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Hypotheses concerning the circulation of the northern North Sea

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The circulation of the northern North Seas has been a subject which has occupied the attention of scientists since the end of the last century. Many of the early ideas were simple and were based on the limited observations made at that time. During the early part of the present century a vast amount of observational data was obtained by means of drift bottles and water sampling and this gave rise to suggestions of water movements which were far more complex than those originally suggested. These circulation patterns of which two were suggested by Böhnecke and Tait, have subsequently commanded much attention with the result that the earlier work on North Sea circulation was ignored. They survived time because no reasonable alternatives could be put forward. From the early sixties technology enabled scientists to measure by direct means the currents of this area and it soon became obvious that the traditional concepts of circulation ignored points of detail which were in fact suggested at the beginning of the study on circulation. One such important feature is the shelf edge current, a flow of oceanic water which enters the Skagerak by way of the continental slope and the western edge of the Norwegian Channel. Another current, the existence of which had shrunk into comparative obscurity during the past fifty years was the flow of mixed waters which entered the North Sea through the Orkney-Shetland Channel and which can be traced across the North Sea towards the Skagerak. Although current measurements show this flow to be persistent its axis is subjected to large and rapid fluctuations in position. East of the Orkney Islands the width of the current is usually less than 8 nm and has a strength in excess of 10 cm s^{-1} which makes it a rather distinctive feature in the northern North Sea. Consequently although recent measurements demonstrate that the circulation pattern is basically simple and easily identifiable its variability suggests that residual current patterns at any location are complex.

Introduction

For many years the structure of water masses and currents in the northern North Sea has been assumed to be complex and several conclusions have been held to be correct because of the absence of information that could support or refute them. These conclusions have been reached from studies on the distribution of temperature and salinity and drift bottle results, and depend on many assumptions.

Measurements of currents in the northern North Sea using such direct method as parachute drogues and recording current meters are few in number but are probably sufficient to throw light on the significance of the conclusions previously reached. This paper discusses what has been learned about the northern North Sea since the introduction of recording current meters.

Historical background

Studies of the circulation of the northern North Sea using drift bottles were undertaken principally by Fulton (1897) and Tait (1937). Fulton deduced an average circulation from drift bottle results taking full account of the effects of wind and tide on the movement of the bottles. He deduced the existence of a flow round the north Scottish coast entering the North Sea between the Orkneys and Shetlands, and passing southwards along the east coast of Scotland and England to as far as the Wash, then in an east-northeast direction towards the coast of Denmark. From a consideration of the movement of the tide down the east coast of Britain, he interpreted the apparent southerly movement of water in this area to be a consequence of tidal currents. That a progressive tidal wave would generate such a movement was pointed out recently by Longuet-Higgens (1969) thereby providing support for Fulton's interpretation. Fulton's circulation pattern for the northern North Sea was substantially corroborated by Böhnecke (1922) who derived his current diagram from distributions of surface salinity.

Tait's drift bottle work in the 1930s tended to complicate the simple picture deduced by Fulton. As was pointed out by Tait (1934), his conclusions were in reasonable accordance with those of Böhnecke (and Fulton) south of latitude 58° N but they conflicted markedly with them north of this latitude.

The reason for this conflict was partly due to Tait's technique of 'cartographical analysis' in interpreting drift bottle returns and partly due to the influence of the work of Robertson and Helland-Hansen which immediately followed that of Fulton. One of their conclusions was that there is an inflow of Atlantic water to the east of the Shetland Islands which was first suggested by Robertson (1909), on the basis of temperature and salinity investigations carried out between 1906 and 1908. Robertson states: "An offshoot of the Atlantic stream is continually flowing southwards along the east coast of Shetland, flooding a great part of the north-western area with water of high salinity". There is no evidence from direct measurement that this is so.

Another conclusion which originated at this time was that the inflow of Atlantic water into the northern North Sea varies seasonally. In his report for the years 1902–1903, D'Arcy-Thomson (1905) writes: "But we now see at least good reason to believe that the great Atlantic inflow which sweeps round the north of Scotland is indeed periodic, growing in intensity through winter until early spring and then subsiding until autumn". This interpretation was based largely on the fluctuations in the location of the surface 35‰ isohaline in the northern North Sea.

