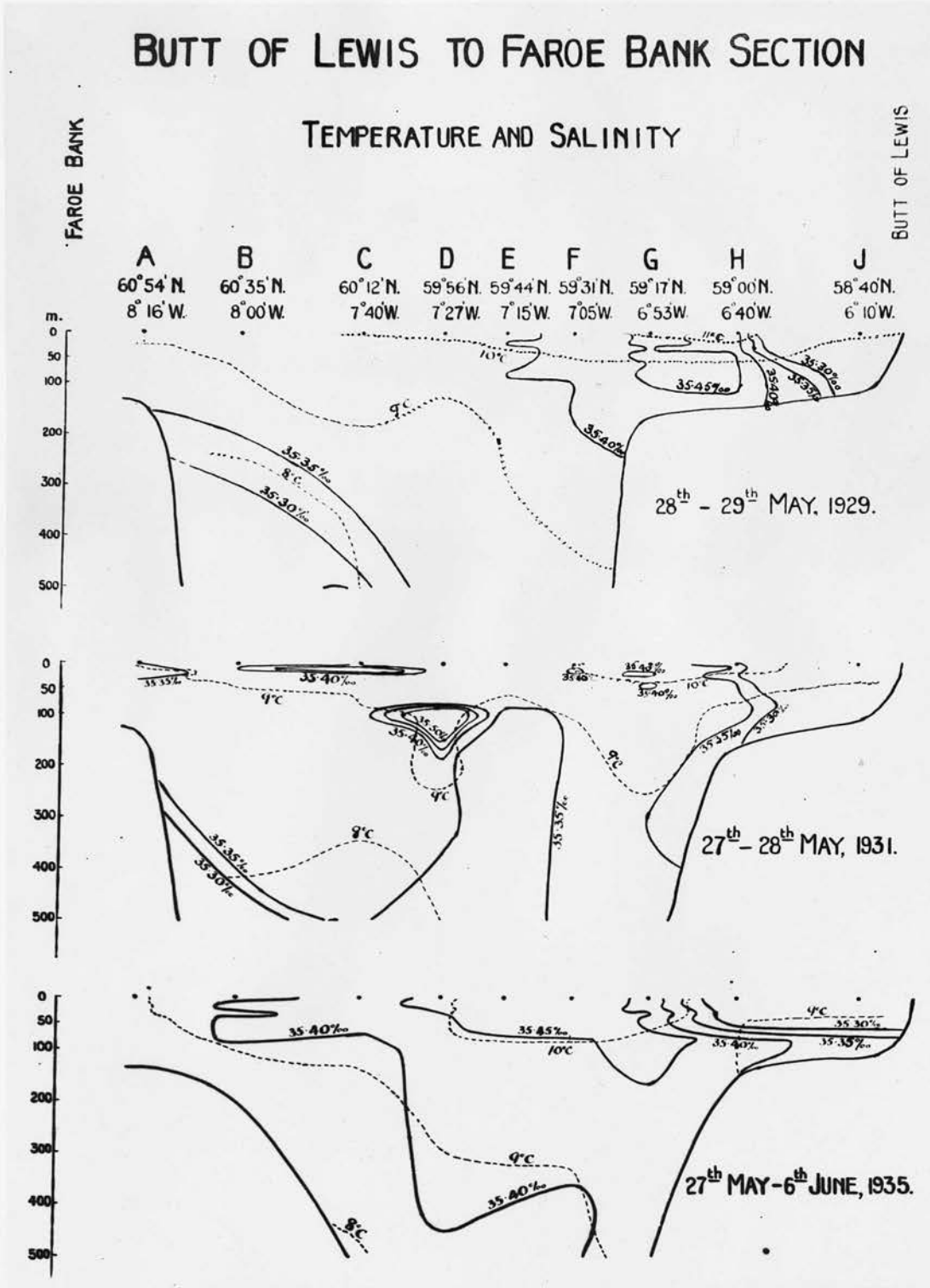

BUTT OF LEWIS TO FAROE BANK SECTION
TEMPERATURE AND SALINITY
FAROE BANK
BUTT OF LEWIS
A 60°54'N. 8°16'W.
B 60°35'N. 8°00'W.
C 60°12'N. 7°40'W.
D 59°56'N. 7°27'W.
E 59°44'N. 7°15'W.
F 59°31'N. 7°05'W.
G 59°17'N. 6°53'W.
H 59°00'N. 6°40'W.
J 58°40'N. 6°10'W.
m.
0
50
100
200
300
400
500
28th - 29th MAY, 1929.
27th - 28th MAY, 1931.
27th MAY - 6th JUNE, 1935.

Figure 3.

