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Currents and Water Masses

Introduction

Two papers have been published in recent years, viz., Lee and Ramster (1968) and Lee (1970), which between them provide a basic background knowledge of the physical oceanography of the North Sea, with particular emphasis on the water masses and current systems. The aims of the present paper are: first, to review briefly some of the major points of these two previous papers; and second, to attempt to bring them up to date by presenting, albeit in a rather preliminary fashion, some further data which have become available since 1969, when Lee's paper was actually written.

The Water Masses

As indicated by Lee (1970), it is generally accepted that the major inflows to the North Sea consist of Atlantic water of high salinity entering (i) from the north, between the Shetlands and Norway (North Atlantic) and (ii) from the south via the Straits of Dover (Channel), the northerly inflow being the greater source of Atlantic water, and (iii) the Baltic outflow, which is of lower salinity (Skagerrak). These three inflows provide the three primary water mass types, but five secondary water masses are derived from them and the run-off from the land masses, as illustrated by Laevastu (1963) in Figure 1. These are named Scottish Coastal, English Coastal, Continental Coastal, Northern North Sea, and Central North Sea, and in general terms they extend from surface to bottom in the regions indicated in Figure 1. It will be noted that the main difference in coverage between seasons is that, during the summer, Northern North Sea water is found over an area extending much further to the west, occupying part of the area covered in winter by the North Atlantic water mass. This reflects a generally, but not universally held belief (e.g., Svansson, 1965) that the major inflow of North Atlantic water takes place during the autumn and winter months, i.e., from September to February. Of the three primary water masses the North Atlantic and Channel types also extend generally from surface to bottom, but the Skagerrak type, in both the Norwegian Rinne and in the Skagerrak itself, overlies water of North Atlantic origin in the deep channel around the south-western coast of Norway. In a recent paper Dooley and Martin (1969) have suggested, in fact, that much of the North Atlantic water within the North Sea is derived from a core of Atlantic water which flows along the edge of the continental

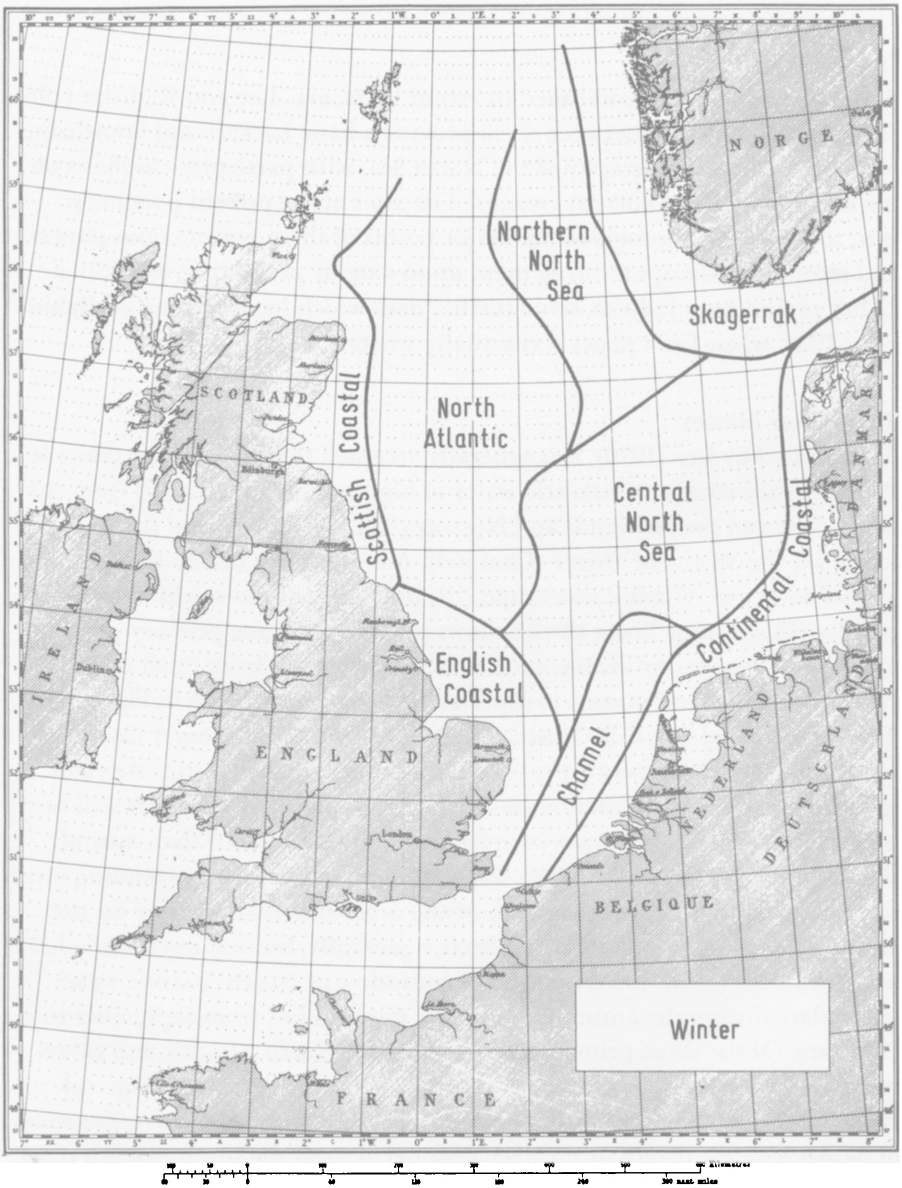

Figure 1a Water masses of the North Sea in winter (after Laevastu, 1963).

