The circulation of the northern part of the Northeast Atlantic

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ABSTRACT

Circulation and water masses are discussed for the area between Scotland and Iceland. For most of this area the circulation is still not well known with any certainty. The upper waters are dominated by two moderately different water masses of Atlantic origin. These feed into the Norwegian Sea through the Faroe-Shetland Channel and north of the Faroes and are the main contributors to the oceanic heat flux from the Atlantic to the northern sea areas. Several estimates have been made of the Faroe-Shetland Channel transport, but the disagreement is large. Transport estimates north of the Faroes are even more uncertain. The circulation of the deep water is also known only for part of the area although the Overflow water forms a distinctive signal in several regions.

INTRODUCTION

The submarine ridge system between Iceland and Scotland is the natural limit towards the north and east of the North Eastern Atlantic. The magnitudes of warm, salty water flowing over this ridge out of the Atlantic and of cold, fresher water flowing into the Atlantic are of major interest both for the problem of the World Ocean circulation and for climatic studies. The region southwest of the ridge, the northern part of the Northeastern Atlantic, is the Atlantic buffer area for these flows.

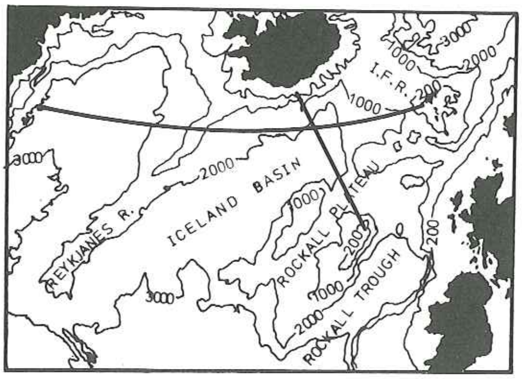

Fig. 1. Topography of the northern part of the Northeastern Atlantic. Heavy lines are sections shown in Fig. 2.

The ocean region discussed comprises two basins: The Rockall Trough (or Rockall Channel) and the Iceland Basin (or South Iceland Channel) and in between these the Rockall Plateau with its extensions to the Faroe Islands (Fig. 1). The Reykjanes Ridge is a natural border towards the west, while the ridge system between Iceland and Scotland over the Faroe Islands separates the region from the Norwegian Sea towards the east. The 3000 m isobath may rather arbitrarily be used as a southern delimitation.

The southeastern parts of the region have been intensively investigated for most of this century, and a large number of treatises have been published on that area. The northwestern and central parts, on the other hand, have been much less studied and reviewed.

This contribution was intended as a background paper for the discussion of tracer studies of the region and focuses on unsolved questions in relation to the circulation and especially on the exchange of water between the Atlantic and the Norwegian Seas.

THE ATLANTIC APPROACHES

The upper parts of the water column are dominated by water of Atlantic origin throughout practically the whole region. This water enters the area through its southern and western boundaries. A notable feature on maps of surface temperature or salinity (e.g. Dietrich et al. 1980, p. 539) is the divergence of isolines around 55°N and 25°W. This divergence naturally appears also on maps of the geostrophic surface current (e.g. Rossov 1972; Wegner 1973; Stommel et al. 1978). Thus most of the current seems to turn northwards after having passed the Reykjanes Ridge. This feature has been discussed by a number of authors, e.g. Lee (1974), and Dietrich et al. (1980, p. 542) display the current system as a set of branches.

To some extent this has been verified by recent experiments employing modern instrumentation. Thus Meincke and Sy (1983) cite results of a large experiment on the Reykjanes Ridge, showing two major branches of the North Atlantic Current crossing the ridge, the northern one apparently fixed topographically to the area with the prominent fracture zones. The fate of this branch farther east and its supposed northward turn still rests, however, on geostrophy. A direct verification of this feature would represent a major advance in our knowledge of this region.

The northward going flow east of the Reykjanes Ridge is associated with the Oceanic Polar Front and this area has highly variable T-S characteristics. The southern approaches, on the other hand, are more constant. Harvey (1982) discusses Θ-S for the southern waters of the region. For the intermediate layers (4°−12°C) he finds three main water masses: Mediterranean Water (MEDW), Sub-Arctic Intermediate Water (SAIW) originating in the Polar Front area, and a water mass which he terms Eastern North Atlantic Water (ENAW), produced in the North Eastern Atlantic area of deep convection. This water mass is associated with the Subpolar Mode Water (McCartney and Talley 1982). There is some confusion about names of water masses in this region partly due to the lack of knowledge of areas of formation and modification. For the waters dominating the Iceland Basin we will use the term MNAW (Modified North Atlantic Water) which is used commonly for the eastern part of the area. Its characteristics follow those of the ENAW.

In the deeper layers (0°−4°C) one finds in addition to the MEDW also Labrador Sea Water, Overflow Water, and deep NADW probably originating further south (Broecker and Takahashi 1980).

THE ROCKALL TROUGH

The Rockall Trough has been regularly investigated, especially by Scottish scientists, for a long period, and the southern part of the trough has been thoroughly discussed by Ellett and Martin (1973). Based on a number of geostrophic sections from all seasons they found a general anticyclonic circulation in the upper layers, which are generally fairly homogeneous due to the deep reaching winter and early spring convection (Meincke 1967). They noted, however, that this circulation scheme is not constant, a fact which is well demonstrated by later current measurements made by the SMBA laboratory (contributions by Ellett, Edelsten and MacDougall in Ann. Biol. for the years 1978 to 1981). These indicate a large variability (Booth 1983).

A major conclusion of Ellett and Martin's

1973 review paper is that the dominant upper water mass of the southern part of the Rockall Trough does not derive directly from the North Atlantic Current, but has a more southerly origin. This is consistent with the previously mentioned northward turn of the North Atlantic Current further west. The authors did not, however, exclude the possibility of a different origin in other decades.

This results in the occurrence of two different upper Atlantic components found in the Trough (Ellett et al. 1983). One is the classical North Atlantic Water (NAW), which enters the Trough from the south and west and has a relatively high salinity due to admixture with the deeper MEDW. The second is the Modified North Atlantic Water found especially in the North Rockall Trough, which probably enters the Trough northeast of Rockall, as was already suggested by Helland-Hansen and Nansen (1909, see Fig. 5).

Above the continental slope in the Rockall Trough investigations have revealed the extistence of a narrow, strong current following the topography. This is the Continental Slope Current hypothesized to be a general feature along the slope region of the European continent (Ellett, Dooley and Hill 1979). Its constancy in the Rockall Trough has been confirmed (Ellett et al. 1980; Booth and Ellett 1983).