Although the idea of a winter inflow of Atlantic water across the northern boundary is still held by many workers the only evidence for it is provided by observations such as the above, but they can have alternative explanations. For example, Schott (1966) demonstrated the dependence of seasonal salinity fluctuations in the North Sea on factors such as land run-off, precipitation and evaporation. Similarly Bowden (1950) was able to relate the salinity of the Celtic Sea to such factors and he showed quantitatively that a summer minimum in salinity was related to decreased evaporation rates over the sea at that time. This is due to the dependence of evaporation on wind speed and sea-air temperature differences. By comparing Bowden's precipitation and evaporation figures for the Irish Sea with salinity fluctuations in the North Sea it is possible to reach similar conclusions (Fig. 1). Positive values of the monthly integrated precipitation-evaporation anomalies indicate salinities lower than the annual average. Likewise negative values indicate salinities greater than the annual average (Fig. 1a). The annual variation in this anomaly is comparable with the mean southerly extent of the 35‰ surface isohaline which moves from latitude 55°20′N in summer, a distance of 120 nm (Fig. 1b). Combining this fact with the average south-north salinity gradient of 0·1‰ per 100 nm this indicates an annual range of salinity of 0·12‰ which is somewhat larger than predicted from Bowden's figures (0·03‰ measured over 100 m depth) probably because only surface salinities have been considered. Both graphs in Figure 1 are similar, however, indicating that seasonal variations in the 'volume of Atlantic water' are at least partly accountable for by precipitation-evaporation differences.

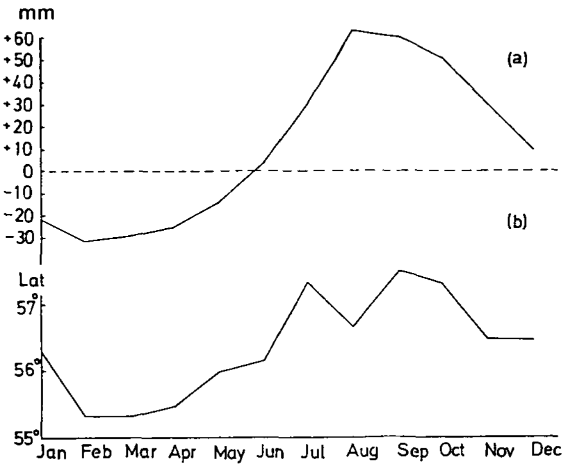

Figure 1. (a) Cumulative seasonal variation of precipitation-evaporation in mm. (b) Seasonal variation of southerly extent of 35 ‰ isohaline in the North Sea.

Dickson (1967) did not think that the role of evaporation in the North Sea was as significant as presumed by Schott (1966). His conclusions are discussed by Lee (1970) in his comprehensive review of the hydrography of the North Sea.

Near land, variations in run-off also play some part in the distribution of salinity (Schott, 1966) and may be the cause of variations which have been attributed to changes in the flow of Atlantic water into the North Sea. For example, in view of the complete absence of low salinity water in the northern North Sea D'Arcy-Thomson (1909) wrote: "The year 1905 was marked by a conspicuous abnormality as compared with previous years, a great inflow of Atlantic water having come into the North Sea in the (autumn) of that year at which season the inflow of salt water from the ocean is usually at a minimum". Similar conclusions could be drawn for the autumn of 1971 on the basis of the salinity distribution. It is interesting to note, however, that both of these years were marked by the exceptional absence of snowfall over the Scottish highlands during the previous winter-spring and were followed by generally dry conditions throughout the summer months (Meteorological Office, 1971). Thus another explanation of the presence of a large area of high salinity water in the northern North Sea is simply the consequence of a low freshwater run-off.

