The circulation of Norwegian Sea overflow water in the eastern North Atlantic

Circulation
Water masses
Geostrophic transports
Neutral surfaces

Circulation
Masses d'eau
Transports géostrophiques
Surfaces neutres

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ABSTRACT

Neutral surfaces are defined from historical hydrographic data on which the spreading of Iceland-Scotland overflow water (ISOW) may be examined in the eastern North Atlantic and the Irminger Basin. Each of these neutral surfaces occurs at less than 400 m on the Iceland-Faroe rise, but they descend to depths in excess of 2 600 m (shallowest) and 3 600 m (deepest) in the area of study. Salinity distribution on these surfaces provides a first indication of circulation patterns. θ-S water mass analysis, using successive mixing stages of ISOW is generally found to be satisfactory, but in the south-eastern part of the region a third water mass characteristic is required. Oxygen data from cruises between 1957 and 1962 are re-examined and, after the application of new corrections, are considered to be internally consistent and suitable for this purpose. The resultant charts of the spreading of ISOW on neutral surfaces show that more than 40% of the water flowing through the Charlie-Gibbs fracture zone (CGFZ) at about 2 400 m has the original overflow water characteristics. Geostrophic calculations with a reference level of no motion selected on the basis of the water mass analysis are used to derive quantitative circulation patterns of all deep water below the reference level and of the original overflow water. A total of 5.5 Sv of deep water including 1.8 Sv of original overflow water are found to enter the eastern basin between Iceland and Scotland; some appears to undergo cyclonic circulation in the Iceland Basin, before it all passes through the CGFZ into the western basin.

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RÉSUMÉ

Déversement d'eau de la mer de Norvège dans l'Atlantique Nord

A partir de données hydrologiques historiques, des surfaces neutres ont été définies pour étudier le déversement de l'eau d'Islande-Écosse (ISOW) dans l'est de l'Atlantique Nord et le bassin d'Irminger. Chacune de ces surfaces neutres se trouve à moins de 400 m sur le seuil Islande-Feroe, mais elles plongent à des immersions comprises entre 2 600 et 3 600 m dans la région étudiée. La répartition de la salinité sur ces surfaces apporte une première indication sur la circulation. L'analyse θ-S des masses d'eau en suivant les étapes du mélange de ISOW est en général satisfaisante, mais dans le sud-est de la région, une troisième caractéristique de la masse d'eau est nécessaire : les données d'oxygène recueillies entre 1957 et 1962 ont été retenues, après corrections. Les cartes de l'écoulement de ISOW le long des surfaces neutres montre que plus de 40% de l'eau traversant la zone de fracture Charlie-Gibbs (CGFZ) vers 2 400 m présente les caractéristiques de l'eau originale. Les calculs géostrophiques, avec pour référence un niveau de vitesse nulle choisi par l'analyse des masses d'eau, fournissent des modèles quantitatifs de circulation pour toute l'eau profonde au-dessous de la surface de référence et pour l'eau originale. Au total, un flux d'eau profonde de 5,5 Sv, dont 1,8 Sv du déversement original, pénètre dans le bassin oriental entre l'Islande et l'Écosse; une partie de ce flux entre dans la circulation cyclonique du bassin islandais, avant que l'ensemble ne pénètre dans le bassin occidental par la zone de fracture Charlie-Gibbs.

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INTRODUCTION

The general features of the circulation of Iceland-Scotland overflow water (ISOW) from the Norwegian Sea in the eastern North Atlantic have been known for some time—*see, inter alia*, Cooper (1952; 1955), Dietrich (1956), Lee and Ellett (1965), Worthington and Volkmann (1965), Worthington (1976), Swift (1984). Cold, dense water from the Norwegian Sea flows through the Faroe Bank Channel (Crease, 1965) and over the Iceland-Faroe rise (Hermann, 1967; Muller *et al.*, 1979); some cold dense Norwegian Sea water also overflows the Wyville-Thomson Ridge into the Rockall trough (Ellett, Roberts, 1973). These overflows, being of more dense water than the overlying North East Atlantic water, form undercurrents following topography with deeper water on their left, initially descending fairly steeply to about 2 000 m, and continue into the western basin of the North Atlantic through the Charlie-Gibbs fracture zone (CGFZ).