At intermediate depths salinity and oxygen data indicate the presence of MEDW between 1000 and 1200 m, and below that again Ellett and Martin (1973) identified a low-salinity, high-oxygen water mass as Labrador Sea Water. The salinity increase and oxygen decrease found at still larger depths has been interpreted as due to Overflow Water (Ellett and Roberts 1973).

A detailed discussion on the water mass distribution of the North Rockall Trough during the JASIN 1978 experiment is to be found in Ellett et al. (1983).

THE ICELAND BASIN

As mentioned in the introduction the information on the Iceland Basin is not nearly as complete as for the Rockall Trough. An important data set for the area is the series of summer sections made for several years by the Danish research vessel Dana along the 62° latitude (contributions by F. Hermann and K. P. Andersen in Ann. Biol. for the years 1948–1958). Figure 2 shows an example of the section together with an Icelandic north-south section (Malmberg and Magnússon 1982).

The homogeneity of the upper waters evident in Figure 2 indicates a deep convection. This makes it difficult to trace the origin of the water mass filling the upper layers of the basin and different authors have used different names and T-S characteristics for this water (e.g. Lee and Ellett 1965). As mentioned previously, we find the term MNAW most appropriate for this water. A detailed discussion on the seasonal and inter-annual variations of surface temperature and salinity of the Iceland Basin was made by Malmberg and Magnússon (1982).

In the deeper waters there is also much uncertainty about the water mass origin. This is especially due to the many different sources feeding into this water, e.g. Irminger Sea, Labrador Sea, the Overflow water masses, which in many cases have only small differences in their T-S relationships. An additional complication is the variability of the region, which is exemplified by Figure 3 showing the depth of the 35.2 isohaline at the same season for six different years in the period 1948–1958.

The circulation pattern of the upper layers was studied already early in this century by drift bottles. Figure 4 shows a current scheme proposed by Ryder (1901). An interesting feature to note is the demarcation line along the Rockall Plateau separating currents turning north and south and implying a cyclonic circulation for the Iceland

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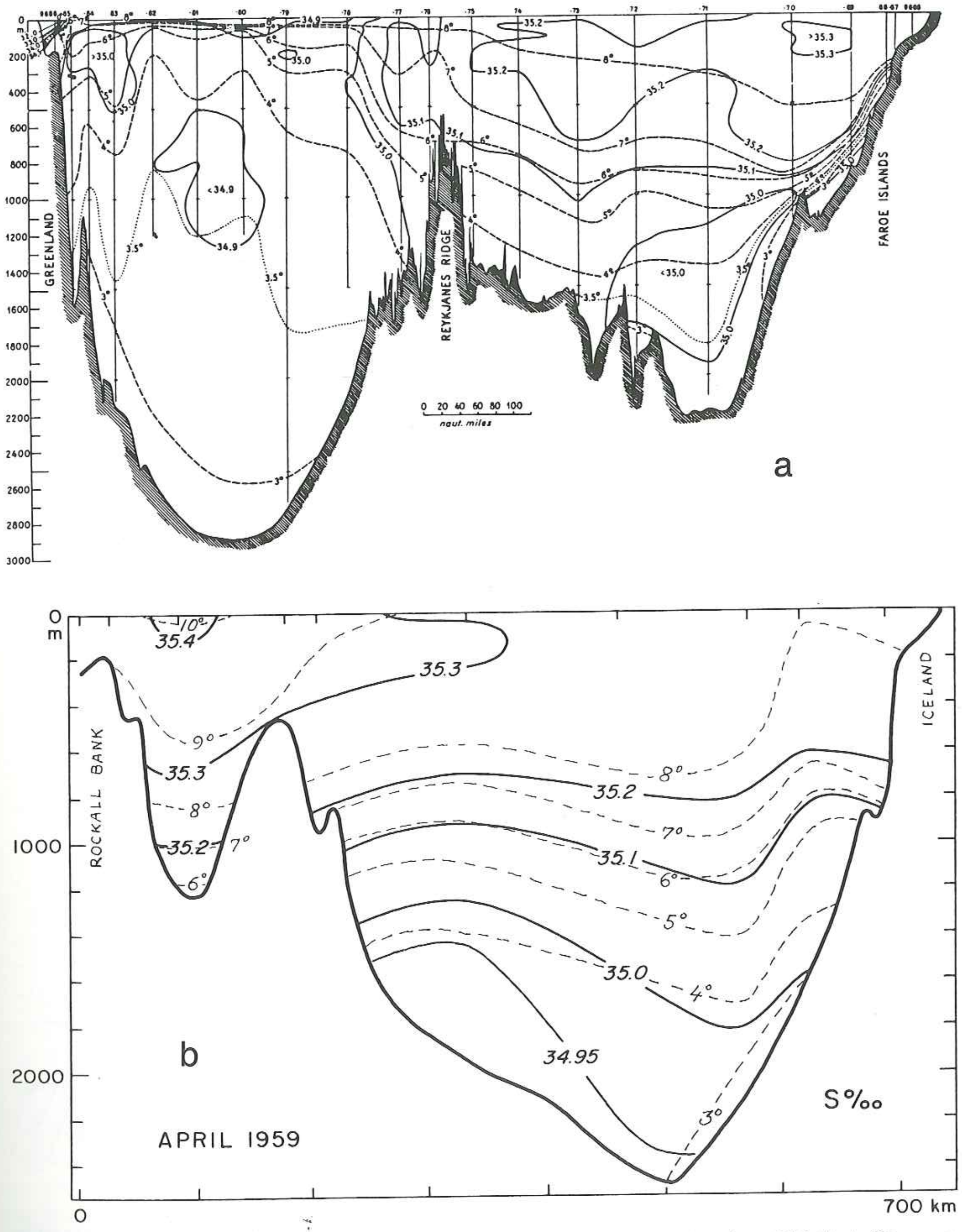

Fig. 2. Vertical sections through the Iceland Basin. (Locations in Fig. 1.) a) Section along 62° latitude (Hermann 1957). b) Section from Iceland to Rockall Bank (Malmberg and Magnússon 1982).

Basin, at least in the eastern part. A more detailed map, based partly on drift bottles and partly on hydrography, was given by Hermann and Thomsen (1946). They described the circulation as mainly anticyclonic.

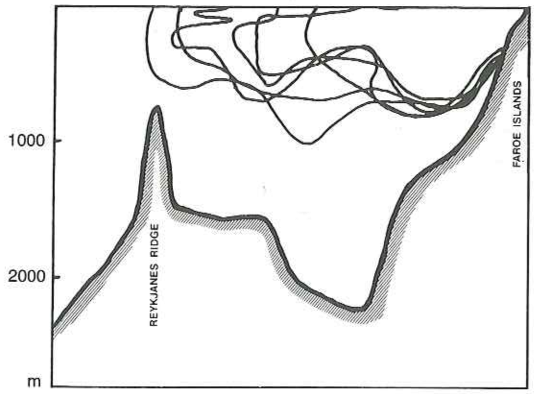

Fig. 3. Depth of the 35.2 isohaline along the 62° latitude in June-July in the years 1948–1958. Based on contributions by F. Hermann and K. P. Andersen in Ann. Biol. for the years 1948–1958.