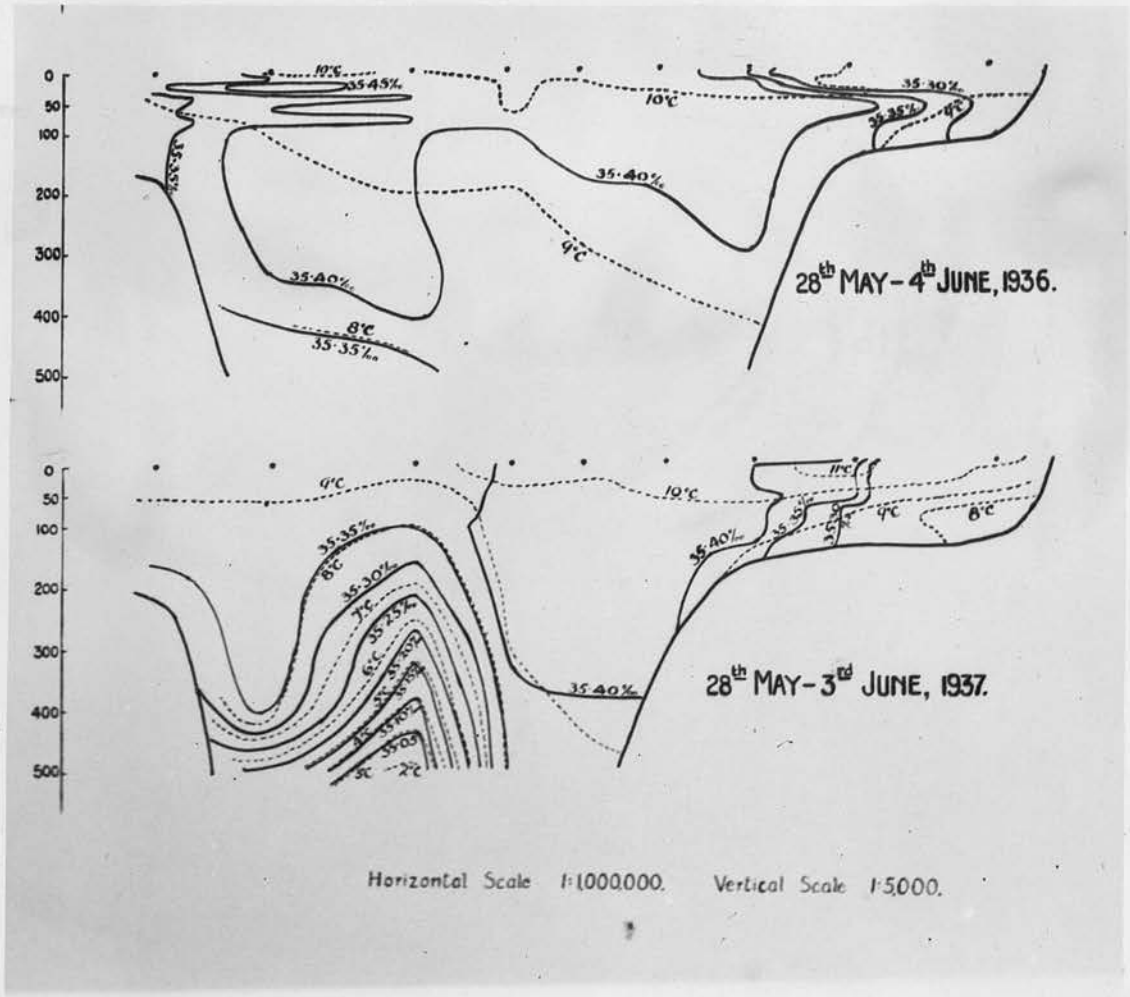

0
50
100
200
300
400
500
10°C
35·45‰
10°C
35·30‰
35·35‰
4°C
35·35‰
35·40‰
4°C
35·40‰
8°C
35·35‰
28th MAY - 4th JUNE, 1936.
0
50
100
200
300
400
500
4°C
10°C
11°C
35·35‰
8°C
35·30‰
7°C
35·25‰
6°C
35·40‰
35·40‰
4°C
8°C
28th MAY - 3rd JUNE, 1937.
Horizontal Scale 1:1000000. Vertical Scale 1:5000.

Figure 3a.

Since 1927 the section has not again been observed ~~over-taken~~ in August to afford material for comparison with that year. In each of the two main calendar groups, the inclusive dates of operations on the section correspond almost exactly. The explanation of those periods which embrace more than two to three days is that the Butt of Lewis terminal station, for convenience or expediency, has sometimes been taken a day or two before, or after, the others.

Consider, first, the five-year group, 1929, 1931, 1935, 1936 and 1937. In each of these five years the section was completed within the last few days of May and the first days of June.

In Figures 3 and 3a the distributions of temperature and salinity to a depth of only 500 metres are shown, there being nothing of note to record in the greater depths on either side of the Wyville Thomson Ridge during these periods. Moreover, taking several groups of equidistant soundings along the summit of the Ridge, its average depth beneath the sea surface works out, as nearly as possible, to 275 fathoms or 500 metres, which is therefore the average thickness in this region of the layer of Atlantic water which passes into the Faroe-Shetland Channel.

The diverse dispositions of the isopleths ~~isolines~~, particularly of the isohalines, from one section to another, is at once remarkable, arguing, even at this same period of these five years, great differences/

differences in hydrographical conditions. Always, the core of the Atlantic stream seems to have been completely crossed by the section, although its position on the section varies, sometimes considerably, from one year to another. Usually, it was situated just beyond the edge of the continental shelf, as can be inferred from the shape of the 35.40°/oo or the 35.35°/oo isohalines. In 1929, however, the central core of water of over 35.45°/oo salinity was definitely, and wholly, over the continental shelf. In 1935, water of similar salinity bulked largely towards the middle of the section, while in 1936, only a very small, thin patch appeared over towards Faroe Bank.

In 1931, there was no large area of 35.40°/oo water as on the other four sections, but in contrast to these, isolated salinity values of 35.57°/oo and 35.64°/oo were recorded on the 1931 section. Each of these values receives some support as to its authenticity, in one instance from the records at the corresponding level at neighbouring stations on either side, and, in the case of the higher value, from a peculiarity in the course of the 9°C. isotherm.

It is also clear that the areas limited by the surface and the different isohalines, as also the different isotherms, varied considerably. Expression is given to this variation in Table II, where the several areas, measured by planimeter, are expressed/

BUTT of LEWIS-FAROE BANK SECTION

27th May - 6th June

SALINITY

YEAR	Max. Salinity ‰	Stn.	Depth m.	Sectional Areas above 500 metres >35·30‰ Km²	>35·35‰ Km²	>35·40‰ Km²	>35·45‰ Km²	>35·50‰ Km²
1929	35·46	G H	0 - 80 40 - 100	87	77·5	14	3·5	-
1931	35·64 35·57 35·41	D C D G	100 10 30 20	103	78·7	3·5	2·0	1·2
1935	35·50	F	0-60	91	89·5	54	8	?
1936	35·50	B	20	105	97·5	43	0·5	?
1937	35·44	D E	80-200 60-300	71	59	27	-	-

TEMPERATURE

YEAR	Max. Temp. °C.	Stn.	Depth m.	Sectional Areas above 500 metres >8°C. Km²	>9°C. Km²	>10°C. Km²	>11°C. Km²
1929	11·17	G	0	88	49·5	7·3	0·5
1931	10·57	G	0	102	27	25	-
1935	10·66	F	10	95	58	7·0	-
1936	10·48	G	10	105	57	4·0	-
1937	11·16	H	0-10	69·5	41·3	8·0	0·6

Table II.

expressed in square kilometres.