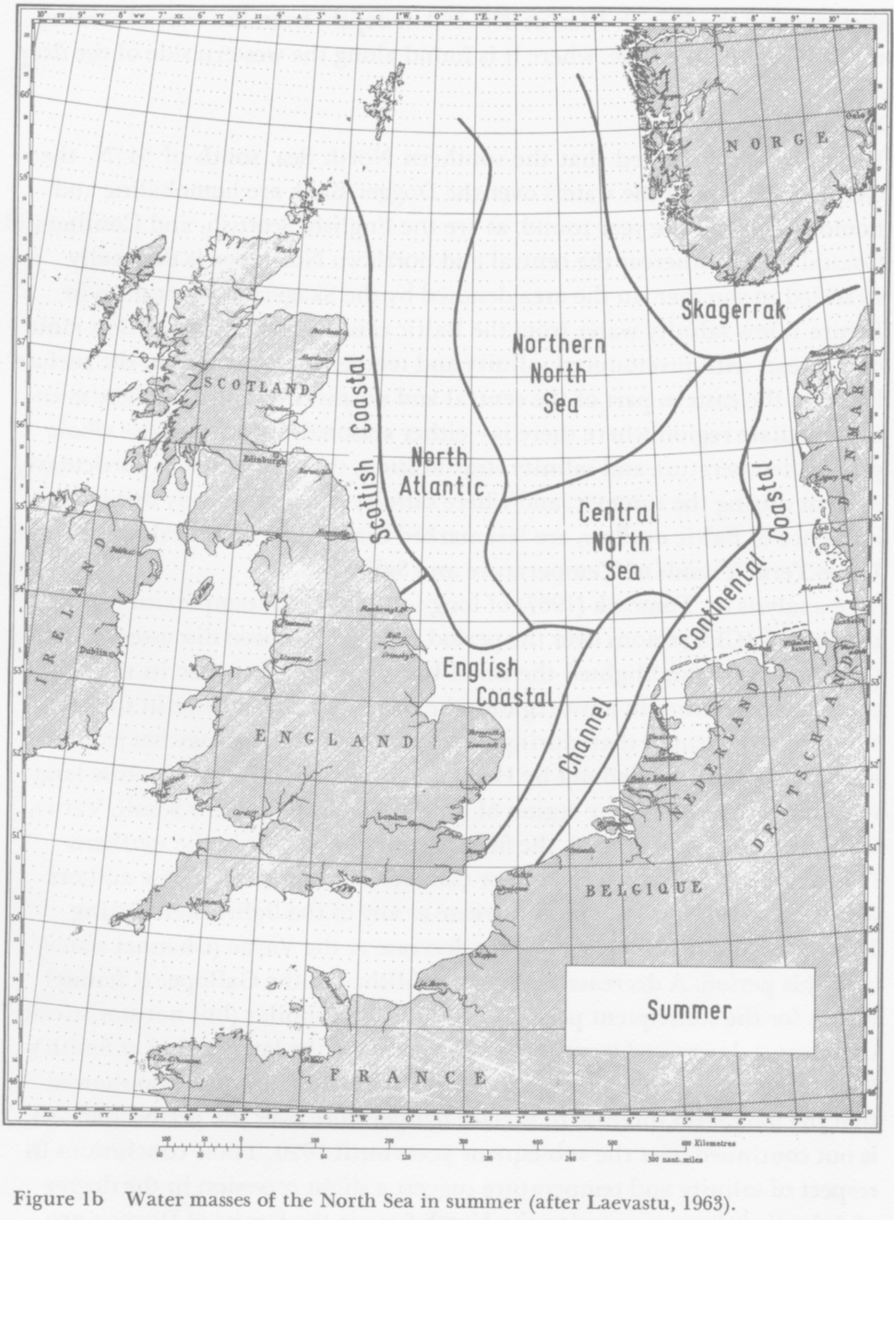

Figure 1b Water masses of the North Sea in summer (after Laevastu, 1963).

shelf around the British Isles, at 200–300 m depth, from the west of Ireland to the Norwegian Rinne, where it is found along the western side of the deep channel.

Stratification

It should also be noted that the southern North Sea, south of 54°N, the German Bight, and the waters over the Dogger Bank are homohaline and homothermal all the year round, as are the English, Scottish, and Continental Coastal waters, whereas the central and northern North Sea is thermally stratified in summer. In the area denoted by the Skagerrak water mass in Figure 1, low salinity water from the Baltic causes haline stratification most of the year, with pronounced salinity and temperature changes in the surface layer. In the eastern part of the central and northern North Sea, there is an intermediate region where there is—either seasonally or during the whole year—a temperature and salinity stratification, the former being particularly evident during the summer, and where salinity changes, mainly due to the influence of Baltic outflow, are less marked than in the Skagerrak water mass.

Long-Term Trends of Temperature and Salinity

The analysis by Tomczak (1967) of long-term trends of temperature in a number of ICES regions over the period 1905–54 has been discussed by Lee (1970), who has highlighted the small but significant increase in the sea-surface temperature in most regions, the increase being greater in the late summer and autumn than during the rest of the year. A somewhat similar analysis has been carried out by Hill and Paramore (1971) to examine long-term salinity trends in the region of four lightvessels (Smith's Knoll, Varne, Galloper, and Seven Stones), the first three of these being in the southern North Sea in the English Coastal or Channel water masses. These authors found no significant long-term increase at any of the lightvessels during 1905–60, and a small but significant decrease at the Varne (Channel water) over this period. A decrease was also established at the Galloper (Channel water) for the subsequent period until 1970, and similar (but not statistically significant) downward trends were detected over the later period at Smith's Knoll (English Coastal water) and Varne. Hill and Paramore also showed that the long-term increase in surface temperature over the period 1905–54 is not continued over the subsequent years until 1970. These conclusions in respect of salinity and temperature suggest a slight recession in the degree of Atlantic influence entering the North Sea via the Straits of Dover since 1955.

It should be noted that we have here been discussing long-term trends, and that these results in no way contradict the real short-term salinity variations in the North Sea, and north-east Atlantic generally, which last for two to four years at a time, and have been shown by Dickson (1971) to be associated with persistent pressure anomaly patterns in the atmosphere.

Current Systems

Any review of currents in the North Sea must almost inevitably start with the charts given by Böhnecke (1922) and presented here in Figure 2, if only because they are quoted so often to this day. Böhnecke's charts of surface current for February and August are deduced from surface salinity charts over the period 1902–14. He showed a wide stream of Atlantic water coming through the North Channel between Scotland and Norway, covering all but the Norwegian coastal strip in February, and perhaps half the width of the northern North Sea in August, flowing down the British coast as far as East Anglia but narrowing considerably to the south. A second stream of Atlantic water flowed north-east from the Straits of Dover across the eastern half of the southern North Sea towards the Skagerrak, where it mixed with Baltic water and flowed out of the North Sea along the Norwegian coast towards the Norwegian Sea. Between these two main streams, and indeed because of them, three large anti-clockwise swirls can be identified, known as the South-West and North-East Dogger Bank and Lindenaes Swirls, and it can be seen that the difference between the summer and winter circulation is basically determined by the size and location of these three swirls. Further swirls appear in the German Bight, the Moray Firth and the Firth of Forth.

During the period from the publication of Böhnecke's charts until the outbreak of the 1939–45 war, a number of studies were carried out using surface and bottom drift bottles, and current measurements were recorded at some of the lightvessels in the southern North Sea, as summarized by Lee (1970). All the work which had been published until that time was coordinated by the British Hydrographic Office in 1940 to produce the residual current system shown in Figure 3. All the features of Böhnecke's charts reappear, plus a large eddy in the northern North Sea, again anti-clockwise, resulting from the many studies of Tait (e.g., 1930a, b, 1932, 1937). It was also concluded that, at least for the southern North Sea, the surface currents shown had speeds of the order of 10–25 cm/sec and that, generally speaking, bottom currents had a similar pattern but lower speeds, of the order of 2

Figure 2a Surface drift currents in February (after Böhnecke, 1922) showing ICES stations and STAFLO locations.