This paper is based on analysis of hydrographic data, mainly collected between 1955 and 1975, and aims to establish the circulation pattern of this overflow water quantitatively. Data from some 6 000 hydrographic stations in the area of interest (Fig. 1) were acquired from the NODC Washington and from ICES. A selection was made on the basis of depths of stations and depths to which observations were made, quality of temperature and salinity data, and geographical distribution, which reduced the size of the data base to 1 325 stations (*see* Theodorou, 1983, for more details of the selection procedures used).

NEUTRAL SURFACES

Spreading of water masses in the ocean interior is generally assumed to occur predominantly along isopycnal surfaces (*see, e.g.*, Reid, 1981), although certain diapycnal processes such as double diffusive mixing (*e.g.* Garrett, 1982) certainly occur. The definition of appropriate isopycnal surfaces on which to carry out water mass analysis is, however, far from straightforward—the variation of *in situ* density in the oceans is dominated by pressure effects, but due to the non-linear nature of the equation of state of sea-water it is not satisfactory to define density surfaces relative to any single pressure level (such as atmospheric pressure). An extreme example of the problems which may occur in using σ_θ (potential density of water brought adiabatically to atmospheric pressure expressed in kg m^{-3} minus 1 000) is shown in Figure 2 which compares $\sigma_{in\ situ}$ and σ_θ for observations at 1 500 db in a line of stations along 47°N; in the western part of the section, where there are strong thermohaline contrasts (Le Groupe Tourbillon, 1983, Fig. 9 *b*) the direction of the σ_θ gradient is opposite to that of the *in situ* density gradient.

Using the ideas of Pingree (1973), Ivers (1975), Reid (1979) and Shepherd (unpublished manuscript, 1979),