In depths less than 500 metres very little water of salinity below 35.30°/oo seems usually to occur on this section, although the year 1937 must be taken as an exception, since, no doubt due to the presence of the Wyville Thomson Ridge, a strong upward surge of low salinity and low temperature water appears to have taken place, bringing water of 2°C. and 35.00°/oo on top of the Ridge.

On the evidence of maximum salinity alone, 1931 would appear, among these five years, to have been that of the strongest Atlantic influence on the threshold of the Faroe-Shetland Channel, but, as already remarked, the highest salinities of that year are isolated values, and although each is supported by neighbouring data, they cannot be taken as an index of the intensity of the Atlantic influence in the area. Next to these high records the more common values are those lying between 35.35°/oo and 35.40°/oo. It is evident, however, that, in each of the other four years, there were considerable areas of water of salinity in excess of 35.40°/oo on the section, so that, on this basis, instead of being the year of strongest, 1931 was probably the year of weakest oceanic influence among these five.

Little significance can be attached to the differences among the areal figures representing water of salinity greater than 35.30°/oo, since this measure, to an important extent, depends/

depends upon the shape of the bottom as estimated solely from the soundings at the nine stations of the section, and this shape varied somewhat as between one year and another, which is scarcely surprising in a region of such complex topography. In lesser degree, the same applies to the cross-sectional areas of 35.35°/oo water and over. The 1935 figures especially, under these two heads, are too low.

Greater reliance can be placed on the figures of the next two columns, namely, those for water of salinity in excess of 35.40°/oo and 35.45°/oo respectively, especially perhaps the former. 1935 is obviously the "best" year, so to speak, that is, the year apparently of the greatest Atlantic influence in the Wyville Thomson Ridge area. Next in order seem to come 1936, 1937, or 1929, and lastly 1931.

The order would appear to be the same when we consider temperature, and for the following reasons.

Maximum temperatures of 11°C. and over, are practically valueless as indicators of the relative intensities of the oceanic influence in the five years concerned, since, when they occurred, they were confined to the surface and within a very small sectional area, as shown by the last column of Table II. Because they depend so much upon the shape of the bottom the areas of water in excess of 8°C. are not really ~~inter~~-comparable. Taking the 9°C. cross-sectional areas, and with them the figures for 10°C., 1935 was clearly again the "best" year, especially when it is recognised that the value of 58 Km^2 is too

low/

low. I936 obviously seconds I935 and probably I929 comes next before I937. I93I is again last.

It must be recognised, however, that the foregoing deductions as to the relative intensities of the oceanic current into the Faroe-Shetland Channel in the different years are fundamentally indirect, in that no account is taken of any dynamic factor with which the intensity, itself a dynamic rather than a static conception, may be directly associated. The inferences made depend on the assumption that the intensity is proportional more or less to the areal content of oceanic water on a vertical section normal to the current, and for reasons already given on page 4 this assumption is not valid under all circumstances.

Now, therefore, let us consider this question of annual fluctuations in oceanographical conditions from the point of view of the volume-transport of Atlantic water over the Wyville Thomson Ridge, for, by the consideration of velocity which this entails, direct as distinct from the above indirect estimations can be made regarding the intensity of the oceanic incursion.

It is necessary here to digress in order to explain the meaning of certain terms and symbols used in the calculation of volume-transport in the sea.

Modern dynamical oceanography is founded on the work of V. Bjerknes and his collaborators* who, by studying the distribution of gravity, pressure, and specific volume in the sea, evolved a method for computing ocean currents from temperature and salinity observations, these, together, determining the density of the water <u>in situ</u>. In general terms their conclusions may be stated as follows.

In the /

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* V. Bjerknes & Collaborators. " Dynamic Meteorology and Hydrography." Vol.I. Carnegie Institution of Washington Publications, No. 88., I9I0.

In the northern hemisphere, if the water on the eastern side of a current is lighter than that on its western side, then the current is flowing either in a northerly direction with the velocity greatest at the surface and decreasing with increasing depth, or southwards with a maximum velocity at some point below the surface. On the other hand, if the water is heavier on the eastern than on the western side, the current is flowing either southwards with maximum velocity at the surface, or northward with maximum velocity lower down.

In referring to depth, however, in hydrodynamical calculations, it is dynamic depth, not geometric depth, which is involved. Dynamic depths are those at which true level surfaces occur, that is, surfaces of equal gravity-potential, or equipotential surfaces. The relationship of dynamic depth D, in dynamic metres, to geometric depth z, in common metres, is given by the equation,

$$D = gz/10. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

Pressure p at the depth z is expressed by,

$$p = \bar{\rho} g z \quad .$$

where $\bar{\rho}$ is the average density of the water-column of length z.

Substituting for gz from equation (I) to obtain the pressure in terms of dynamic metres,

$$p = k.10\bar{\rho}D \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2).$$

where the value of k depends upon the unit of pressure. The pressure of one dynamic metre of pure water at its maximum density point is 10^5 dynes per square centimetre, or one decibar. Adopting this as the standard unit of pressure, $k = 1/10$ and (2) reduces to

$$p = \bar{\rho}D \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3).$$

And since specific volume α is the reciprocal of the density,

$$D = \bar{\alpha} p \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4).$$

In/

In practical applications $\bar{\rho}$ and $\bar{\alpha}$ are generally unknown and because of their variation with depth the integral formulae

$$p = \int \rho \, dD \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5).$$

$$D = \int \alpha \, dp \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6).$$

extended over the whole water-column must be used in place of (3) and (4).

Now, problems of motion in the form of what are called gradient-currents, like the Atlantic current through the Faroe-Shetland Channel, can be investigated in vertical sections normal to their courses by the consideration either of the dynamic depths of standard isobaric surfaces, or of the pressures in standard dynamic depths. The former is preferable, for, with pressure expressed in the standard unit of one decibar, its value, except in the deepest parts of the sea, is only about one per cent. more than the geometric depth in metres, whereas the dynamic depth is about two per cent. less than the geometric depth at ordinary levels. In practice, therefore, it is better to compute the dynamic depths of standard isobaric surfaces, the pressure in decibars being accepted as equivalent in value to the depth in metres, rather than to compute pressure at the standard dynamic depths, taking the latter as being coincident with the goemetric depths. These computations are usually made with the aid of specially prepared tables.

Now as to their employment in hydrodynamical calculations.