When it is considered that the typical winter

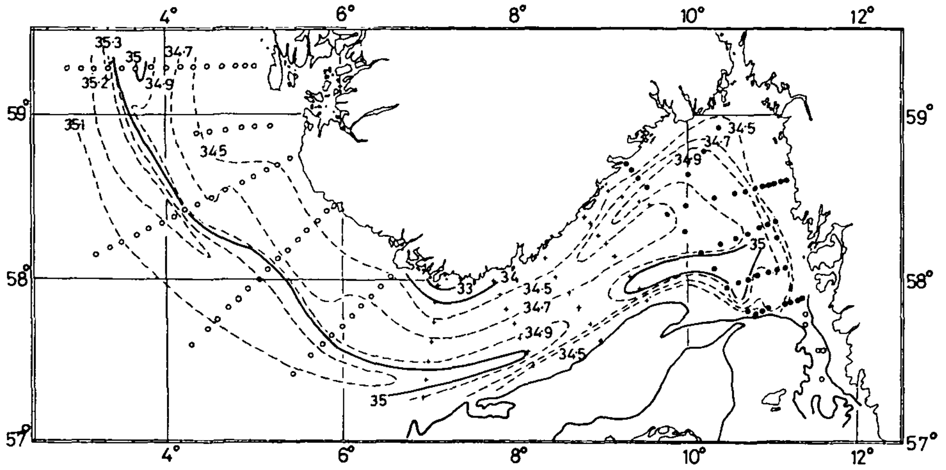

Figure 2. Horizontal distribution of salinity at 50 m depth during Joint Skagerrak Expedition 1966.

picture of surface salinity distribution is one of a southward pointing tongue of high salinity Atlantic water, flanked on its southern, eastern and western boundaries by central North Sea water, Norwegian coastal water and Scottish coastal water respectively, the classical picture of the circulation would appear reasonable. On the other hand, there is now sufficient information in the literature which suggests that the distribution of salinity may be an indirect consequence of strong but narrow inflows of oceanic water and mixed coastal/oceanic waters. The results of current measurements in the northern North Sea by the Marine Laboratory, Aberdeen and others favour this latter interpretation.

The shelf edge current

Before the Marine Laboratory, Aberdeen, began its current measurement programme in the northern North Sea there was already a certain amount of information which threw light on where to look for areas of inflowing oceanic water. One such area was the western edge of the Norwegian Channel. As early as 1891, Pettersson and Ekman deduced that water entered from the North Atlantic over the northern plateau and the western edge of the Norwegian Channel (see Svansson, 1965). This was partly confirmed by Ljøen (see also Svansson, 1965) who demonstrated by direct measurement of currents that oceanic water flows southward in the western part of the Norwegian Channel beneath a surface of low salinity water. More recently, the Joint Skagerak Expedition of 1966, sponsored by ICES, confirmed its existence. Charts of salinity distributions at 50 m depth (Fig. 2), constructed from the results of this Expedition, illustrate the course of this high salinity inflow. As it enters the Skagerak it deepens and mixes with less saline water before returning northward along the Norwegian coast below the brackish surface layer of coastal water (Tomczak, 1968). Figure 3 demonstrates how the current pattern is associated with the water mass structure across the Norwegian Channel at 59°N at the time of the Expedition.

This inflow of Atlantic water can be traced northwards and westwards along the 200 m contour round the edge of the continental shelf (Dooley and Martin, 1969). The flow splits at Tampen Bank (Helland-Hansen, 1905); part enters the western edge of the Norwegian Channel as described above and part flows northwards into the Norwegian Sea.

As yet measurements have not been made to indicate the western limit of the oceanic flow in the Norwegian Channel but measurements made along the shelf edge to the north of the Shetlands show that the strength of flow diminishes rapidly with distance on to the shelf. Many drogue measurements over a period of years indicate that the eastward flow in this area rapidly decreases towards the south to such an extent that along latitude 61°N on the North Sea shelf only tidal and wind driven movements can be measured. This same effect can be observed to the west of Shetland where at 4°W, on the shelf edge, the northeasterly flow of water can diminish from 100 cm s^{-1} to 25 cm s^{-1} within a distance of 8 nm (Dooley, in preparation).

Superimposed on this large spatial variability is a rapid time variability of flow that is a feature of most current meter measurements made in the North Sea. Figure 4 demonstrates how this variability is closely