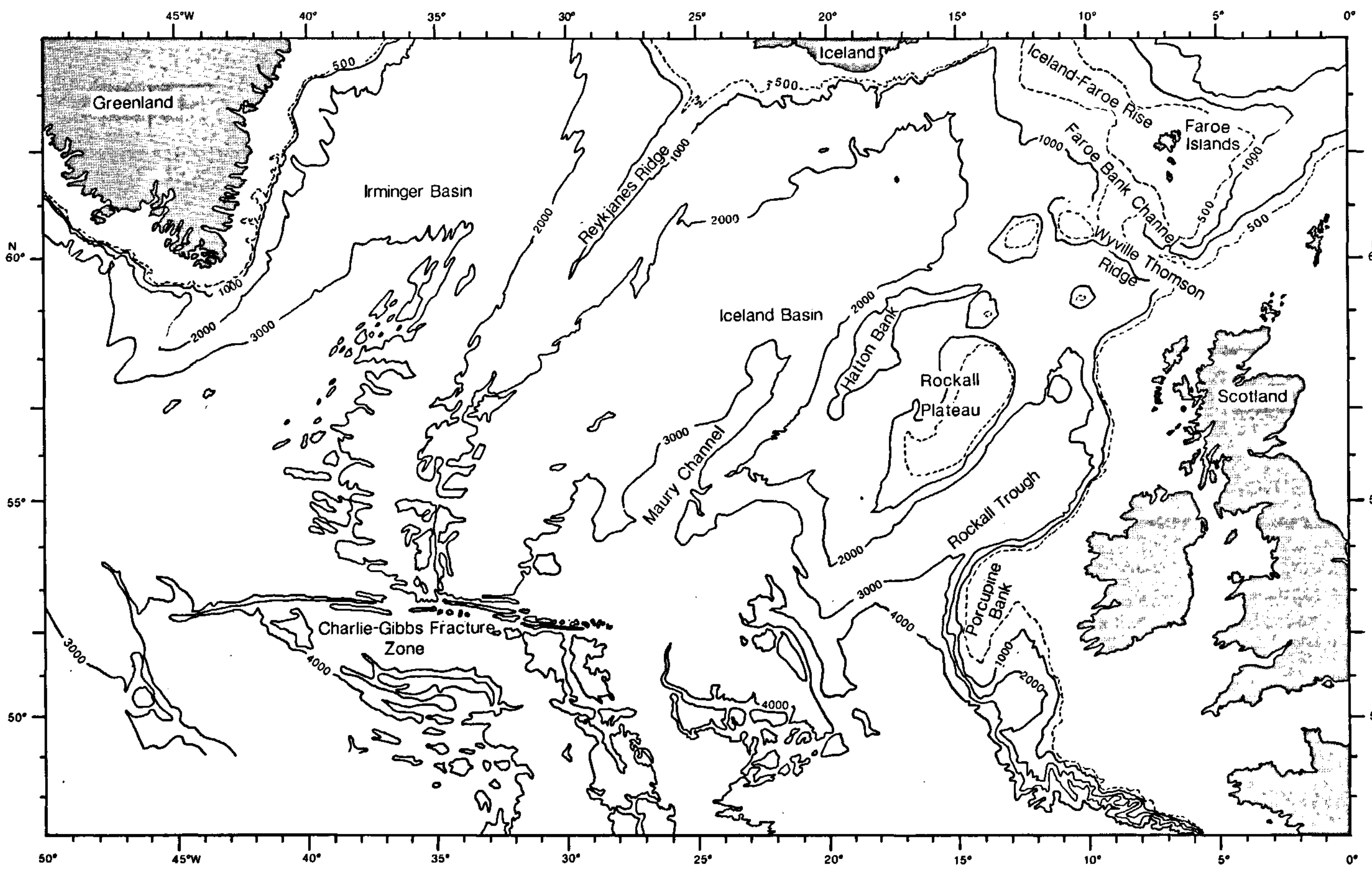

Figure 1
Area of study.

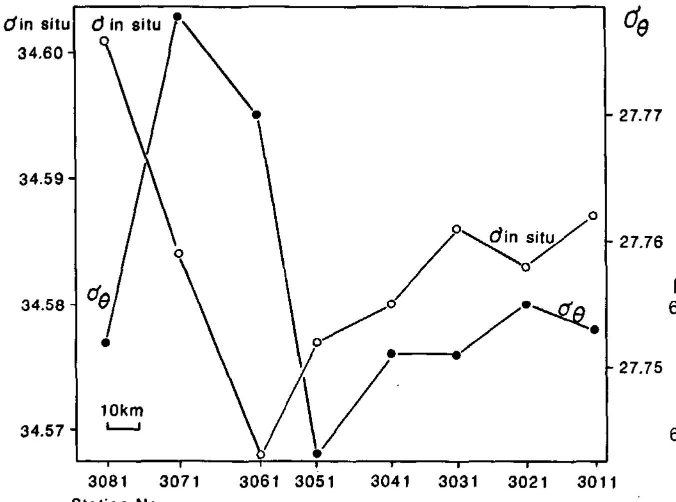

Figure 2
$\sigma_{in\ situ}$ *and* σ_θ *at 1 500 db along 47°N netween 14° and 16°W.*