Bt a modification of Bjerknes's original Circulation Theorem, Helland-Hansen derived the following formula whereby the difference in the velocity of a current at different depths may be calculated.

$$v - v_1 = \frac{IO}{\lambda L} (D'_A - D'_B) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7).$$

v being the average velocity component in metres per second at right angles to the vertical section between two stations A and B, at an upper isobaric surface/

surface p (decibars), and v_1 the corresponding quantity at a lower surface p_1 ; D'_A and D'_B are the thicknesses, in dynamic metres, of the water-layer between the two surfaces at these two stations. L is the distance in metres between A and B, $\lambda = 2\omega \sin\varphi$, where ω is the angular velocity of the earth's rotation and φ the mean geographical latitude of the two stations.

The assumptions of Helland-Hansen's formula are that stationary conditions exist, that is, that there should be no acceleration which for the time being cannot be neglected, and that friction can be disregarded. It gives, as already stated, velocity differences as between different levels, and if the velocity at one of these levels is known, (it may, for instance, be zero), the velocities at other levels can be calculated.

As Anton Jakhelln points out, however,* it is more convenient to compute the average velocity component through the section between the two stations and thus find the water-transport directly. By a further development Jakhelln leads to the method for computing the volume-transport of gradient currents which is used in this paper in relation to the current in the Faroe-Shetland Channel.

If $\bar{v}$ be the average velocity component between the sea surface and the depth z_1 metres (where $v = v_1$) at right angles to the vertical section between A and B,

$$\bar{v}z_1 = \int_0^{z_1} v.dz.$$

The volume of water which flows through the section in unit time is

$$V = L.\bar{v}.z_1 = L\int_0^{z_1} v.dz \text{ (cubic metres per second).}$$

Substituting/

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* Anton Jakhelln. " The Water Transport of Gradient Currents." Geofysiske Publikasjoner, XI, No.II. Norske Videnskaps-Akademi i Oslo, I936.

Substituting from Helland-Hansen's formula, we obtain,

$$V = L\int_0^{z_1}\left\{v_1 + \frac{IO}{\lambda L}\,(D'_A - D'_B)\right\}dz$$

and further,

$$V = Lv_1z_1 + \frac{IO}{\lambda}\left\{\int_0^{z_1} D'_A\,dz - \int_0^{z_1} D'_B\,dz\right\}$$

$$= Lv_1z_1 + \frac{IO}{\lambda}\,(Q_A - Q_B)$$

where

$$Q = \int_0^{z_1} D'_\bullet\,dz = \int_0^{z_1}(D_1 - D)dz = D_1 z_1 - \int_0^{z_1} D_\bullet\,dz \quad . \quad . \quad . \quad . \quad . \quad (8).$$

Q_A and Q_B are the values of the integral Q at the two stations A and B.

If $v_1 = 0$, that is, if the water at the depth z is motionless, we obtain,

$$V = \frac{IO}{\lambda}\,(Q_A - Q_B)\ m^3 / \text{sec.} \quad . \quad . \quad . \quad . \quad . \quad (9).$$

If, therefore, the dynamic depth D of standard isobaric surfaces is computed, volume-transport can be calculated from the formulae (8) and (9), the second term of the quantity Q, which must be computed for each station, being obtained by numerical integration using a calculating machine.

In the present case, the necessary computations of dynamic depths in respect of the standard isobaric surfaces 0, IO, 20, 30, 40, 60, 80, IOO, 200, 300, 400, and 500 decibars were made with the aid of tables prepared by Hesselberg and Sverdrup.* Then, using the above formulae (8) and (9) due to Anton Jakhelln, and assuming the 500-metre level (the average depth of the summit of the Wyville Thomson Ridge) as the so-called zero-level, or the level z_1 at which $v_1 = 0$, the figures given in Table III were obtained in respe respect of the volume-transport of Atlantic water across the Ridge between successive pairs of stations from B to G, at each of which depths more or less in excess of 500 metres were registered. On the basis of the general theory /

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* Th. Hesselberg und H. U. Sverdrup. "Beitrag zur Berechnung der Druck- und Massenverteilung im Meere." Bergens Museums Aarbok, 1914-1915, No. 4.

BUTT of LEWIS - FAROE BANK SECTION

27th May - 6th June

Volume Transport of Atlantic Water

	B	C	D	E	F	G	Totals
			$m^3/sec. \div 10^6$				
1929	-1·81	+0·35	-4·77	+4·17	-0·56		-2·62
1931	+0·72	-0·14	-0·43	-0·01	-0·99		-1·85
1935	+0·39	-0·74	-0·19	-0·11	-0·50		-1·15
1936	-0·66	-0·61	+0·49	-0·65	-0·26		-1·69
1937	+4·74	-5·99	-1·15	+0·49	+0·38		-1·53

Table III.

theory of gradient currents as explained on page 13a, the negative sign in Table III signifies northeastward, and the positive sign, southwestward transport at right angles to the Butt of Lewis-Faroe Bank section. The figures themselves, denoting millions of cubic metres per second, strikingly illustrate the enormous scale of the mass water-movements in this important region from the point of view of the seas of northwestern and northern Europe.

It is clear also that the order of the years is not the same here as was inferred from the salinity-temperature distributions on the appropriate sections. Indeed, except for 1929, the order now is practically the reverse of that previously given. 1935, which was previously considered the "best" year from the point of view of Atlantic water influence about the Wyville Thomson Ridge is here obviously shown to have been actually the poorest year as regards the volume-transport of Atlantic water northward across the Ridge. And 1931, which was before the poorest, in the present connection, and save for 1929, was apparently the year of greatest oceanic activity in this region. Thus it would appear that, as a general rule and as already pointed out, the greater the extension of a typical water-mass on a hydrographic section more or less normal to its direction of movement, the less is the intensity of that movement.

In all five years there evidently were oppositely-directed movements across the section, the nearest approach to

universal/

universal northward movement, which, as was to be expected, is the prevailing movement, occurring in 1931 and in 1935. In these two years the only southerly tendency was over towards Faroe Bank. The net transport, then, from these calculations, appears always to be northward, but the differences between the amounts transported in the several years are very great.