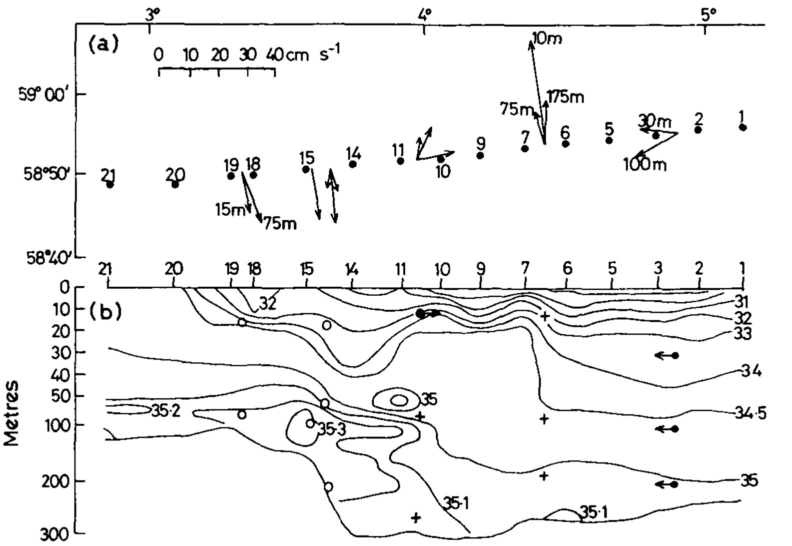

Figure 3. (a) Parachute drogue trajectories across Norwegian Channel at 59°10'N. (b) Salinity section across Norwegian Channel at 59°10'N. ○ current out of page. + current into page.

related to fluctuations in the wind velocity. This is also considered in detail elsewhere (Dooley, in preparation).

The Orkney-Shetland Channel inflow

A very consistent feature of the salinity pattern over the western part of the northern North Sea is the area of strong salinity gradient which marks the boundary between Scottish coastal waters and the oceanic water (Fig. 5). It is apparent off the west coast of Scotland and around the north Scottish coast where it usually passes through the Orkney-Shetland Channel. Within the North Sea it can be traced eastwards towards the Skagerak at roughly 57°30'N. Near the Scottish coast the boundary is a very stable feature and the usual pattern is disturbed rarely, e.g. in 1905 and 1971.

Robertson (1913) first suggested that this boundary may be associated with an inflow of mixed oceanic and coastal waters through the passage between Orkney and Shetland. Subsequently Smed (1947) demonstrated, from dynamic computations, using the bottom as reference level, that an inflow of the order of 2–3 cm s^{-1} must frequently exist in the Orkney-Shetland passage and Fraser (1949, 1952) deduced from a study of plankton indicator species that there was a frequent inflow, at least between Fair Isle and Orkney.

Direct current measurements in this area are few, chiefly because it is also an area of intensive fishing activity. The Marine Laboratory, Aberdeen, has, on three separate occasions since 1968, moored current meters at positions A and B (Fig. 6) at approximately half depth (50 m). Position A is very close to the boundary of mixed waters and consequently fluctuations in the current flow were frequently measured. These fluctuations may be related

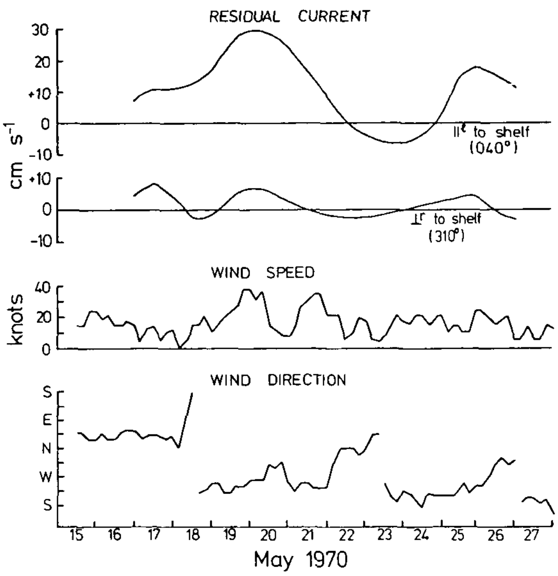

Figure 4. Residual current and wind velocity during period 15–27 May 1970 at 61°22·5'N 1°17'W. Current meter at 27 m depth.

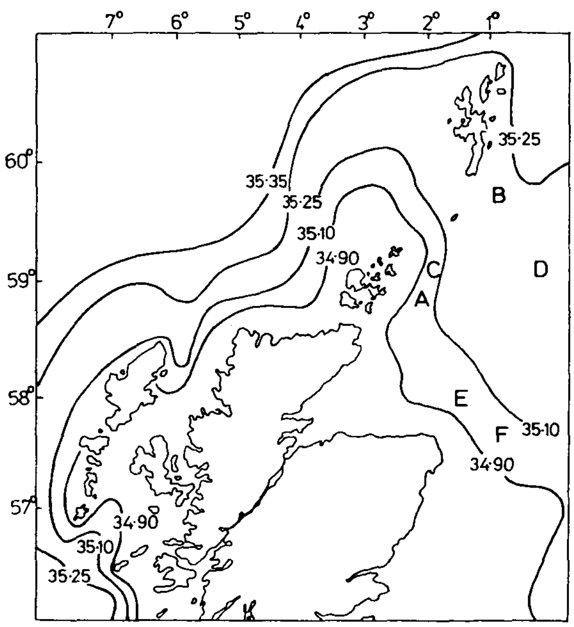

Figure 5. Typical salinity distribution around the north of Scotland. The letters A–F indicate positions of current meters referred to in the text.