Drift bottle results must of course be interpreted with caution, but the same applies to geostrophic calculations without current measurements for calibration. Dietrich (1957) showed the dynamic topography for parts of the Iceland Basin, based on a 1400 m zero reference level, as cyclonic, while Wegner (1973) synthesized the IGY data with a 1000 m zero reference level and got a more or less anticyclonic circulation. Direct instrumental evidence is sparse, but current measurements during Overflow-73 gave support for a cyclonic circulation. A mooring at a depth of 1300 m to bottom west of the Iceland-Faroe Ridge showed consistent residual currents towards northwest (along the topography) at six different depths from 86 m to 1293 m during most of a month (Koltermann et al. 1976). An arrow representing the flow at 86 m depth has been drawn on Ryder's drift map (Fig. 4). This is also in substantial agreement with the circu-

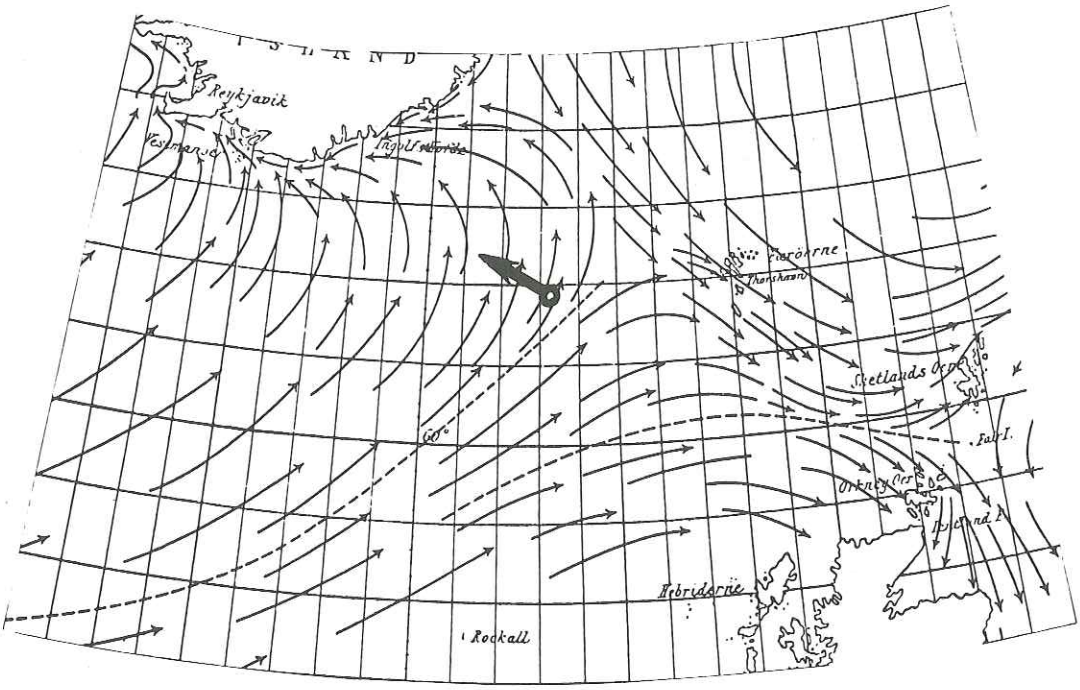

Fig. 4. Surface circulation of the Eastern Atlantic according to Ryder (1901) based on dirft bottle data. Heavy arrow shows direction of mean current of upper water during Overflow-73 at the location shown by the open circle (see text).

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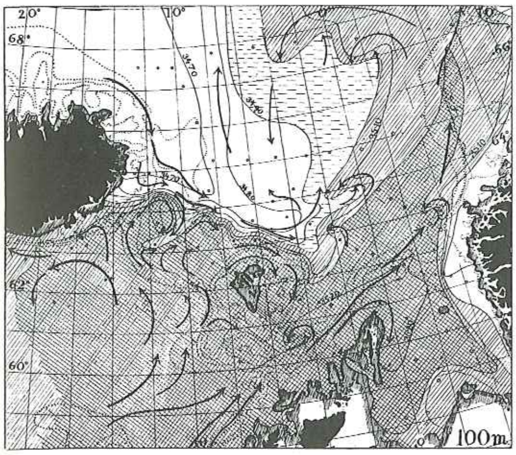

Fig. 5. Horizontal distribution of salinity at 100 m, May 1904. The arrows indicate the circulation pattern according to Helland-Hansen and Nansen (1909).

lation scheme proposed by Helland-Hansen and Nansen (1909) based largely on water mass tracing (Fig. 5).

In the deeper layers the isolines of Figure 2 show dense water along the northern, eastern and southern flanks of the basin below 1500 m with lighter water in the central part. Indeed a number of authors (e.g. Shor 1978) report a west-going near bottom current at 1400 to 1800 m depth on the East Katla Ridge on the southern Iceland slope. This is interpreted as remains of the Overflow through the Faroe Bank Channel and over the Iceland-Faroe Ridge to be discussed presently. The occurrence of heavy water also on the deep southern flank of the basin and the previously mentioned deep current measurements from the Overflow-73 experiment, might indicate a cyclonic circulation at depth. This is in conflict with a map of geostrophic currents at 2000 m depth made by Lappo (1963), but his zero reference level of 1500 m would appear quite *ad hoc* for this area.

In conclusion, there is some evidence for a cyclonic circulation of the eastern part of the Iceland Basin, both in the upper layers and at depth, but the evidence is weak. Further use of tracer techniques could be very fruitful, especially for studies of the deep circulation.

THE ROCKALL PLATEAU

The Rockall Plateau is the shallow area separating the Iceland Basin from the Rockall Trough. It has a typical depth of 1 km with several banks arising from it to quite shallow depths from the Rockall Bank in the southwest to the Faroe Bank and the Faroe Plateau in the northeast.

Over the Rockall Plateau and its northern slope a high salinity core is often found. It is seen in Figure 2, in this case between Rockall Bank and Hatton Bank. Farther to the northeast a high salinity core is also generally found over the northern slope of Faroe Bank (Tait 1957 and the "Dana sections", loc. cit.) and we may hypothesize that there is a current flowing towards the east north of Rockall Bank, part of it turning into the Rockall Trough, as previously noted, part of it continuing along the northern slope of Faroe Bank and part of it possibly recirculating into the Iceland Basin into the proposed cyclonic gyre.