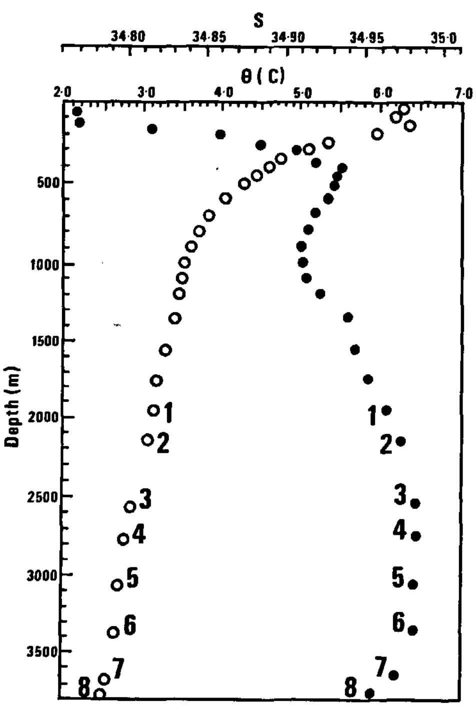

Figure 3
Vertical profiles of potential temperature, θ (○), and salinity, S (●), at Atlantis II station 365. The numbers 1 to 8 indicate the values used to delineate the neutral surfaces. For a θ-S diagram of the water with θ<4°C at this station see Harvey (1980), *Figure 2.*

we have identified a series of "neutral surfaces" which are intended to be normal at every point to the gradient of potential density which is referenced to the pressure at the point in question, and thus along which water parcels can be inter-changed without any work being done against buoyancy forces. For this we took a set of water parcels with temperatures and salinities as observed at eight depths from 1 949 to 3 748 m (*see* Fig. 3) at Atlantis II station 365 (52°44′N, 35°35′W, 10 April 1964) which was identified as being in the course of the overflow water as it passes from the eastern to the western basins of the North Atlantic through the CGFZ (Harvey, 1980). The levels at which the adiabatic density gradients for each of these eight parcels intersect the *in situ* density profile at each station in the data set determine the levels of each of the eight neutral surfaces at that station. The results for neutral surfaces 1,4 and 8 (Fig. 4*a*, *b*, *c*) show all to be at less than 400 m on the Iceland-Faroe rise and to descend to depths in excess of 2 600, 3 000 and 3 600 m