1929 stands out as a year of pronounced oceanic activity and it is interesting to note that Helland-Hansen found likewise on his Sogne Fjord section*. With due allowance for the fact that in the above calculation we have not included all the Atlantic water which, at the same time, passed through the Faroe-Shetland Channel, the difference between the above figure of 2.62 and Helland-Hansen's figure of 3.31 million cubic metres per second, is almost certainly much more apparent than real.

As between 1929 and 1931 there appears to have been a decrease of almost 30% in the intensity of the Atlantic drift, which, if it was regular, means a decrease of 15% per annum. Between 1931 and 1935 the total decrease amounted practically to 40% or, say, 10% per annum. On the other hand, an increase of at least 45% seems indicated as between 1935 and 1936 while, in the following year, a decrease of 10% is demonstrated by these figures.

Turning/

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* B. Helland-Hansen: "The Sogne Fjord Section." James Johnstone Memorial Volume. University Press, Liverpool, 1934.

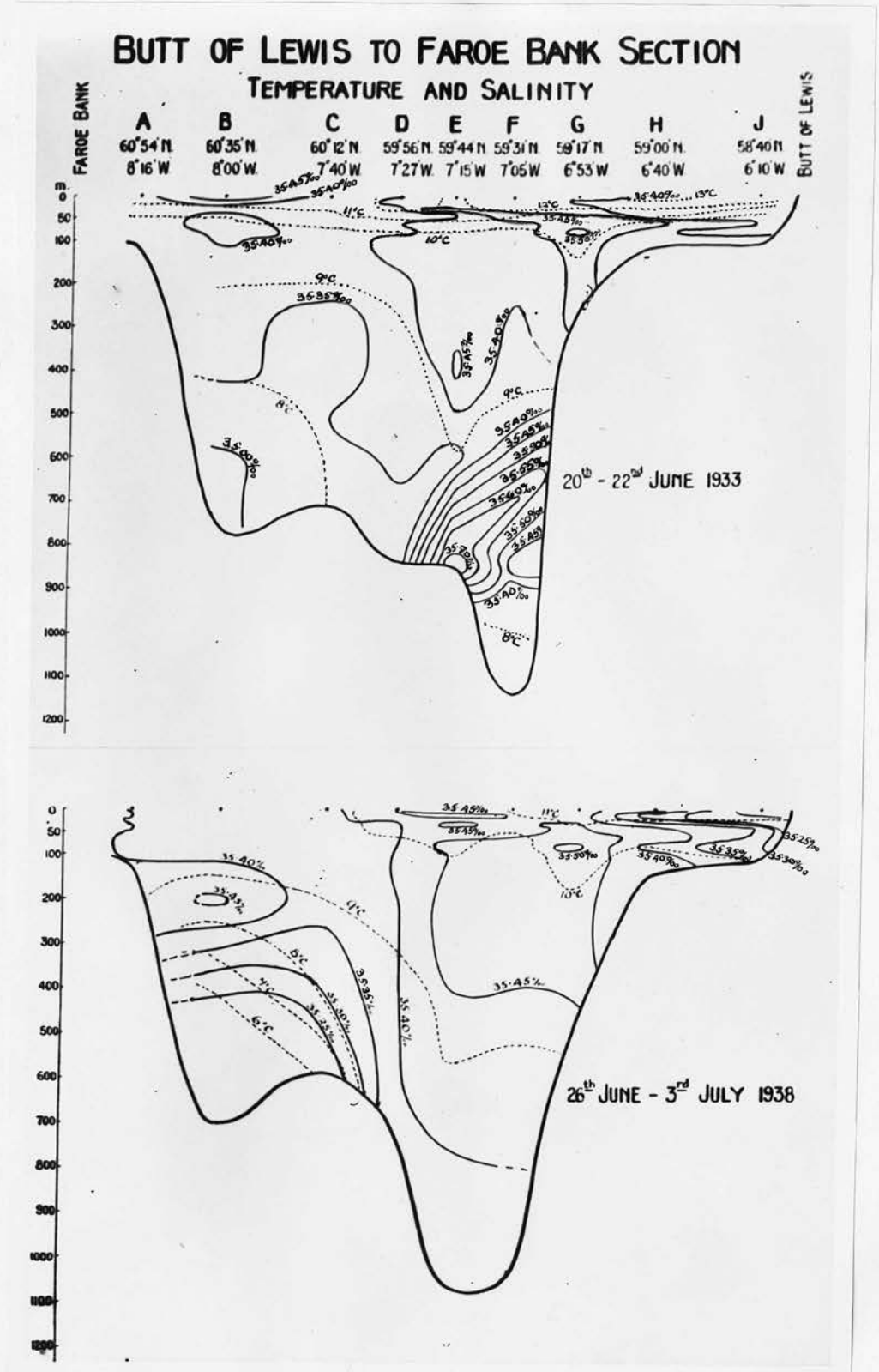

BUTT OF LEWIS TO FAROE BANK SECTION
TEMPERATURE AND SALINITY
FAROE BANK
BUTT OF LEWIS
A B C D E F G H J
60°54'N 60°35'N 60°12'N 59°56'N 59°44'N 59°31'N 59°17'N 59°00'N 58°40'N
8°16'W 8°00'W 7°40'W 7°27'W 7°15'W 7°05'W 6°53'W 6°40'W 6°10'W
m.
0
50
100
200
300
400
500
600
700
800
900
1000
1100
1200
20th - 22nd JUNE 1933
26th JUNE - 3rd JULY 1938

Figure 4.