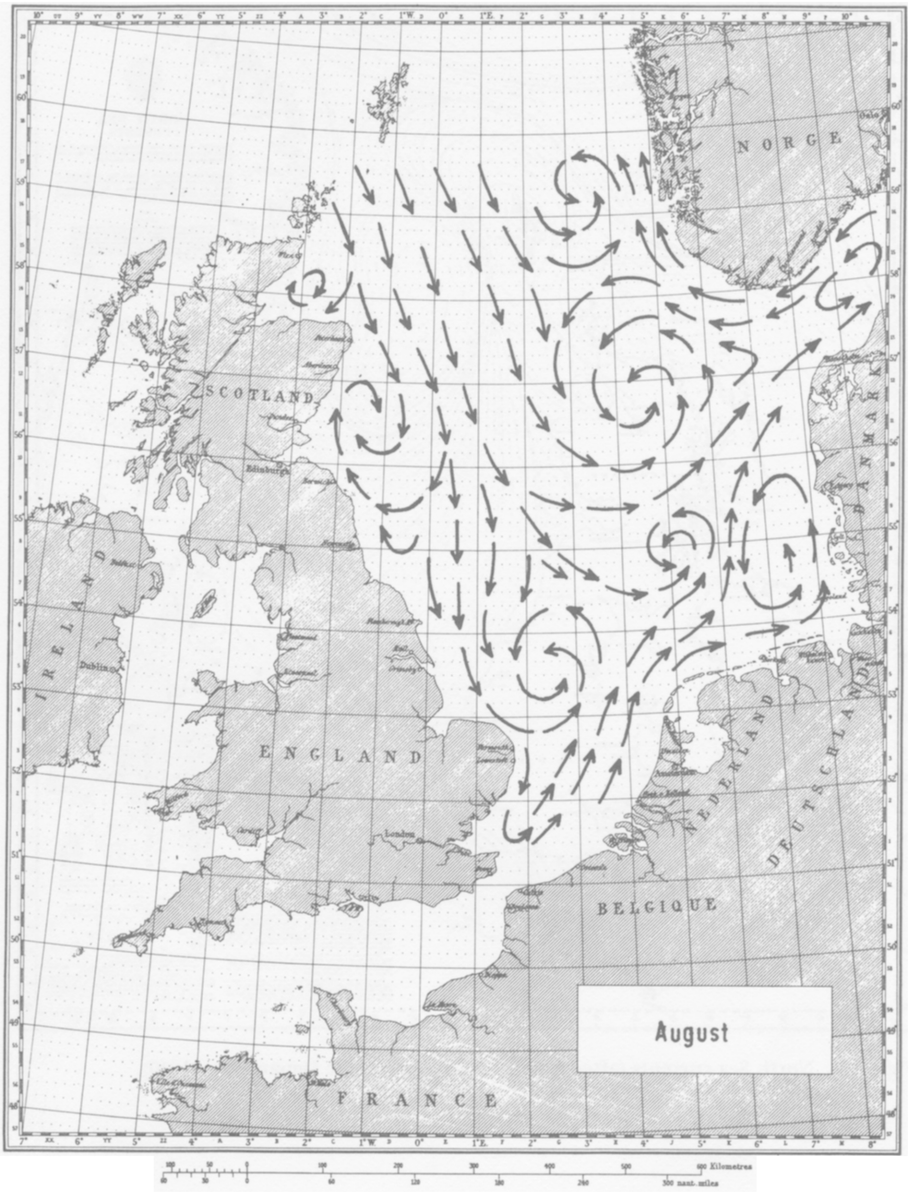

Figure 2b Surface drift currents in August (after Böhnecke, 1922).

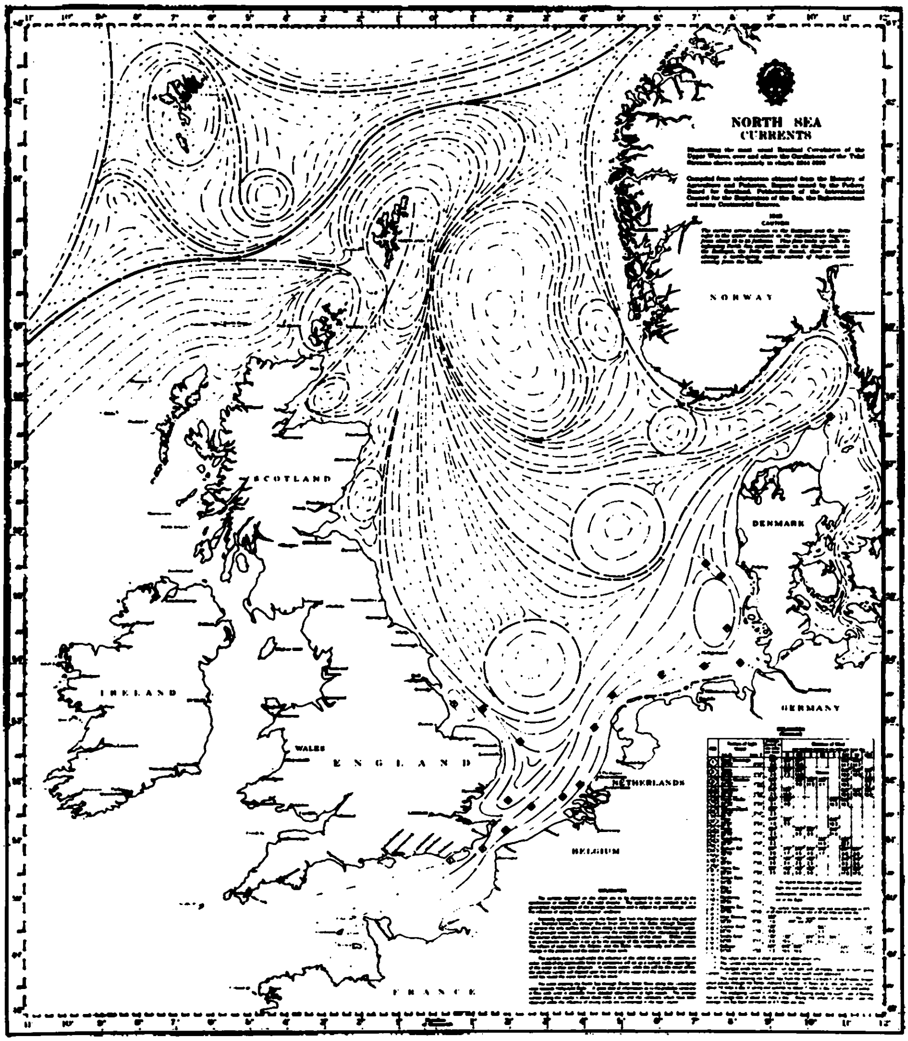

Figure 3 North Sea currents (after Admiralty Hydrographic Department, 1940).

cm/sec. However, during this time, Carruthers (1935, 1939) had emphasized that the surface current system was influenced by the seasonal winds over the North Sea. This was in fact a conclusion of considerable importance, and, to see why, we must now define what we mean by surface current.

After all the higher frequency tidal oscillations have been taken out, we now believe we are left in the surface layer with a residual current system, which is not directly influenced by local winds. Superimposed on this residual current system there is a wind drift current system, caused by the stress of the local wind system on the surface waters, which is most marked at the surface skin, and decreases fairly rapidly with depth. Much has been written of this wind-water relationship, first reported by Ekman (1905), and it has been amply reviewed by Lee and Ramster (1968). Now much of the corroborative evidence for the current systems shown in Figures 2 and 3 is based upon drift-bottle data, which are acted upon both by the residual and wind drift currents; the latter are obviously very variable and may, in the depth of water occupied by a drift bottle, often equal or exceed the magnitude of the residual current. Lee (1970) has demonstrated, using the results of the 1911 drift-bottle experiment, not only that surface bottles tend to reflect the wind system, but also that a system of onshore and offshore winds could cause periodic strandings of drift bottles, which in past work have often been assumed to be due to eddy systems. How much faith, then, can we have in the current systems of Figures 2 and 3? Clearly, what we really need is a reliable indication of the residual current system (which itself may be seasonal) on which we can superimpose a wind drift effect for specific instances, such as the prediction of the movement of a patch of pollutant.

Wind Drift Currents

Let us first look a little more closely at the second of these two requirements. Lee and Ramster (1968) concluded from their review that if $u = KW$ (where u = current speed in cm/sec, and W = wind speed in m/sec) then the constant K normally varied from about 2.0 to 4.2 for drift cards, with a slightly lower range of values for drift bottles. These authors felt that the biggest criticism of the values obtained was that only in one instance had workers tried to eliminate part of the residual current from the wind drift effect. Lee (1970) attempted to do this in the analysis of the 1911 drift-bottle experiment, arriving at a value of $K = 2.2$ after eliminating the residual current; in a similar fashion he inferred an anti-clockwise residual eddy off the Lincolnshire coast which is not in accord with Böhnecke's South-West Dogger

Bank Swirl. A more recent attempt by Hill and Horwood (1971) to estimate K (and also the angle of deflection θ of the current to the right of the wind) using three types of surface drifter, after eliminating the residual current, has suggested that for drift envelopes K probably lies between 3.4 and 3.8, and θ probably lies between 5 and 10 degrees, while, for surface drifters representing increased thickness of the surface layer, K decreases and θ increases, which is of course in accord with Ekman's theory.