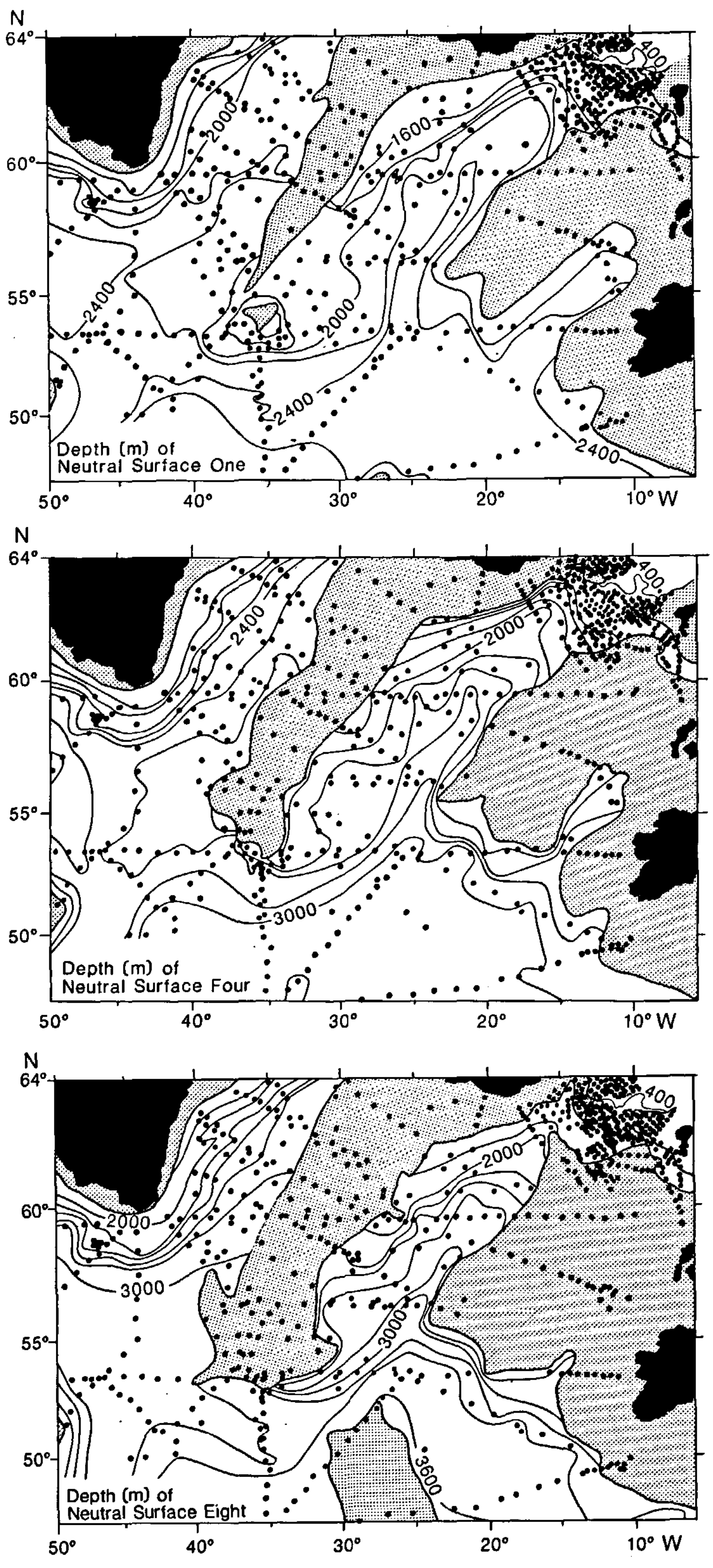

Figure 4
Topography (m) of neutral surfaces:
a) neutral surface 1; b) neutral surface 4; c) neutral surface 8.

respectively. All of the surfaces slope up towards the eastern side of the Reykjanes Ridge and towards the northern side of the CGFZ: there is also a slope upwards towards the eastern side of Greenland associated with the Denmark Strait overflow.

SALINITY DISTRIBUTION

Salinity is believed to be a conservative water mass characteristic, and thus the distribution of salinity on these neutral surfaces (Fig. 5) may provide a first indi-