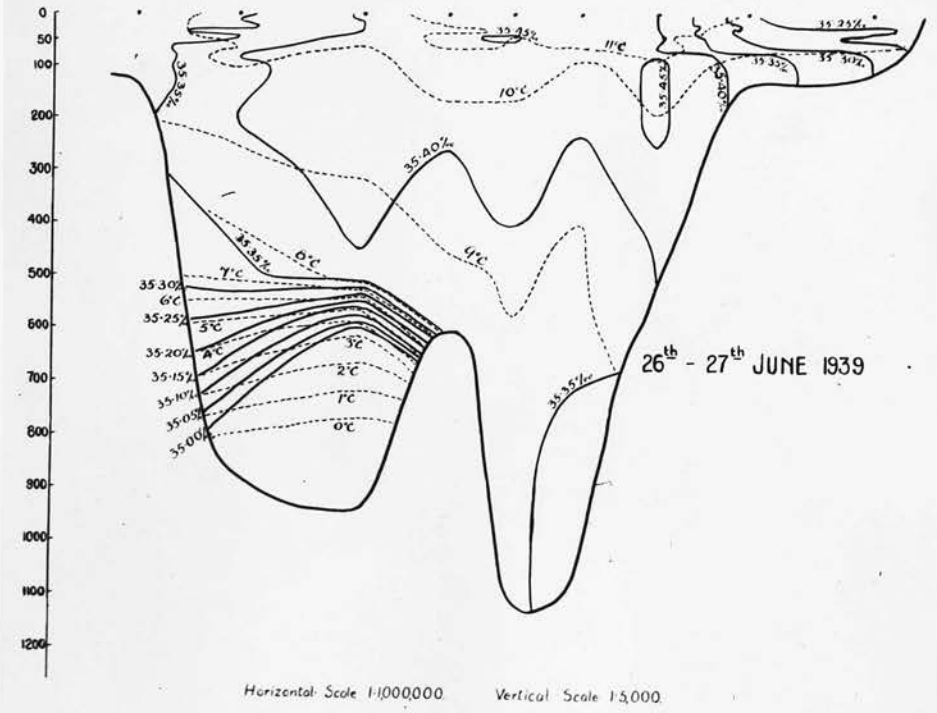

0
50
100
200
300
400
500
600
700
800
900
1000
1100
1200
35·45‰
11°C
10°C
35·40‰
9°C
7°C
6°C
5°C
4°C
3°C
2°C
1°C
0°C
35·30‰
35·25‰
35·20‰
35·15‰
35·10‰
35·05‰
35·00‰
26th - 27th JUNE 1939
Horizontal Scale 1:1,000,000
Vertical Scale 1:5,000

Figure 4a.

Turning now to the second group of three years, 1933, 1938 and 1939, Figures 4 and 4a give the temperature-salinity distributions as constructed from the original observations.

These sections were observed about one month later in the year than those of the previous group, and this circumstance is reflected in the higher average salinities and temperatures in the upper waters of the later sections. In this case the complete sections are shown and that for 1933 shows a peculiarity which is entirely absent from any of the others. The mass of water below 500 metres on the Atlantic side of the Ridge, with a temperature of between 8°C and 9°C. and salinity ranging from about 35.40°/oo to 35.70°/oo was almost certainly of Mediterranean origin, and some of it evidently passed upwards and over on to the continental shelf. The actual salinity values upon which the deep-water curves are based are 35.73°/oo at bottom (840 metres) at station E, and 35.61°/oo in 700 metres at station F. In addition, the bottom salinity at station G, in 265 metres, was 35.60°/oo (the average salinity of the uppermost 200-metre water-column at this station being 35.46°/oo) and that at the bottom (113 metres) at station J, 35.58°/oo, the average salinity here being 35.23°/oo. It may be recalled that the year 1933 was signalised by the number of extraordinarily high salinities recorded within the limits of the northern North Sea,*/

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* J.B. TAIT. " Recent High Salinity Records from the Northern North Sea." Cons.Intern. pour l'Explor.de la Mer., Rapp. et Proc.-Verb.,XCIV, 1935.

BUTT of LEWIS-FAROE BANK SECTION

20th June - 3rd July

SALINITY

YEAR	Max. Sal. ‰	Stn	Depth m.	Sectional Areas above 500 metres >35·30‰ Km²	>35·35‰ Km²	>35·40‰ Km²	>35·45‰ Km²	>35·50‰ Km²
1933	35·62	F	30	100	86	39	6·5	?
	·57	F	10					
	·51	F	40					
	·55	G	0					
	·52	G	80					
	·60	G	165					
	·58	J	110					
1938	35·52	G	80	98·5	88·5	57·5	26	?
1939	35·46	E	40	131	97	56	2	-
		G	100-200					

TEMPERATURE

YEAR	Max. Temp. °C.	Stn.	Depth	Sectional Areas above 500 metres >8° °C	>9° °C	>10° °C	>11° °C	>12° °C
1933	13·34	H	0	100	71·5	19·5	10·5	4·4
1938	11·35	G	10	95	75	17·3	2·5	-
1939	11·68	F	0	107	89	27·5	7·5	-

Table IV.

BUTT of LEWIS - FAROE BANK SECTION

20th June - 3rd July

Volume Transport of Atlantic Water

	B	C	D	E	F	G	Totals
			$m^3/sec \div 10^6$				
1933	-1·53	-1·10	+0·17	-0·38	+0·36		-1·53
1938	-1·59	-0·17	+0·02	+0·23	-1·06		-2·57
1939	+2·54	-1·80	+3·91	-3·62	-1·22		-0·19

Table V.

Sea, not one of the records in question being a surface value. The connection seems clear.

Treating these sections in similar fashion to the previous group, Table IV gives the relative areas of waters of various temperatures and salinities above 500 metres on these three sections.

On the whole, and taking both temperature and salinity into consideration, oceanic influence in the Wyville Thomson Ridge region would appear to have been greatest, among these three years, in 1939, that is, in the present year. Next comes 1938, judging rather from salinity than from temperature, for, as between 1938 and 1933, the figures for temperature show little appreciable difference, except as regards water of over 11°C. of which 1933 had obviously the greater amount.

Turning to the hydrodynamical calculations for these three years the figures shown in Table V were obtained in the same way as before.

Once again, instead of being the year of greatest oceanic activity among these three, as implied by the temperature-salinity distribution, 1939 was evidently the poorest. But the converse does not hold in this case. 1933 was indicated as the year of poorest Atlantic water represented by temperature and salinity distributions. Hydrodynamical calculations place it intermediate between 1939 and 1938, the latter apparently having been a strong year. The circumstances under which this/