Before leaving wind drift currents, which are normally thought of as affecting the surface layer, it should be noted that Lee (1970) has reported several cases of bottom drifters responding to the wind system in the shallower southern North Sea.

Sub-Surface Currents

Most of the pioneering work on the measurement of sub-surface currents in the North Sea must be attributed to Carruthers (1926, 1928, 1935, 1939; Carruthers, Lawford, and Veley, 1950), but Veley (1960) used Carruthers' results from lightvessels to show that, at about 5 m depth, the residual current could be separated from the wind-induced current, and concluded that in the southern North Sea the residual current system agreed with Böhnecke's charts, the residual current speeds varying between 2.6 and 6.4 cm/sec (i.e., about one-quarter of the values quoted above), whereas the wind-induced current was associated with a value of K between 0.8 and 2.4.

Since 1950, several recording current meter arrays have been used in the southern North Sea by the Deutsches Hydrographisches Institut (DHI) and the Fisheries Laboratory, Lowestoft (Lee, 1970); their results have in general terms corresponded fairly well in direction with the Böhnecke circulation, except for that associated with the ICES RHENO experiment in August 1965, which was apparently located in the middle of the Lindenaes Swirl, but no evidence of such a swirl was apparent in the results. Furthermore, Lee concludes from other sources that some considerable doubt exists concerning the extent and location of such a swirl, which may well vary from year to year, and seasonally. He also shows that there is a marked short-period variability in many of the records of residual currents from these moored arrays, which seem to be correlated with wind direction only at wind speeds above 15 knots. This is not altogether surprising, since the near-surface current meters are normally moored at depths of 10–12 m and hence we might expect the wind-induced effect to be small, the records being more representative of the underlying near-surface residual current system.

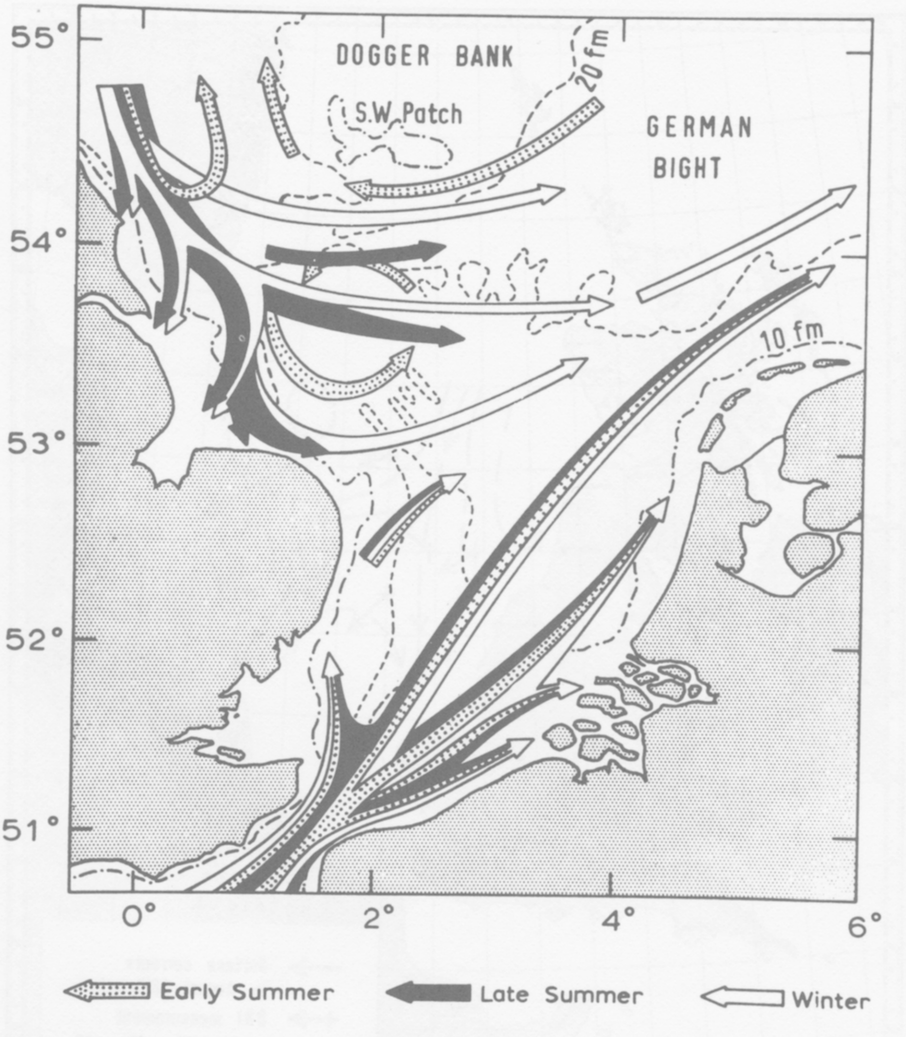

Figure 4 Bottom current residuals (after Ramster, 1965).