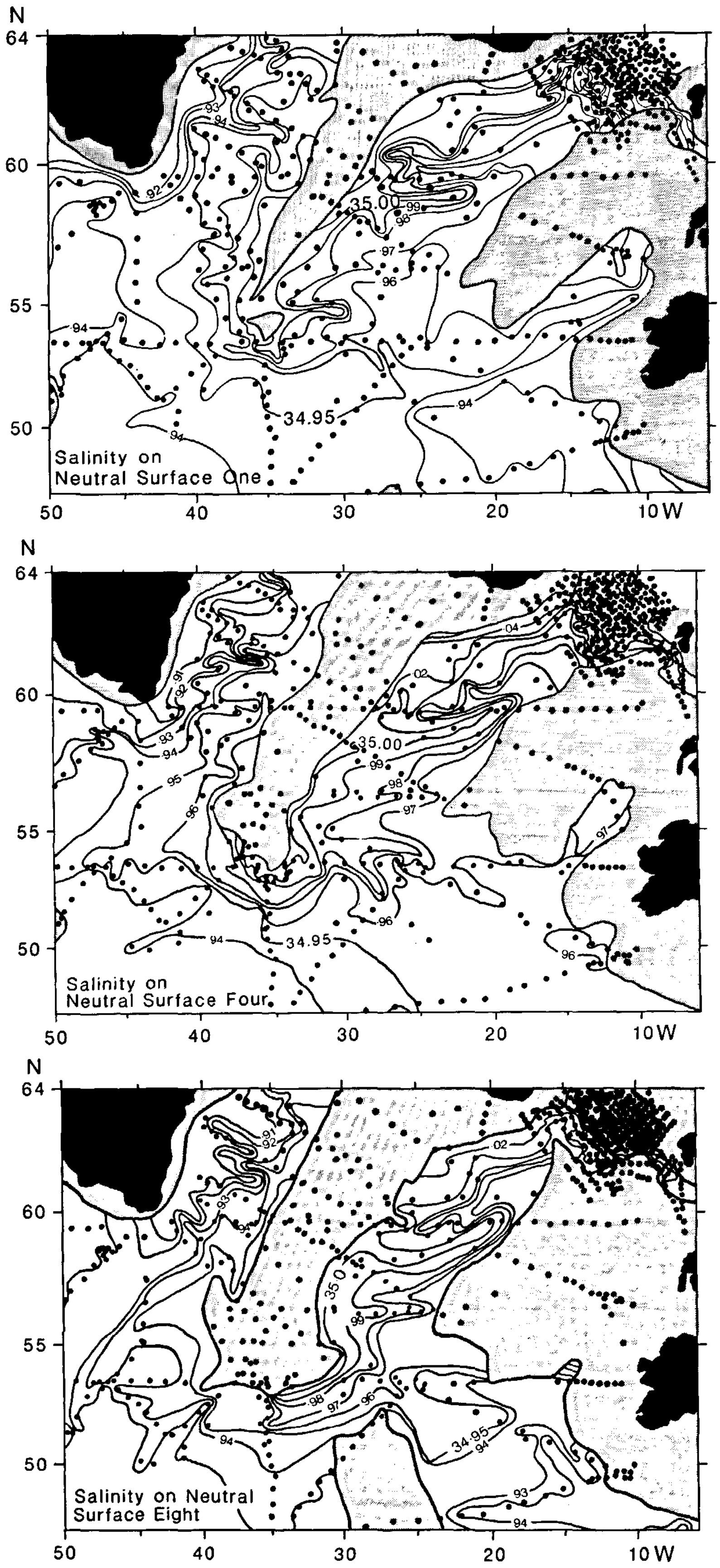

Figure 5
Salinity on neutral surfaces:
a) neutral surface 1; b) neutral surface 4; c) neutral surface 8.

Table 1
Successive mixing stages of Iceland-Scotland overflow water.

	NEAW	NI/AI	LSW	ISOW	$ISOW_1$	$ISOW_2$
First mixing stage	19	+ 13		+ 68%	= 100%	
Second mixing stage	8		+ 25%		+ 67%	= 100%
Thus $ISOW_2$ comprises						
ISOW: 67 of 68%			= 45%			
NEAW: 8% + 67 of 19%			= 21%			
NI/AI: 67 of 13%			= 9%			
LSW:			25%			
			100			

cation of circulation patterns; ISOW is characterised by relatively high salinities for its density range. Salinity has been estimated by linear interpolation at the level of each of the neutral surfaces at each station from the available observations above and below. In interpreting the patterns it must be appreciated that salinity along each line of stations may show mesoscale variability, and that differences between adjacent lines of stations may result from changes with time or may be artefacts resulting from differences in salinity determinations. Nevertheless, many features stand out clearly:

1) The tongue of higher salinity water extending southwards on the eastern side of the Reykjanes Ridge and, particularly on the shallower surfaces, continuing northwards on the western side of the ridge.

2) Plumes of higher salinity water extending eastwards or north eastwards across the Iceland Basin which might indicate paths of cyclonic circulation in this basin. Further indications of such a circulation are presented by McCave *et al.* (1980).

3) A source of higher salinity water at the northern end of the Rockall Trough, attributable to overflow across the Wyville-Thomson Ridge.

4) A source of higher salinity water in the south-east, attributable to outflow from the Mediterranean Sea (the influence of this water at depths down to 3000 m and latitudes up to 52° N has already been noted by Harvey, 1982).