This circulation scheme is inconsistent with the notion of a cyclonic circulation around Rockall Bank generally proposed in older literature (e.g. Lee 1974), but is supported by a direct current measurement experiment lasting more than 3 months due north of Rockall Bank near the 500 m isobath (Dooley and Henderson 1980). This mooring showed a fairly steady residual current flowing towards the east. Dooley (1984) has proposed an anticyclonic Taylor column circulation around Rockall Bank, with speeds increasing towards the bottom.

A major part of the water in this flow is obviously MNAW. How much of it derives directly from the North Atlantic Current, and how much has been recirculated in a possible gyre in the Iceland Basin is an open question, as are the details of the flow over the Rockall Plateau and around its banks.

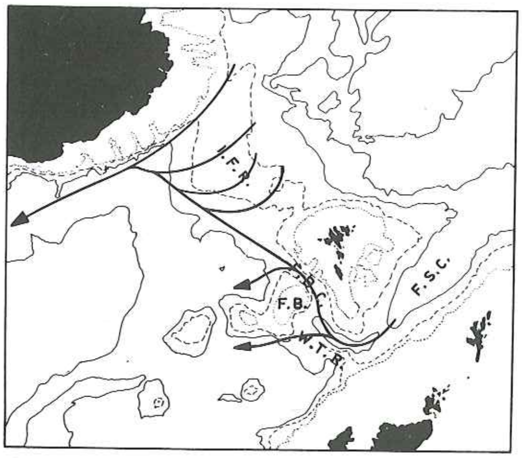

Fig. 6. Topography of the eastern boundary. Arrows indicate Overflow paths.

THE EASTERN BOUNDARY

The ridge system dividing the Northeastern Atlantic from the Norwegian Sea (Fig. 6) is in two parts: The Iceland Faroe Ridge (IFR) and the Wyville-Thomson Ridge (WTR), both of them with sill depths of the order of 500 m. They are separated by the Faroe-Shetland Channel (FSC) continuing into the Faroe Bank Channel (FBC), which has a sill depth around 850 m and is the deepest gap in the Greenland-Scotland ridge.

Northeast of the ridge system the Atlantic water meets colder and slightly fresher water masses (Fig. 7). The deeper parts of the Norwegian Sea are filled with the Norwegian Sea Deep Water (NSW) with temperatures below −0.5°C and salinity equal to 34.92. Above that is found warmer and fresher water deriving from various sources. Usually it is dominated by a mixture of North Icelandic Winter Water (Stefánsson 1962) and Arctic Intermediate Water. This water mass, usually termed NI/AI water, has temperatures around 2°−3°C and varying salinities less than 34.9. The meeting of the NI/AI water and the Atlantic water occurs in the Subarctic Front (Fig. 7).

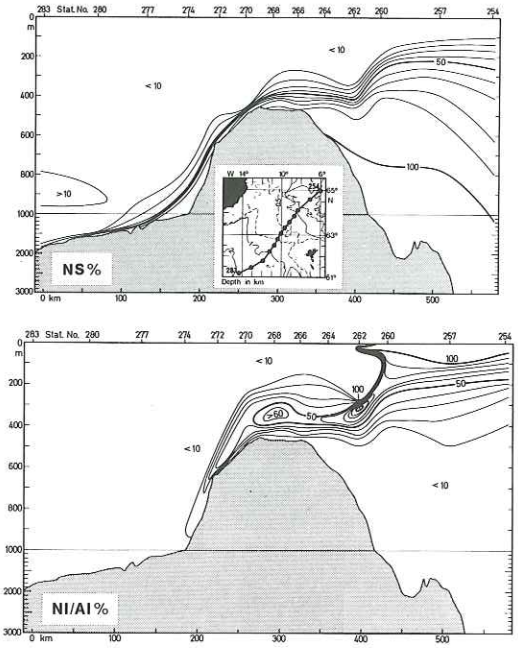

Fig. 7. Distribution of NSW and NI/AI water on a section across the Iceland-Faroe Ridge. Hansen and Meincke (1979). Based on data from R. V. Meteor during Overflow-73.

The transport of Atlantic water out of the Northeastern Atlantic occurs over the IFR and through the FSC (in addition to the northgoing flow west of Iceland). The inflow to the North Eastern Atlantic of the cold water masses (Overflow) occurs over the IFR, through the FBC and over the WTR (in addition to the Overflow through the Greenland-Iceland Channel). As mentioned in the introduction, transport values for these flows are of paramount importance and have received much attention. A much cited balance estimate is that by Worthington (1970) shown in Figure 8. It was based partly on measurements available at that time and partly on balance considerations. The evaluation of this balance is coupled to an understanding of the circulation pattern along the boundary, and we shall discuss this for the inflow (Overflow) and outflow separately.

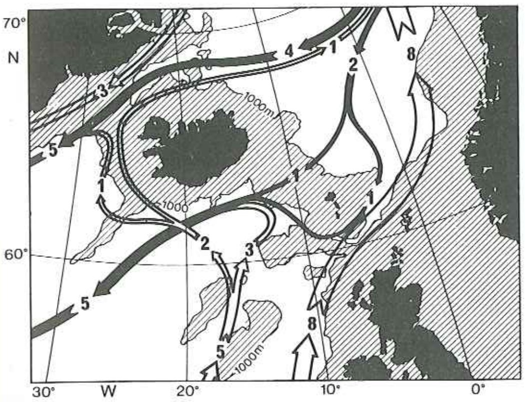

Fig. 8. Worthington's (1970) estimate of Atlantic outflows (open arrows) and inflows (Overflow) of cold water (filled arrows). Numbers in Sv.

THE OVERFLOW

The overflow of cold, relatively fresh water across the Iceland-Faroe Ridge was known already early in this century (Nielsen 1904), but its significance (together with other Overflow sources) for the production of the bottom water of the World Ocean (Reid and Lynn 1971) does not seem to have been recognized until the late fifties. Since then a lot of research effort has been put into this problem culminating in the two ICES experiments, Overflow-60 (Tait 1967) and Overflow-73 (Meincke 1974).

As a result of these efforts it is clear that the Overflow over the IFR is an irregular process (Meincke 1975), possibly coupled to atmospheric forcing (Meincke and Kvinge 1978), possibly to baroclinic instability of the frontal system in this region (Willebrand and Meincke 1980) and possibly to tides (Nagurny, Dubovik and Bogush 1978). According to Stefánsson (1962) Overflow close to the Icelandic shelf contains little NSW and is a mixture of Atlantic water and NI/AI water. The same apparently applies further south on the IFR (Müller 1978). On the western slope of the IFR, at depths around 1000 m, a consistent temperature minimum indicates the presence of NSW, but as pure NSW has never been observed to overflow the ridge, this water is supposed to derive mostly from the deep outflow through the Faroe Bank Channel (Fig. 6).