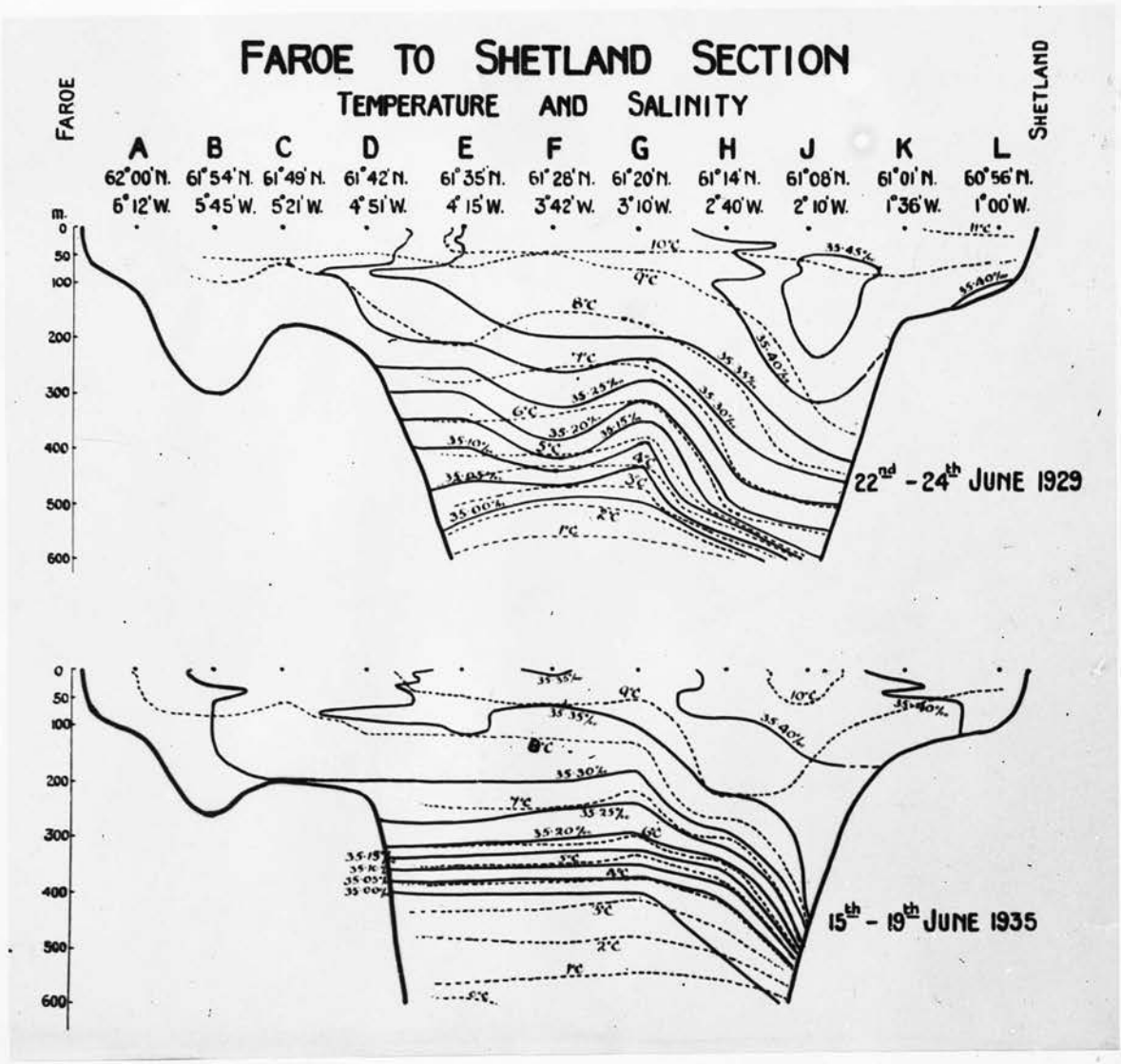

FAROE TO SHETLAND SECTION
TEMPERATURE AND SALINITY
FAROE
SHETLAND
A B C D E F G H J K L
62°00'N. 61°54'N. 61°49'N. 61°42'N. 61°35'N. 61°28'N. 61°20'N. 61°14'N. 61°08'N. 61°01'N. 60°56'N.
6°12'W. 5°45'W. 5°21'W. 4°51'W. 4°15'W. 3°42'W. 3°10'W. 2°40'W. 2°10'W. 1°36'W. 1°00'W.
m.
0
50
100
200
300
400
500
600
22nd - 24th JUNE 1929
15th - 19th JUNE 1935

Figure 5.