WATER MASS ANALYSIS

Our purpose here was to determine the percentage of ISOW present at each observation and at each neutral surface at all stations. For many of the stations we had

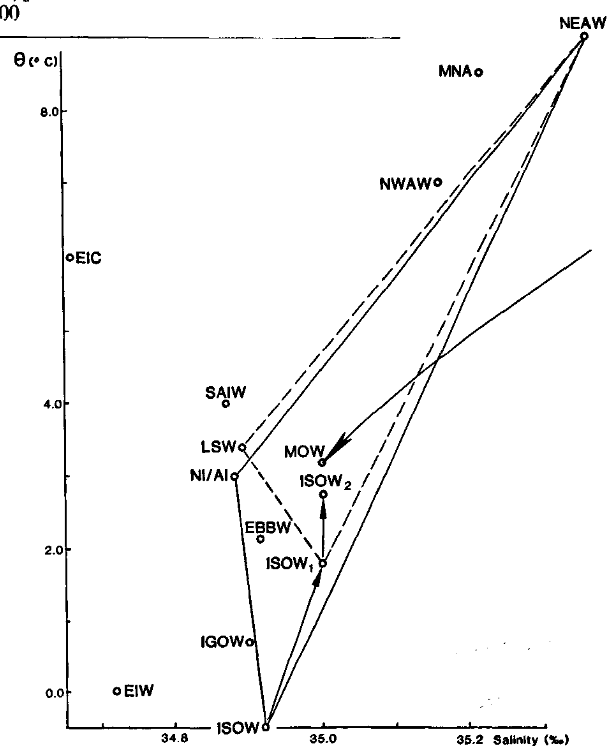

Figure 6
θ-S characteristics of water masses with which Iceland-Scotland overflow water (ISOW) may mix and successive mixing stages of ISOW.
NEAW North East Atlantic water;
MNA Modified North Atlantic water;
NWAW North West Atlantic water;
MOW Mediterranean outflow water;
EIC East Icelandic current water;
SAIW Sub-Arctic intermediate water;
LSW Labrador Sea water;
NI/AI North Icelandic/Arctic intermediate water;
EBBW Eastern basin bottom water;
IGOW Iceland-Greenland overflow water;
EIW East Icelandic winter water;
(see *Theodorou, 1983, Tab. 7.0, for a summary of previous definitions appearing in the literature*).

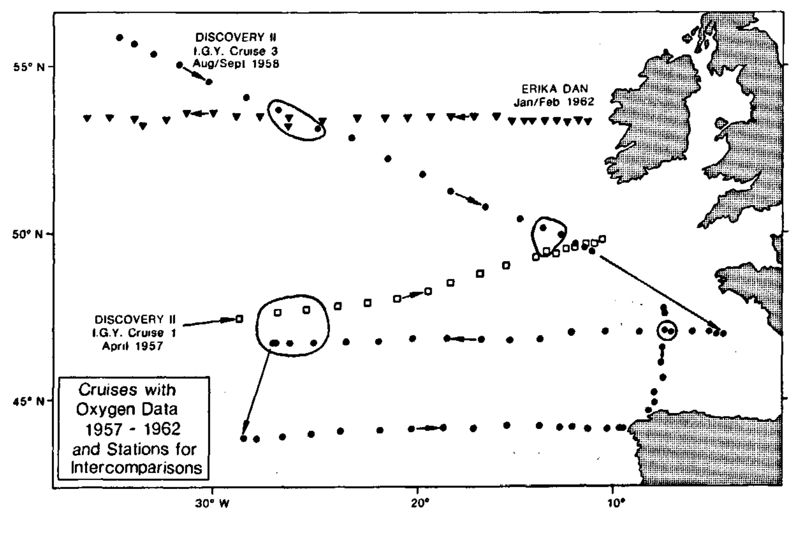

Figure 7
Stations with dissolved oxygen data, 1957-1962. Those used for intercomparisons are enclosed with a thick line.