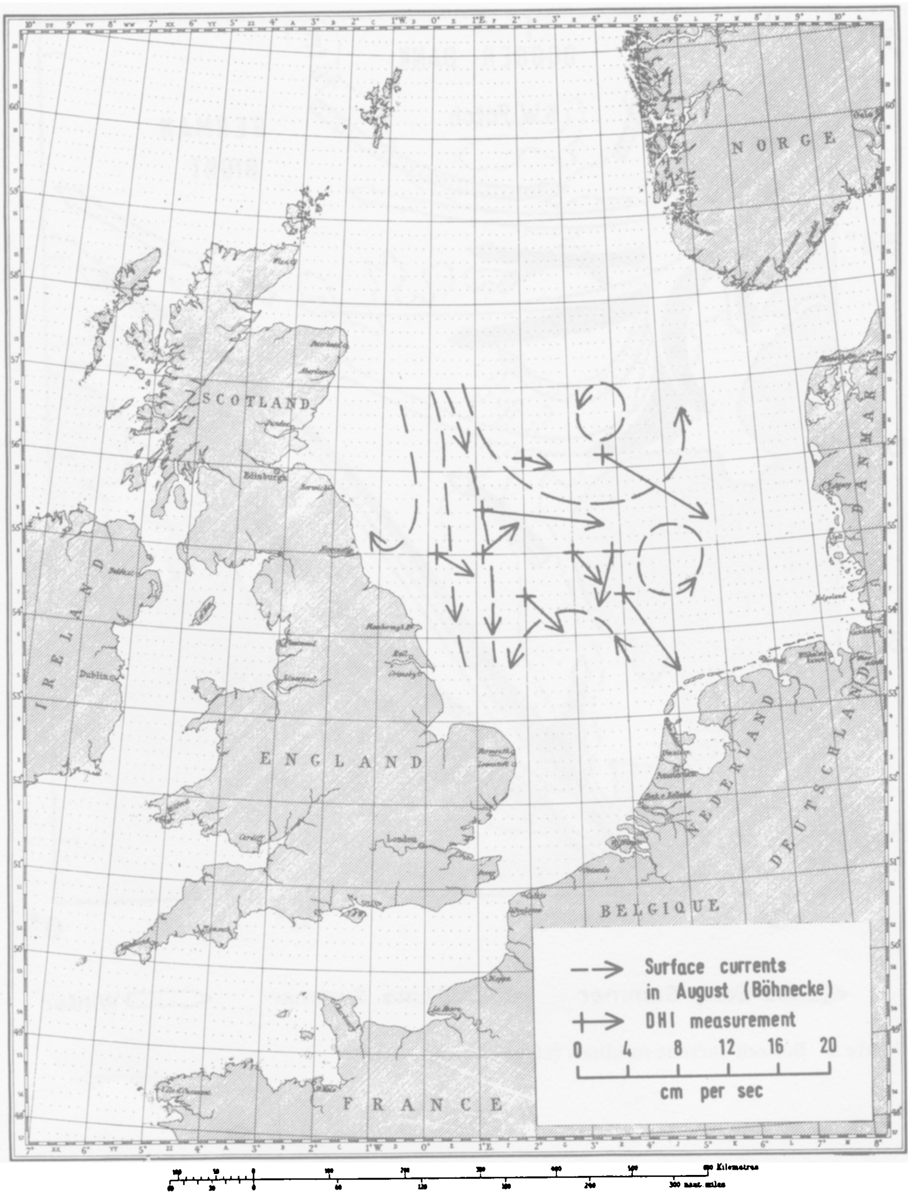

Figure 5 Near-surface mean residuals (DHI, August 1961).

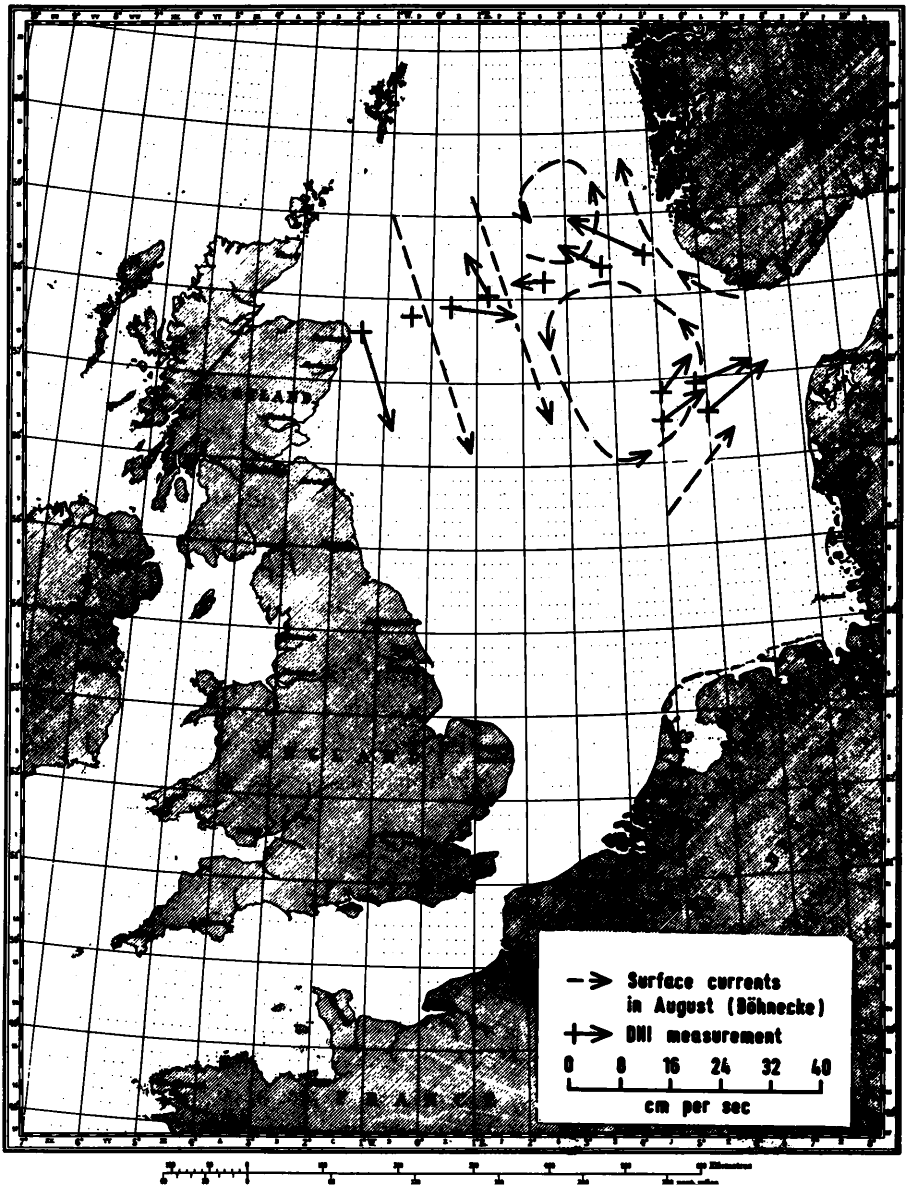

Figure 6 Near-surface mean residuals, DHI, May 1962 (North Channel) and September 1962 (Skagerrak).

The pattern of bottom currents deduced by Ramster (1965) from experiments with Woodhead seabed drifters between 1960 and 1961, and which has since been confirmed by more recent releases, is shown in Figure 4; it can be seen that it does not differ markedly from Böhnecke's surface circulation except that in early summer a reversal of the South-West Dogger Bank Swirl is shown, together with the Lincolnshire coast eddy on the bottom, as reported by Lee and Ramster (1968) at the surface.

Since the two review papers by Lee and Ramster were written, quite a lot of new residual current data have become available from moored arrays, some of which are presented here. The first of these sets of data, from which the mean residual vectors have been estimated, is from an experiment in August 1961, and covered a period of about 17 days (DHI, 1969a). The meters were moored at various depths, but were all in the top 15–50 percent of the water column. At first sight the vector directions, shown in Figure 5, do not match Böhnecke's current system for August (indicated by broken lines) too well, but if we translate the Lindenaes and North-East Dogger Bank Swirls to the west, only the two most westerly stations on 55°N are seriously in contradiction, although one is left in some doubt about the position of the South-West Dogger Bank Swirl, which it would appear must either be further to the south, or reversed in direction. The winds during this period were mainly light to moderate, averaging overall only 6.5 knots westerly, which would not be expected to influence the current meter records to any marked extent. Mean residual velocities varied from about 2 to 10 cm/sec.

Residuals estimated from the second set of data, also from DHI (1969b), show the situations in May/June 1962 between Scotland and Norway and in September/October 1962 off the Skagerrak. I have shown these near-surface residuals, the former measured over about 14 days and the latter over about 21 days, in Figure 6, again indicating the main features of Böhnecke's circulation in broken lines. It can be seen at once that the DHI results from the Skagerrak agree well with the more southerly part of the Lindenaes Swirl and again, by displacing the two swirls shown to the north, a reasonable agreement can be reached, except for the two stations which show a residual flow to the north-west and east where Böhnecke's chart clearly shows the main southerly flow of Atlantic water. The mean wind for this period at Dyce, near Aberdeen, was 6.4 knots from the west-north-west, which does not seem to have any bearing on the discrepancies, since if anything it would