This outflow contains water which has passed through the FSC below 500 m, before it turned northwestward into the FBC. In the FSC it is overlain by variable amounts of NI/AI water partly mixed into the upper water of Atlantic origin. As will be discussed presently, only small amounts of the NI/AI water seem, however, to follow the NSW into the FBC, and thus the FBC overflow contains almost pure NSW mixed with Atlantic water (Müller 1978).

The combined outflow through the FBC and over the IFR follows the western flank of the IFR towards Iceland, and continues, as previously mentioned, along the deep parts of the southern Icelandic slope passing the East Katla Ridge at about 1500 m depth. This current continues westwards and turns towards the south following the eastern flank of the Reykjanes Ridge until the Charlie Gibbs Fracture Zone (CGFZ), where most of it appears to leave the Eastern Atlantic Basin and continue into the Western Basin. According to Harvey (1980) its depth in the CGFZ is between 2500 and 3000 m, and it displays a high variability, which is only to a small degree seasonal or interannual.

The irregularity of the flow has thus been established at all parts of the path, and that of course makes transport estimates difficult. Harvey and Shor (1978) on the basis of long-term moored current meters and a hydrographic section estimated a total transport of Overflow water (including the entrained Atlantic water) through the CGFZ of 2.0 Sv (10^6 m^3/s) varying between 0 and 4.7 Sv in different months. This is less than Shor's (1978) point estimate of 5.0 Sv past the East Katla Ridge but is not inconsistent with that. From his data Shor (1978) estimated that 39% of the water in the flow (2.0 Sv) was NSW.

The transport of NSW out of the FBC was estimated from the Overflow-73 data by Dooley and Meincke (1981) to be 1.1 Sv with an additional amount of 0.3 Sv of NI/AI water. This is of the same order of magnitude as that reported by previous authors (Crease 1965; Hermann 1967; Sætre 1967) as indeed is required considering the general opinion (Hermann 1959) that the FBC Overflow is a fairly continuous and constant process.

The transport over the IFR is more difficult to estimate due to its irregularity. Hermann (1967) used the Overflow-60 data to estimate 1.1 Sv overflowing the ridge along four different paths (Fig. 6), and later investigations do not seem to have given any reason to revise this estimate.

All of the Overflow does not, however, follow the current on the southern Iceland slope to the CGFZ. There are at least two other branches of the flow. According to Crease (1965) part of the outflow through the FBC descends through a narrow channel turning westward on the northern slope of the Faroe and Bill Bailey Banks (Fig. 6), and sections from the RV Shackleton Overflow-73 cruise show very high concentrations of NSW in this channel (Müller et al. 1979) at about 1700 m depth. The transport magnitude and further fate of this flow remains unknown, although it appears against the western flank of the Rockall-Hatton Plateau at the 2.4° to 2.8°C potential temperature surfaces of Worthington and Wright's (1970) atlas, without any evidence that this branch also flows into the Western Basin.

The other Overflow branch which remains in the Eastern Basin is the Overflow over the Wyville Thomson Ridge entering into the northern Rockall Trough (Ellett 1976). Its magnitude during Overflow-73 was found to be 1.2 Sv total flow, of which 0.3 Sv was NSW (Ellett and Edwards 1978). This flow is also highly variable and this figure may be an overestimate. Dooley and Meincke (1981) estimated only 0.1 Sv for the NSW transport across the WTR.

In conclusion, there are discrepancies between estimates of the transport made at various times and locations, but these are no larger than was to be expected, taking into account the variability of the processes and the uncertainties inherent in transport estimates. Further, there seems to be no reason for revising Worthington's estimate of 2 Sv of undiluted Overflow water, although the uncertainty of this estimate is at least 50% at present. Also, the fraction of the Overflow continuing into the Western Basin is unknown, but probably it is a major part.

THE ICELAND-FAROE RIDGE

The flow of Atlantic water into the Norwegian Sea occurs over the Iceland-Faroe Ridge and through the Faroe-Shetland Channel. Thus there are two main branches of Atlantic flow between Iceland and Shetland.

The first of these is illustrated in Figures 5, 7 and 9a. The front is obviously topographically locked to the IFR, but in the surface layer it is highly meandering (Hansen and Meincke 1979).

The path of the Atlantic water as it approaches the IFR is not well known. The horizontal distribution of temperature and salinity along the ridge axis appears quite homogeneous on the ridge proper (Meincke 1972), but changes when approaching the shallower areas at both the Icelandic and the Faroese ends of the ridge. On the Faroese end a high salinity core is often found, which appears to be a continuation of the core north of Faroe Bank, previously mentioned.

Further towards the east this core is much more evident, and an often repeated north-south section at about 6°W (Tait 1957 and contributions by F. Hermann and K. P. Andersen in Ann. Biol. for the years 1948–1957) always shows this core (Fig. 9a) with steeply sloping isolines indicating a strong

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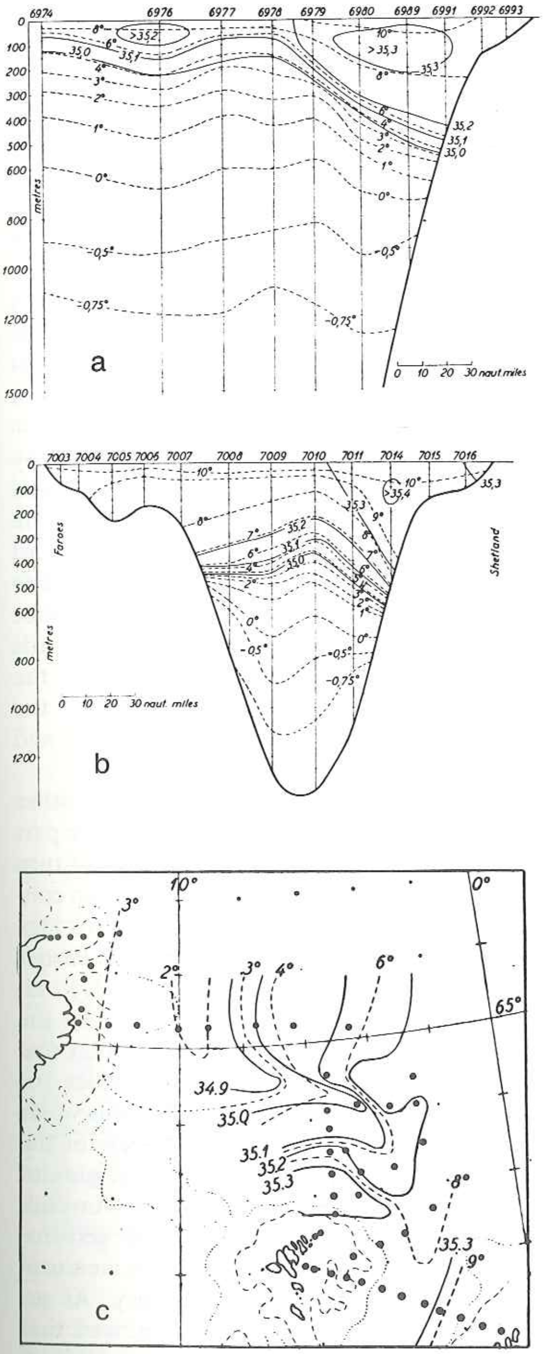