to fluctuations in the position of this boundary as shown in Figure 6 which illustrates the observed conditions in September 1969. The absence of any significant residual current at B indicates that the inflow was confined to the area of salinity gradient and had a width of less than 30 n m. Further evidence regarding its width was revealed when a current meter, moored at position A during January 1971, was inadvertently towed by a trawler 10 n m towards the east. The south-going flow was reduced from 15 cm/sec to 6 cm s^{-1}. After a few days at this position the mooring was broken adrift and analysis of the record from the drifting current meter indicated that a southerly flow was confined only to the narrow zone adjacent to the Orkney Islands (Dooley, 1971). More intensive current measurements in this area during May 1972 corroborate these conclusions (Fig. 7). The current at position C (Fig. 5) has a persistent southerly component which fluctuates in strength from near zero to 25 cm s^{-1}. These fluctuations can be attributed both to meteorological conditions and to spatial variations in the current field that are not always directly related to the meteorological conditions (Dooley, 1973). Twenty miles west of this position (D, Fig. 5) the current is variable and flows southwards for a short period about the 28th May (Fig. 7). This coincides in time with strong northeasterly winds.

It is not likely that this Fair Isle current would continue its southerly direction south of the latitude of the Moray Firth because here the water shallows considerably. Instead its course may be modified by the bottom contours which lie in an east-west direction. Published current meter data (Deutsches Hydrographisches Institut, 1969) support this contention as easterly flows are present in a number of records. In addition the existence of such a flow at about 57°30′N was inferred by Dietrich, Sahrhage and Schubert (1959) who demonstrated that the influence of such a current was to dissect the cool bottom waters of the central and northern North Sea (Fig. 8).

To confirm these speculative conclusions, current meters were deployed at positions E and F (Fig. 5) during August to October 1972, to monitor the flow as it changes its direction from south to east (Fig. 9).

Further eastwards it is likely that the flow will back northeastwards round Ling Bank before finally entering the Skagerak.

Although Figures 7 and 9 confirm, qualitatively, the spatial distribution of this current flow they

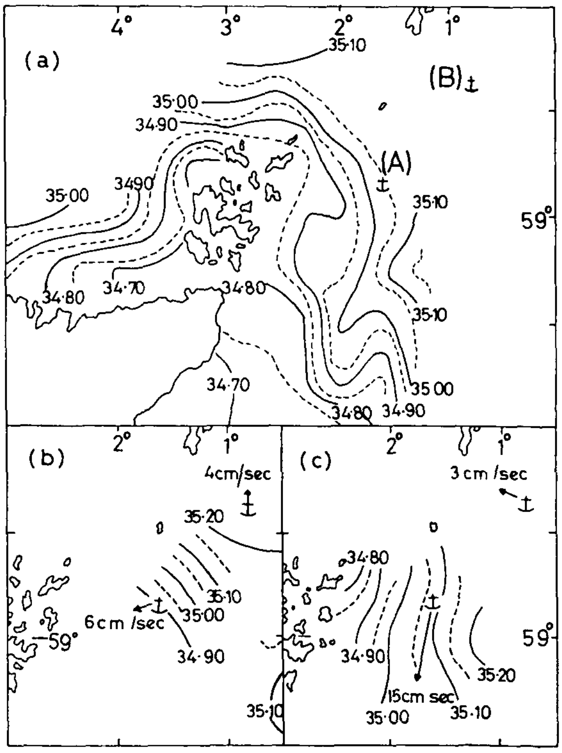

Figure 6. (a) Distribution of salinity around Orkney Islands 15 September 1969. (b) Current vectors with salinity distribution superimposed, 17 September 1969 and, (c) for 20 September 1969.