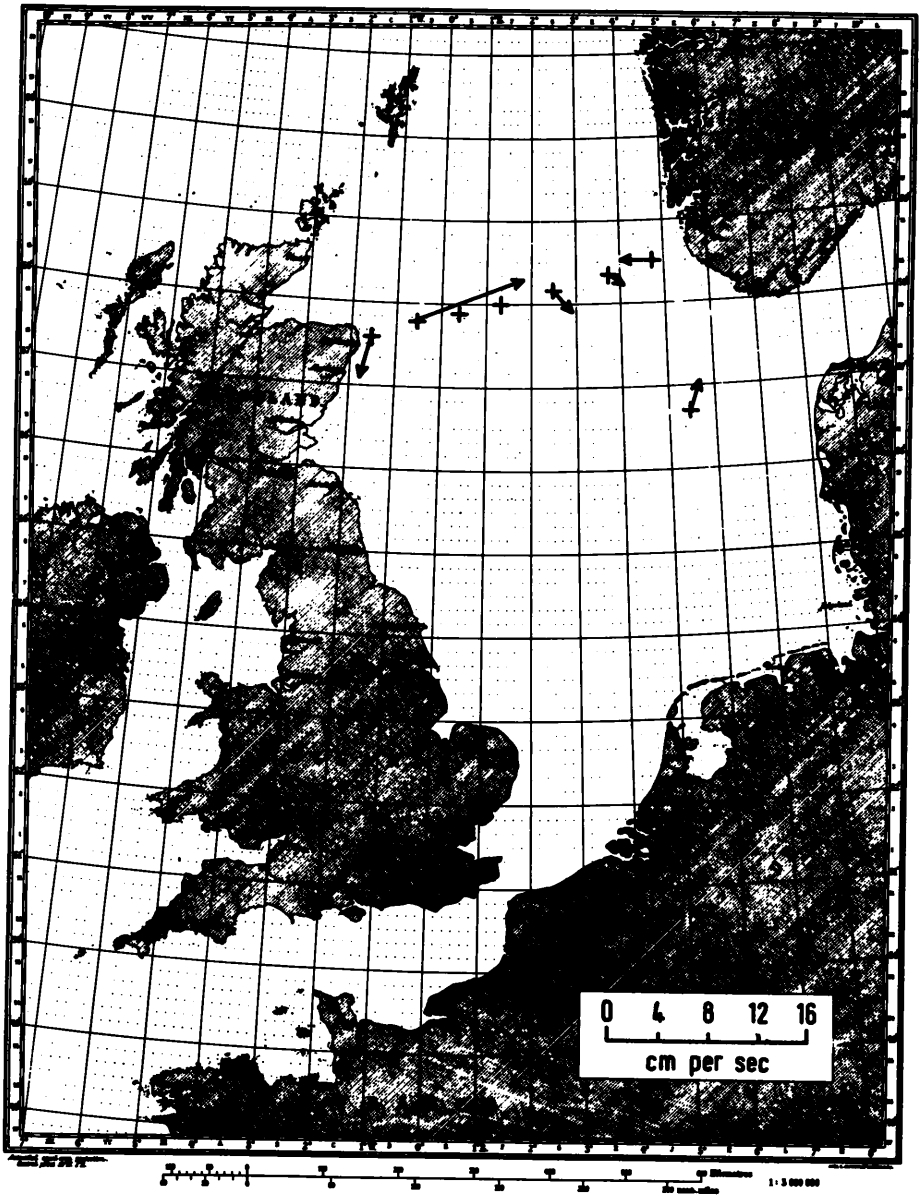

Figure 7 Sub-surface mean residuals, DHI, May 1962 (North Channel) and September 1962 (Skagerrak).

have been expected to increase the southerly transport of the surface waters. It is also noteworthy that the nearest station to the Norwegian coast showed a strong northerly component for the first half of the period and a consistent southerly component for the second half. On this occasion DHI also put meters in the bottom half of the water column at some of the stations; the residuals from these are shown in Figure 7. A surprising feature is the 9.1 cm/sec residual at 73° in a midwater depth some 45 miles off Peterhead, which again is contrary to Böhnecke's system.

The third set of data, as yet mostly unpublished, relates to the ICES Pilot Network of moored current meters in the southern North Sea which was operated during the period September 1970–September 1971 by England, Scotland, Netherlands, Germany, Norway, and Sweden. The Fisheries Laboratory, Lowestoft, maintained three current meter stations during the period January–September 1971 at positions A, B, and C on Figure 2a, with meters in the near-surface and near-bottom layer at each station. Some of the results are given in Figure 8 as mean monthly vectors of residual current. At Station A the monthly currents are consistent with Böhnecke's system in that they have generally a southerly component, but it is seen that directions were different in the two layers on most occasions, the near surface normally being towards the south-east and the near bottom towards the south-west, but in April there was a short-lived north-easterly residual near the surface. Mean residual velocities were never above 5 cm/sec in either layer, and usually speeds were lower near the bottom.

At Station B, where from Böhnecke we might have expected a current flow similar to that at Station A, viz., southerly, the situation was almost reversed near the surface, confirming Lee's Lincolnshire eddy in the near-surface layer over a period of several months, but the near-bottom residuals were consistently onshore, at a fairly steady mean 3 cm/sec.

At Station C the data are more limited, due to losses we experienced because of fishing activity, but the data gathered are certainly not consistent with the easterly flow expected in the southern part of the North-East Dogger Bank Swirl.

The mean monthly winds from January until July at Kilnsea, 53°37′N 00°09′E, are shown in Figure 9. It is apparent that there is little immediate correlation with the monthly current residuals.

Preliminary results from another of the ICES Pilot Network stations, operated by the Netherlands, have recently been published by van der Veen

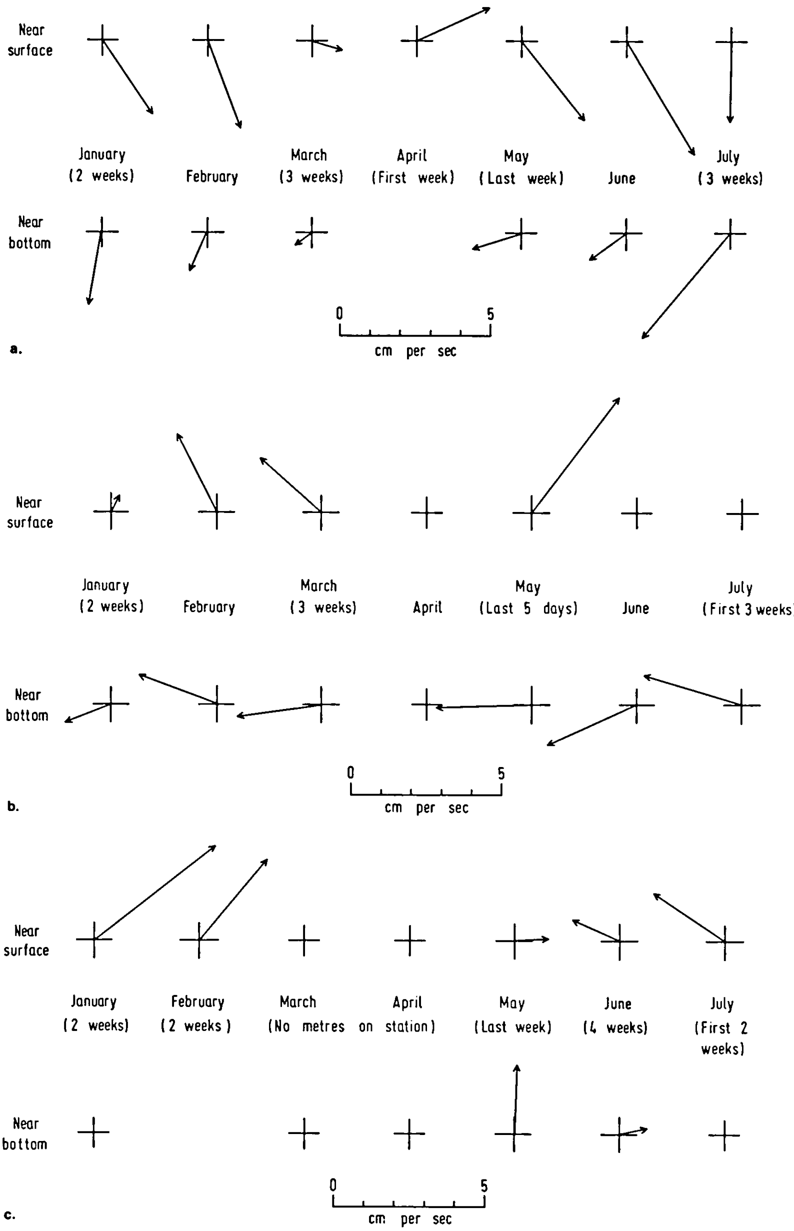

Figure 8 Mean residual currents at ICES stations, 1971: a, Station A; b, Station B; c, Station C.