Fig. 9. Vertical sections August 1948 (Hermann 1948): a) From the Faroes northwards. b) Faroe-Shetland sections. c) Map with sections and temperature and salinity at 100 m.

flow. Thus there is some evidence of both a concentrated flow along the northern flank of Faroe Bank continuing on the northern Faroe slope and also a broader flow over the ridge, both of these concentrating east of the ridge at about 6°W. This pattern is in good agreement with Helland-Hansen and Nansen's (1909) circulation map (Fig. 5).

Over the northeastern flank of the Ridge Figure 5 agrees well with the dynamic current computations from the Overflow-60 data set (Bogdanov et al. 1967) but not over the southwestern flank. The dynamic method is, however, very difficult to use on a ridge, and Figure 5 is in substantial agreement with the available information from drift bottle experiments and direct current measurements (Fig. 4). This flow has been denoted the Faroe Current by Hansen and Meincke (1984). Its core seldom greatly exceeds 35.3 in salinity and 9°C in temperature. Probably it represents fairly undiluted water from the eastern part of the Iceland Basin and the term MNAW seems to have originated with this water mass.

The core of this flow is surrounded by slightly colder and fresher water, but as the T-S relationship of NI/AI water lies close to the T-S curve for MNAW in the Iceland basin, it is difficult to distinguish between these two water masses, especially taking into account the variability of both.

The Subarctic Front slopes towards south and west with depth. It meets the IFR at the crest (Fig. 7) and the Faroe slope at depths of 300 to 500 m (Fig. 9a). Below the Faroe Current there is thus a layer of NI/AI water which derives from the East Icelandic Current and gives a salinity minimum between the overlying MNAW and the NSW, which is found in increasing amounts from about 500 m and downwards.

East of about 5°W the surface isolines tend to diverge horizontally (Fig. 5), and a cold tongue protruding far towards the Faroese shelf is a common, although irregular feature, which may be connected to the well documented meandering and instabilities of the Subarctic Front (Hansen and Meincke 1979; Willebrand and Meincke 1980). In the divergence zone the flow splits up into two components, one continuing towards east and northeast into the Norwegian Sea and one turning towards the south and flowing southwards east of the Faroes into the Faroe-Shetland Channel.

Below the MNAW in the surface this flow contains increasing amounts of NI/AI water with depth down to the salinity minimum, which according to Meincke (1978) rises to depths of about 200 m as the tongue rounds the eastern corner of the Faroe Plateau and then sinks again in the FSC. Below the NI/AI water is again found the NSW. Thus this current transports three different water masses into the FSC.

THE FAROE SHETLAND CHANNEL

The FSC has been the object of many scientific cruises throughout this century and must indeed be one of the most intensively investigated ocean areas in the world. In spite of this, the magnitude of water transport through the channel and even the basic circulatory pattern is still a subject for discussion. A major reason for this is to be found in the complexity of the hydrography of the area.

The best known part of the channel is the bottom layer beneath about 500 m, in which the NSW flows southwestwards through the FSC (Fig. 9b) and continues northwards through the FBC, where it contributes to the Overflow. In addition to this resultant flow there are indications of a cyclonic recirculation at depth.

In the upper layers the tongue from the Faroe Current containing MNAW mixed with NI/AI meets the flow from the Atlantic. This flow derives mostly from the upper 500 m of the North Rockall Trough and consists mainly of NAW and MNAW. The classical NAW is, however, concentrated in the core of the current over the Shetland slope (Tait 1957). In addition there may be a flow southwards through the FBC, but this is still an open question. The main component of that flow would undoubtedly be MNAW. Thus the two flows converging in the FSC, the flow from the Faroe Current and the more direct flow from the Atlantic, both have MNAW as their main component in the upper layers. This fact complicates a water mass tracing of the flow and may be one reason for the discrepancy found between earlier literature on the circulation of the FSC and later contributions.

The discrepancy may be illustrated by Figures 5 and 10. Helland-Hansen and Nansen (Fig. 5) assume the flow from the Faroe Current (flowing southwards east of the Faroes) to join the more direct flow from the Atlantic in a gyre in the FSC, after which both components flow jointly towards northeast along the Shetland side of the channel. The same idea is implicit in the works of Jacobsen and Jensen (1926) and Jacobsen (1943).

Dooley and Meincke (1981), on the other hand, consider about half of the upper part of the flow from the Faroe Current to turn westwards south of the Faroes and then continue northwest through the FBC. This idea of an anticyclonic gyre around the Faroes seems to originate with Tait (1937), although he probably thought mainly of the shelf waters. Müller (1978) and Dooley and Meincke (1981) used the existence of MNAW in the FBC to argue that this water must derive from the FSC. In view of the preceding discussion on the origin of MNAW in the area, this argument is invalid.

It might be thought that either geostrophic calculations or direct current measurements could settle the discrepancy. As regards geostrophy, it must be stressed that the FSC is an area of intense variability, both spatially and temporally. Under these circumstances the geostrophic method is questionable. In addition, the choice of a reference level is difficult. The standard source on this subject is the monograph by Tait (1957) on the FSC, in which he chooses the 35.0 isohaline as a zero flow reference level or the bottom, whichever is shallower.

In this choice is the implicit assumption that the water above this isohaline flows from the Atlantic into the Norwegian Sea and vice versa. For a section between Shetland and Faroes this *a priori* excludes Helland-Hansen and Nansen's circulation scheme (Fig. 5), but furthermore a detailed analysis of the data demonstrates that Tait's assumption is internally inconsistent. Thus an evaluation of the vertical geostrophic shear (independent of reference level) for 28 sections between the Faroes and Shetland (Hansen 1973) gave the result that in the middle of the channel 22 of these had a larger northeast going component of the flow at depth than in the upper layer, and only 3 had the opposite. Tait's choice of reference level then implies that in the middle of the channel the NSW (Deep Norwegian Sea Water) generally flows in the direction from the Atlantic into the Norwegian Sea. The exclusion of barotropic flow, implicit in Tait's work, is not realistic for the FSC.