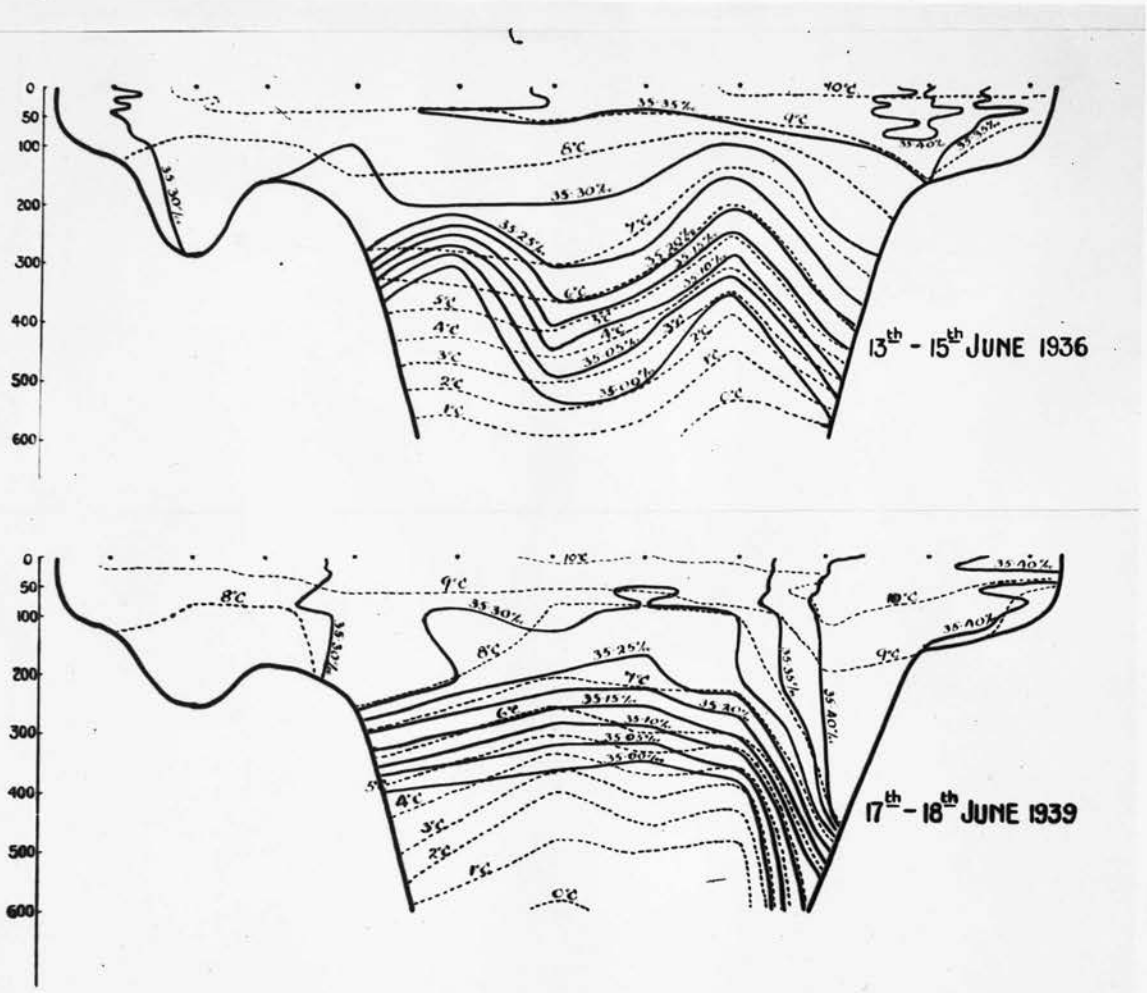

0
50
100
200
300
400
500
600
10°C
8°C
7°C
6°C
5°C
4°C
3°C
2°C
1°C
0°C
35·35‰
35·30‰
35·25‰
35·20‰
35·15‰
35·10‰
35·05‰
35·00‰
35·40‰
13th - 15th JUNE 1936
9°C
17th - 18th JUNE 1939
Horizontal Scale 1:1000,000
Vertical Scale 1:5,000.

Figure 5a.

this particular section was worked, however, throw considerable doubt upon the transport-number obtained. Owing to stress of weather, a break of five days occurred between stations D and E, that is, in the middle of the section. The weather conditions before and after the break were very different, especially as regards wind, and this may have had sufficient effect on the oceanographical conditions to vitiate the above calculations.

Assuming a regular diminution in the intensity of the Atlantic impulse between 1933 and 1939, the annual percentage diminution works out at about 15% which would be in accordance with values already given.

With reference now to fluctuations in the Atlantic water intensity between Shetland and Faroe, four sections of closely corresponding calendar periods have been selected, namely, those ~~overtaken~~ observed between the 13th and 24th of June in the years 1929, 1935, 1936 and 1939.

Temperature-salinity distributions in the uppermost 500 metres on these sections are represented in Figures 5 and 5a, and 1929 again stands out as a year in which oceanic influence was evidently very strong in the Faroe-Shetland Channel region. In none of the other four years was there any water on this section of temperature greater than 11°C. and salinity in excess of 35.45°/oo.

By the figures of Table VI, 1935, in virtue of its relatively/

SHETLAND-FAROE SECTION

13th-24th June

SALINITY

YEAR	Max. Sal. ‰	Stn.	Depth m.	Sectional Areas above 500 metres >35·00‰ Km²	>35·30‰ Km²	>35·35‰ Km²	>35·40‰ Km²	>35·45‰ Km²
1929	35·47	J	60-200	103	60	45·5	21	3·8
1935	35·44	J	10-80	91	61	34	11·5	-
1936	35·42	K	40&80	92·5	47	12	1·5	-
1939	35·43	K	0.80&100	87	44	21	14	-

TEMPERATURE

YEAR	Max. Temp. °C	Stn.	Depth m.	Sectional Areas above 500 metres >8°C Km²	>9°C Km²	>10°C Km²	>11°C Km²
1929	11·41	L	0	56	33	11·7	0·5
1935	10·13	J	0-20	46	20	1·0	-
1936	10·54	L	0	35	16·5	1·8	-
1939	10·65	K	0-10	47·5	24	7	-

Table VI.

relatively greater cross-sectional areas of water with salinities in excess of $35.30^{o}/_{oo}$ and $35.35^{o}/_{oo}$ may be ranked next to 1929 in point of oceanic influence, to be followed closely by 1939 which possessed distinctly the greater amounts of water with temperatures above 9°C. and above 10°C. 1936 would seem to have been the year of poorest oceanic influence in this region.

Calculations of the volume-transport of Atlantic water across the Faroe-Shetland Channel proper, in these four years, do not, in this case, reverse the order of the years suggested by the corresponding temperature-salinity distributions. The figures are given in Table VII. Although some doubt must exist as to the accuracy of the 1936 figure of $+0.05 \times 10^{6}$ cubic metres per second, indicating a small resultant transport of oceanic water towards the south-west, this year was probably the weakest of the four as regards the intensity of the oceanic influence, the year 1929 being by far the strongest.

The close similarity between the transport-number for 1929, namely, 3.61×10^{6}, and the corresponding figure of 3.31×10^{6} found by Helland-Hansen from his Sogne Fjord Section of that year, traversed about one month in advance of the Scottish Faroe-Shetland section, is very striking, and may be taken as evidence of the accuracy of these calculations.

Clearly, then, the amounts of warm, salt, oceanic water which are continuously passing northwards over the Wyville Thomson Ridge into and through the Faroe-Shetland Channel,

SHETLAND - FAROE SECTION

13th - 24th June

Volume Transport of Atlantic Water

	E	F	G	H	J	Totals
			$m^3/sec \div 10^6$			
1929	+1·48	-0·57	-2·25	-2·27		-3·61
1935	-0·21	+0·08	-0·93	-1·22		-2·28
1936	-0·37	+1·06	+1·84	-2·48		+0·05
1939	+1·44	-0·70	+1·91	-3·90		-1·25

Table VII.

towards northern European seas, reach enormous proportions and fluctuate annually by such huge amounts as must inevitably have important repercussions upon the marine biological and probably other, e.g. meteorological, phenomena of these and neighbouring regions. Given a sufficiency of points at which the basic observations of temperature and salinity are taken in respect of this influx, the means are available for its measurement, thus pointing the way to further advance, which, it may confidently be anticipated, will be of an all-important character, in the association of marine biological with hydrographical phenomena.