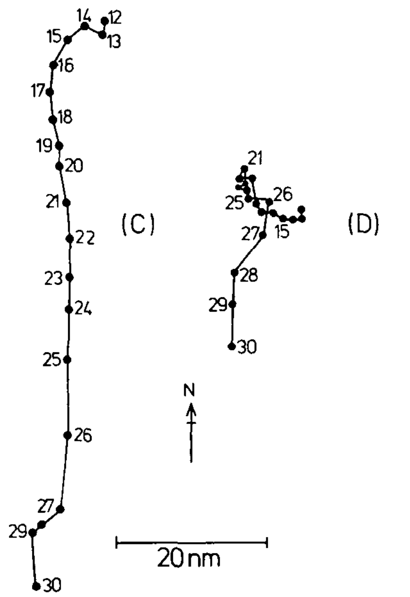

Figure 7. Virtual displacements of 25 hour mean currents at position C and D during period 12–30 May 1972.

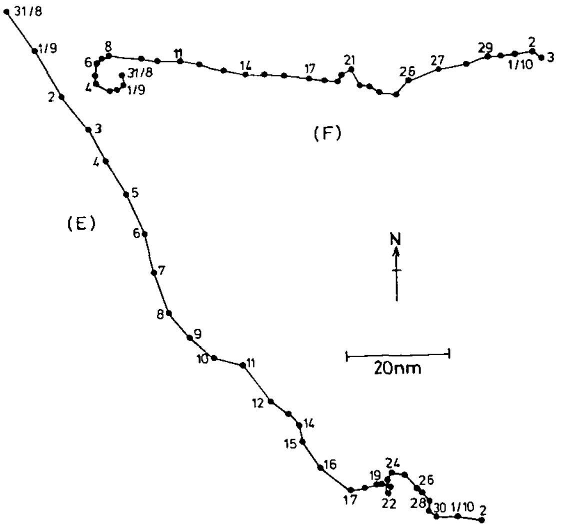

Figure 9. Virtual displacements of 25 hour mean current at positions E and F during period 31 August – 2 October 1972.

demonstrate only its presence at half depth, about 50 m. To produce a picture of vertically meaned currents from these data it is necessary to assume that these currents vary little with depth. This assumption is justified for position C where direct measurements show only very small variations in current with depth. Furthermore, at positions C to F the water was vertically homogeneous and in view of the relatively large strength of the observed flows it is reasonable to infer that this current field is vertically homogeneous also. East of the Greenwich meridian the water becomes stratified due to the influence of low salinity water from the Skagerak and in this area the residual current may be depth-dependent.

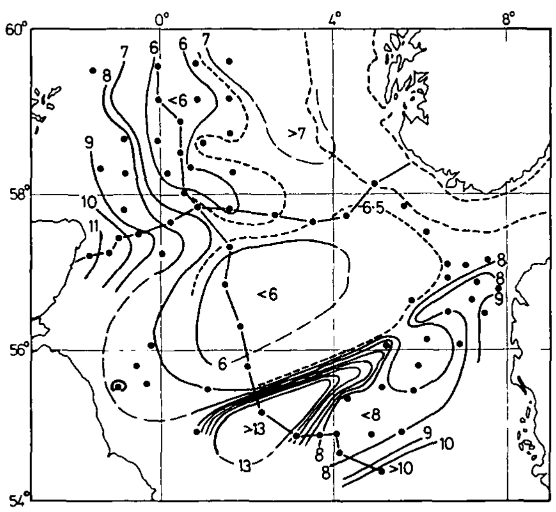

Figure 8. Bottom temperature in North Sea during August 1955 (after Dietrich et al. 1959).

Suggested current system and water balance

On the basis of this discussion, the inflow of water into the northern North Sea can be identified as two intense, narrow currents, one of which is composed of mixed water, the other of undiluted oceanic water. The approximate trajectories of these flows are demonstrated in Figure 10. The only area of outflow is along the Norwegian coast. The surface 20 m or so of this water is usually derived from the Baltic Sea and run-off from the Norwegian coast (Schott, 1966).