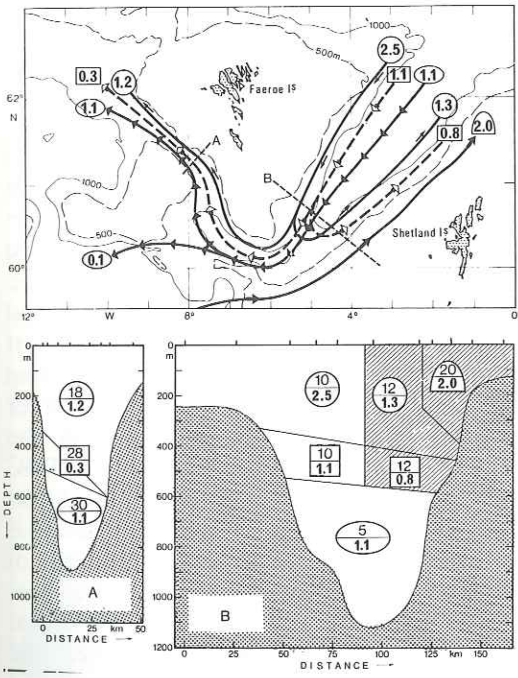

Fig. 10. Circulation in the Faroese Channels during Overflow-73 according to Dooley and Meincke (1981). Numbers in Sv. Above: Flow paths and transport magnitudes. Below left: Magnitude of transport through section A. Below right: Magnitude of transport through section B. Shaded areas indicate flow into the Norwegian Sea.

Dooley and Meincke (1981) reached this conclusion also by comparing geostrophic and measured current velocity. They therefore employed mostly the current measurements collected during Overflow-73, combined with the water mass structure, to arrive at their balance (Fig. 10). Their current meter material is, however, very small taking into account the variability, and it is not surprising if this procedure leads to a large uncertainty.

Certainly the conclusion by Dooley and Meincke (1981), that the upper water in the FBC derives from the FSC, is untenable. The upper waters on the Faroe side of the FSC are a mixture of MNAW and NI/AI, while the upper waters in the main and western part of the FBC are generally almost pure MNAW. This is illustrated by Figure 11 from Hansen (1979) who argued that the unmixed MNAW in the FBC could not derive from the diluted MNAW of the FSC, while the opposite is not inconceivable. Figure 11 is based on data from only one cruise in spring 1978, but the conclusion that the MNAW on the Faroe side of the FSC is diluted, while that in the FBC is pure, seems to be a common phenomenon, and certainly this was the case during the Overflow-73 experiment on which Figure 10 is based, as a perusal of the water mass distribution during the experiment (Müller et al. 1979) documents.

Thus the classical circulation scheme for the FSC (Fig. 5) appears to be the most correct description. The convergence zone of the two MNAW carrying flows is not very apparent in the surface distributions of tem-

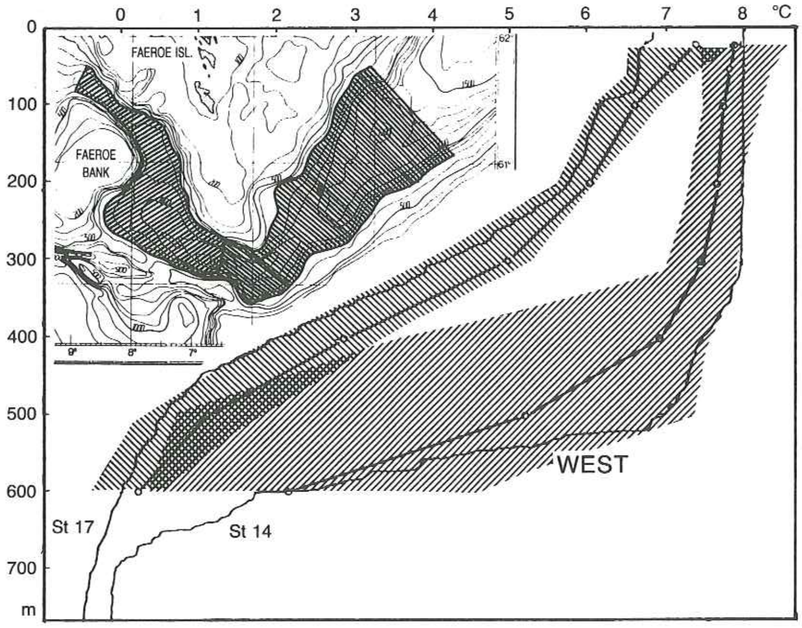

Fig. 11. Temperature profiles at CTD stations respectively east and west of the Faroes at bottom depths larger than 700 m. Station areas shown on map. Light traces: Sample profiles. Heavy lines connecting open circles: Mean profiles. Shaded areas: Range of profiles. Adapted from Hansen (1979).

perature or salinity, but as the percentage of NI/AI water increases with depth in the FSC, the difference becomes evident and a clearly defined front is apparent on temperature maps at greater depths (Fig. 12).

As we proceed towards the shallower waters on the Faroe Plateau, the existence of an anticyclonic circulation can not be excluded. Indeed current meter records on the Faroese shelf do show this feature (Fig. 13) for the northern part of the shelf, but the southernmost mooring is actually in better accordance with the classical circulation scheme (Fig. 5) than with a closed anticyclonic gyre. There is evidence for a flow, possibly intermittent, over the slope of the southern part of the Faroe Plateau from the FSC to the FBC. An example of this is seen in Figure 12c. In all the observed cases this water does, however, keep to the region above the Faroese slope, as it flows north through the FBC, and does not enter the main part of the channel.

For the FBC we may thus exclude the idea of an upper flow driven from the FSC, as a general case. The MNAW in the FBC certainly derives from the west, but whether it has passed north of Faroe Bank and flows south through the channel (Fig. 5) or comes from the North Rockall Trough and flows northwards as suggested by Tait (1937), is an open question. Possibly the balance between these two flows is variable. On the eastern flank of the channel, over the slope of the Faroe Plateau, one may as noted find high concentrations of NI/AI waters at times. At other times salinites approaching 35.4 indicate the presence of the other Atlantic water mass, NAW. Indeed the whole area comprising the FSC and the FBC is dominated by the convergence of different flows, and the balance between these is obviously variable. Thus the situation of Figure 12 was at a time when the East Icelandic Current was fairly strong. A year later, when that current was weaker, the front at 400 m depth (Fig. 12c) was more diffuse and located further to the east (Hansen, unpublished data). On decadal time scales Martin (1976) has described changes in the T-S relationships. Their dynamical implications are as yet not clear.