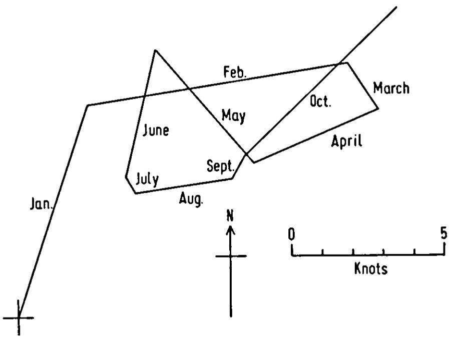

Figure 9 Mean monthly winds at Kilnsea (January–October 1971).

(1971). At this station in position 53°24′N 3°58′E, shown at N on Figure 2a, at both 10 and 20 m depth the residual current was north-westerly in June, north-easterly (as might be expected from Böhnecke) from the end of August until the middle of October, and approximately westerly in December. Residual current data from a fifth ICES station, labelled D in Figure 2a and operated by the Marine Laboratory, Aberdeen, have not yet been published, although the data have been exchanged among the participating nations; the mean near-bottom residuals over the period September 1970 to January 1971 show a northerly flow parallel to the Scottish coast, again not altogether in accord with Böhnecke's system (H. D. Dooley pers. comm., 1971).

The fourth source of data, also unpublished, arises from a cooperative exercise between the Fisheries Laboratory, Lowestoft, and Shell Exploration and Production Ltd., in which currents are recorded at two depths on the STAFLO oil rig. STAFLO is a floating, exploratory rig; but it is of course anchored during drilling operations and hence while currents are being recorded. It was located at a number of positions within the triangle marked S on Figure 2a from June 1969 until February 1971 and at the position marked S1 from March to July 1971. The mean monthly residuals at these positions are shown in Figure 10. From Böhnecke's chart a southerly residual might have been expected at position S; however, a residual between north-east and north-west was found in all months in which records were taken, except July and November 1970 (when a flow just to the south of east was measured), September 1970 (when a south-westerly current was recorded) and January 1971, which was the only occasion when a residual consistent with Böhnecke's chart was recorded. At position S1 the residual direction

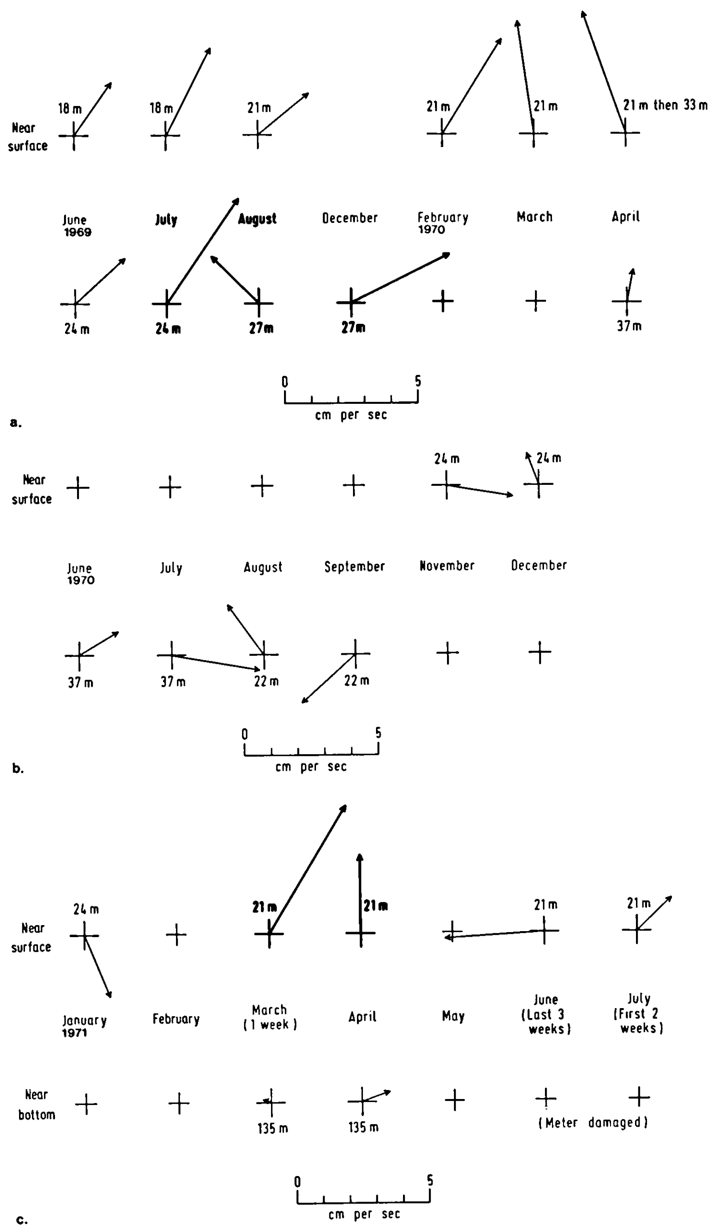

Figure 10 Mean monthly residual currents at STAFLO: a, June 1969–April 1970; b, June–December 1970; c, January–July 1971.

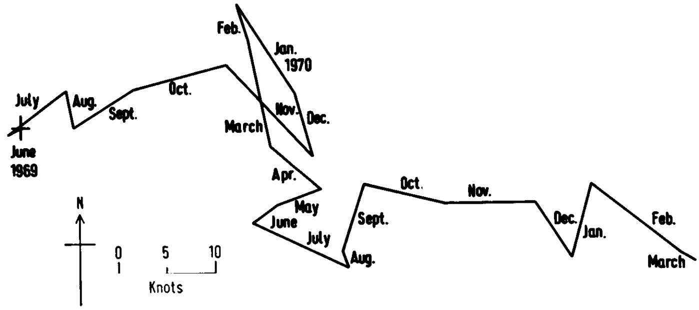

Figure 11 Mean monthly winds at STAFLO (June 1969–March 1971).

near the surface varied from north-east in March and July to west in June at 20 m depth, but was westerly in March and east-north-east in April at 6 m above the bottom. An examination of the mean monthly wind vectors recorded on STAFLO (Figure 11) shows no correlation with these current residuals, even though some remarkably strong mean winds were recorded. During November 1970, for example, the wind averaged 20 knots from the south-west. The largest near-surface residual current recorded on STAFLO, 5.5 cm/sec north-east over a period of one week at the end of March 1971, was associated with one of the smallest monthly mean winds recorded, 1.9 knots.