A very approximate estimate of water balance in the northern North Sea can be made from the various measurements of current made in the areas of inflow and outflow (Table 1). Published figures for the transport from the Baltic Sea and the English Channel are $0{\cdot}02 \times 10^6$ m^3 s^{-1} (Svansson and Lybeck,

Table 1. Volume transport of northern North Sea inflow and outflow

	Location	Type	Volume transport in millions $m^3 s^{-1}$
Inflow........................	a) Orkney-Shetland	Mixed (vertically homogenous)	0·3
	b) Norwegian Channel	Oceanic (subsurface)	1·1
Outflow......................	Norwegian Channel	Mixed (horizontally homogenous)	2·0

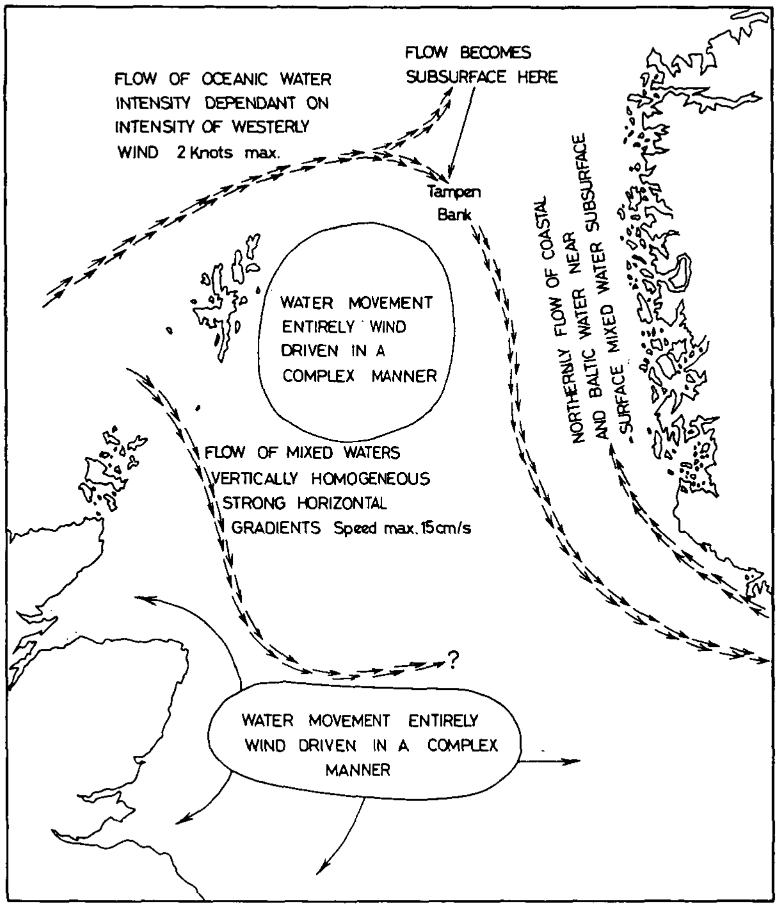

Figure 10. Chart showing areas of persistent residual current flow in the northern North Sea.

1962) and $0{\cdot}05 \times 10^6$ $m^3 s^{-1}$ (Van Veen, 1938) respectively. These appear to make only a relatively minor contribution to the total balance.

Discussion

The purpose of this paper is to review our understanding of the water circulation of the northern North Sea. It has therefore been speculative, testing past hypotheses against recent observations which consist of limited direct current measurements.

The study so far has demonstrated the existence of currents associated with the density gradients between coastal and offshore waters and the subsurface flow of oceanic water adjacent to the western edge of the Norwegian Deeps. The latter flow is unlikely to change much in its geographical location due to bathymetrical constraints. No such constraints exist for the Orkney-Shetland inflow except in the central North Sea; its precise location will probably vary both within and between years.

It would appear, therefore, that the combined use of temperature and salinity observations and drift bottles have failed to achieve a correct interpretation of the northern North Sea water circulation.

This is apparently due to the uncertainty in the interpretation of drift bottle data and because the assumption that the distribution of temperature and salinity is the direct result of advection is probably incorrect. The observed currents are confined to narrow zones and are associated with changes in temperature and salinity.

Similarly the distribution of planktonic species in the central part of the northern North Sea are unlikely to be a direct consequence of advection and this implies that planktonic distributions may be more or less static in this area. This interpretation is partly supported by Saville (1959) who could find no evidence for the presence of an Atlantic inflow east of Shetland from the distribution of haddock eggs and larvae. These hypotheses are also consistent with the findings of Jones (1972) who, on the basis of fish tag returns was able to formulate sub-divisions of demersal fish stocks in the northern North Sea.

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