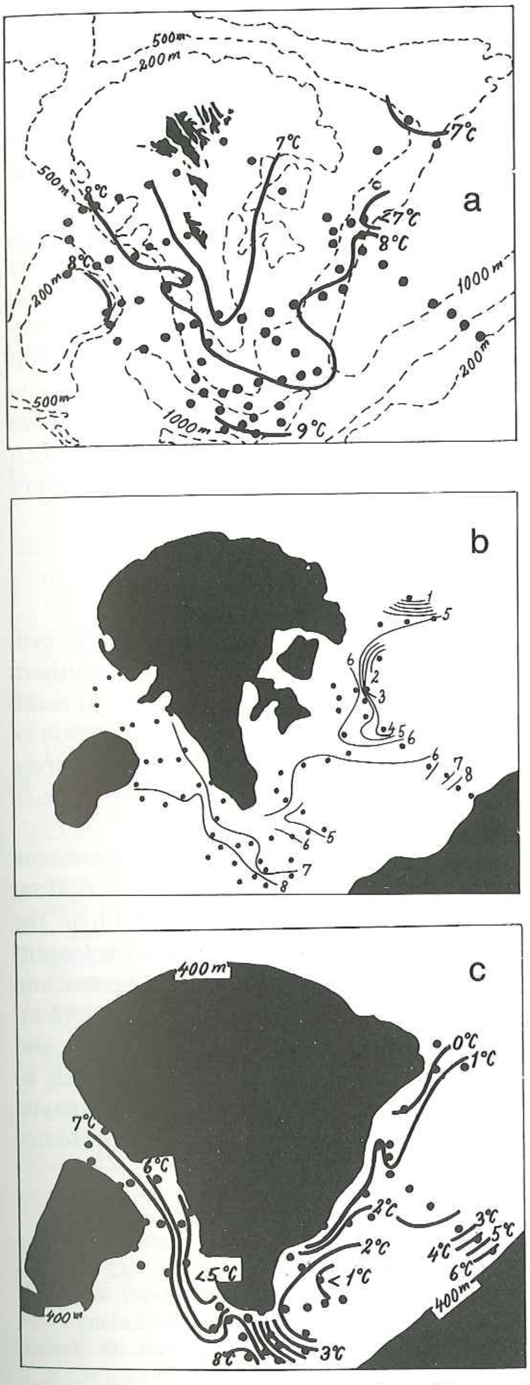

Fig. 12. Maps of temperature at surface, 200 m and 400 m depth, May 1983. Filled circles indicate CTD stations.

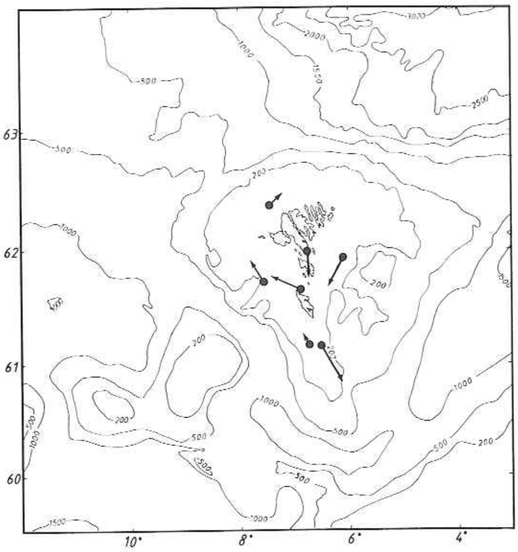

Fig. 13. Direction of residual currents on the Faroese shelf, based on current meter data. (Hansen 1979).

THE VOLUME TRANSPORT OF ATLANTIC WATER

We may now return to the question of the magnitude of the transport of Atlantic water into the Norwegian Sea. A number of authors have evaluated the transport through the FSC based on geostrophic calculations (Jacobsen 1943, Hermann 1948, Timofeyev 1963 among others) and found numbers ranging from 2 to 10 Sv for the mean transport. The most generally cited number is, however, that by Tait in his previously cited monograph (Tait 1957). He found 2.5 Sv to be the transport of Atlantic water (salinity above 35) as a mean of 81 sections (including those of Tait and Martin 1961). As previously discussed the assumptions underlying this number are very questionable, and this must be the case for any geostrophic estimate of the FSC transport. Thus a numerical experiment performed on 25 sections from the period 1957 to 1962 (Hansen 1973) demonstrated that the mean transport is easily doubled by reasonable modifications of the *ad hoc* assumptions.

Neither can we rely on the geostrophic transport values calculated from a more westerly section between Faroe Bank and Butt of Lewis (Tait 1957). This section may be free of the recirculation problem encountered in the FSC, but as it follows the Wyville-Thomson Ridge part of the way, the assumption of no barotropic flow is probably even more unrealistic than for the FSC sections.

The alternative is to use direct current measurements or a combination of these and geostrophy. The attempt by Dooley and Meincke (1981) to do this leads, however, to an unrealistic circulation scheme, as has been demonstrated, and this method "is also fraught with difficulty", to cite those authors. In recent years dense networks of current meter moorings have been deployed over the southeastern slope of the FSC, and when the data from these have been processed, more reliable estimates of that part of the current may be obtainable. For the other side of the channel, the current meter coverage is, however, still far too sparse to allow an estimate of the total transport through the channel by this method.

For the transport over the IFR, the situation is no better. Hermann (1948) estimated the total transport through the section of Figure 9a, north from the Faroes, to be 4.5 Sv, of which, however, only part is Atlantic water. Tait (1957) also cited a number of geostrophic transports through this section of considerably smaller magnitude, while Sukhovey (as cited by Rossov 1972) estimated a transport of almost 10 Sv between Iceland and the Faroes. There does not seem to have been any attempt to evaluate the transport based on observed current, and with the amount of current meter data published for this area this is hardly realistic at present.

In recent western literature the transport over the IFR is generally regarded as insignificant compared to the FSC transport (e.g. Coachman and Aagaard 1974, p. 90). The arguments remain obscure, however. Certainly a visual comparison of two contemporary sections through the two flows (Fig. 9) does not support this view, especially taking into account that part of the flow through the FSC has come through the northern section.

To conclude, there is, in the author's opinion, at present no reliable number for the total transport of Atlantic water into the Norwegian Sea. Worthington's (1970) balance estimate of 8 Sv appears somewhat high but cannot be excluded. Thus a transport of 4 Sv between Iceland and the Faroes and an additional transport of 4 Sv between the Faroes and Shetland are not inconsistent with present knowledge.

CONCLUSION

In this paper it has been attempted to synthesize available knowledge on the northern part of the Northeastern Atlantic, to make an attempt at a consistent interpretation of the observational base, which in some areas is very thin, and to focus on the problems of such an interpretation.

It is a rather depressing conclusion that in many respects the most reliable descriptions of the circulation pattern seem to be the older ones, and that numbers for transport are still not available to any great precision. This underlines the need for much more intensive use of modern techniques, but also stresses that large efforts are required to obtain reliable transport values and maybe even new techniques (e.g. acoustic tomography).

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