Having reviewed the latest data available, we may now return to the question: How much faith should we have in Böhnecke's current system? Clearly, as an indication of residual flow it should be regarded with considerable caution. There seems little doubt that the major inflows into the North Sea are from the three directions indicated, but the true situation, particularly in the northern North Sea and Skagerrak region, would appear to be more complex than is suggested either by Böhnecke or by Tait. Probably there are large swirls caused by the interaction of the three major inflows, but we do not yet know nearly enough about their variability in time and space to chart them as accurately as Figures 2 and 3 indicate. In short, Böhnecke's current system, so often quoted to this day, gives only the very broadest of indications of the circulation of the North Sea, so broad in fact that we should completely disregard the multiplicity of small arrows and the reliability which they infer, except at the precise locations of the lightvessels in the southern North Sea where long series of current data are available. Unfortunately, we are not yet in a position to offer a better alternative, but this need not be far in the future.

Future Plans

Complete analyses have not yet been carried out on any of the four sets of data mentioned above, and indeed there are quite a lot more data already to hand from the ICES Pilot Network which should be available soon. Together with the long series of data on some of the UK, German, and Dutch lightvessels, the extensive bottom drifter returns and the small number of moored arrays from which data are available, these will form a basis on which we can begin to build a reliable current system chart. But many more data are needed urgently. Some progress towards collecting these new data has been made in the setting up of the Anglo-German-Dutch-Belgian Pilot Ocean Data Station Network recently reported on by Hill (1971). Twenty-four stations, as shown in Figure 12, are planned in this network, which will operate from September 1971 until the end of 1972; at many of them currents are already being recorded. In some respects this project is a natural sequel to the ICES Pilot Network, although it is more extensive and has more specific scientific aims in view, particularly the mathematical modelling of the current circulation. Both Norway and Sweden have recently agreed to participate in the project and to maintain their ICES current meter stations over this period, but the biggest limitation at present is the almost complete lack of stations in the northern half of the North Sea. There are certainly plans for short-term moored arrays by individual countries and establishments, some of which may be located in the data-sparse areas, and no doubt these experiments will add reliable data over the next few years. These efforts should be encouraged, but there exists a real need for permanent stations in the North Sea, recording, and in some cases telemetering, a variety of oceanographic and meteorological parameters. There are plans to set up such a network over the whole of the North Sea both by the multinational group mentioned earlier, recently renamed the Joint North Sea Information System (JONSIS), and also by a joint group of EEC and other European countries under the Committee for Co-operation in the Field of Scientific and Technical Research (COST) called Project 43, the latter including also the Baltic and North Atlantic in its planning. However, these plans are unlikely to come into operation on an extensive scale until the middle of the decade or later. In the meantime the required data seem most

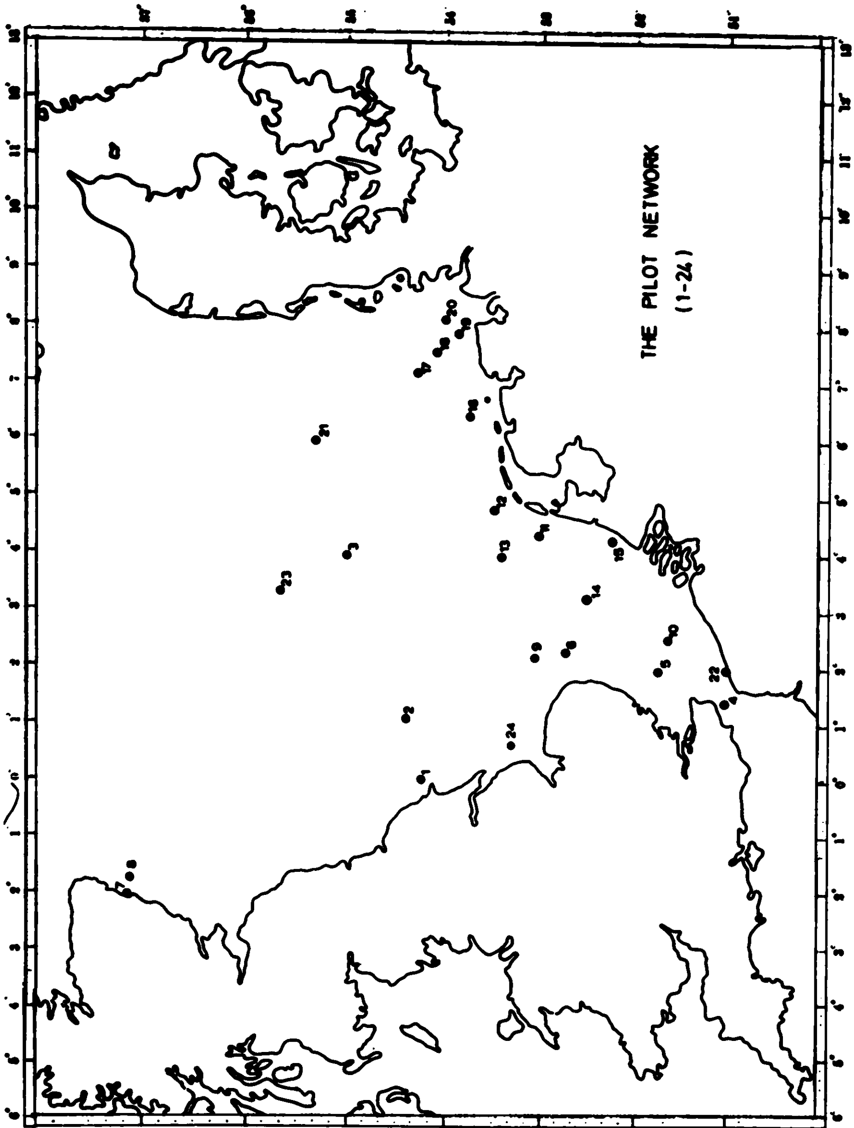

Figure 12 JONSIS (Phase I) network of current measuring stations.

likely to be provided by short-term arrays organized on a national basis, or longer-term arrays organized internationally, backed possibly by two or three prototype large telemetering buoys.

Summary

1. There are three primary and five secondary water masses in the North Sea, viz., North Atlantic, Channel, and Skagerrak (primary) and Scottish Coastal, English Coastal, Continental Coastal, Northern North Sea, and Central North Sea (secondary), the main influx probably being during the months of September to February. All but the Skagerrak water mass occupy the whole water column.

2. In general, the northern North Sea, away from the coastal areas, is thermally stratified in summer, and in the Skagerrak and eastern and central North Sea there is seasonal or annual haline stratification, this being more pronounced in the east.

3. Böhnecke's (1922) description of the surface current system of the North Sea gives only a broad-brush picture, in that the main inflows are from the north, through the Straits of Dover and from the Baltic, while the main outflow is probably along the Norwegian coast. Some eddy systems are probable between these major streams but the detail of his charts is not consistent with modern measurements, except perhaps in the Southern Bight.

4. Bottom currents are broadly similar to Böhnecke's charts in the Southern and German Bights, but a seasonal variability is evident around the southwest Dogger Bank and towards the Lincolnshire coast. In the northern North Sea, the limited amount of sub-surface residual current data available is often quite contradictory to the flow shown on Böhnecke's surface charts.

5. Recent current measurements suggest that there is a considerable degree of variability in space and time in surface and sub-surface residuals, the latter usually being of lower velocity.

6. Recent and planned networks of ocean data stations are pointing the way to a more reliable understanding of the current circulation of the North Sea.

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