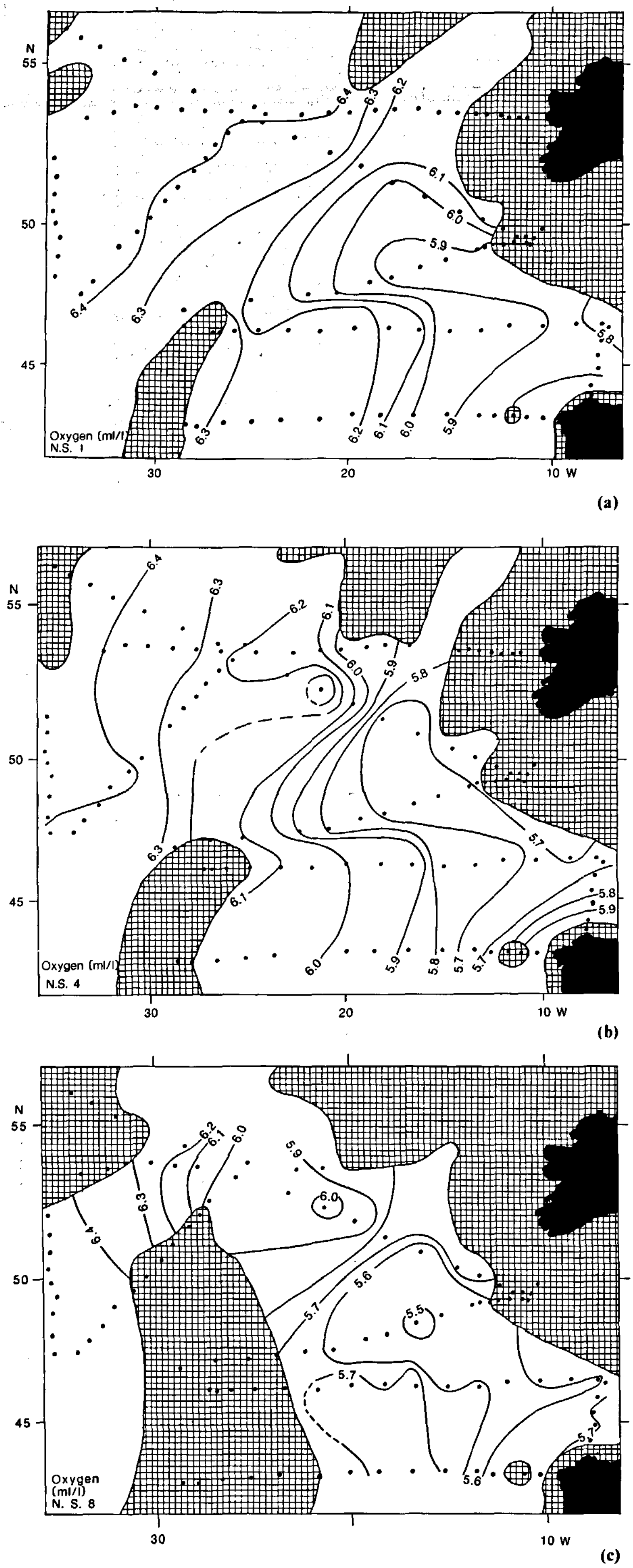

Figure 8
Dissolved oxygen concentration (ml l^{-1}) on neutral surfaces: a) neutral surface 1; b) neutral surface 4; c) neutral surface 8.

only two water mass characteristics available—θ and S, and using the classical θ-S diagram method (*e.g.* Hermann, 1967) we could determine the relative contribution of three water masses each defined by a single point on the θ-S diagram. In its passage from the Iceland-Scotland Ridge through the CGFZ into the Irminger Sea we found, however, that there are perhaps eleven other water masses already identified in the literature (*see* Fig. 6) with which it mixes. To proceed we defined successive "mixing stages" of the overflow water along its path. These were based on composite θ-S diagrams for various geographical areas. The first involved NEAW and NI/AI with ISOW to give $ISOW_1$, and a second involved NEAW and LSW with $ISOW_1$ to give $ISOW_2$ (Fig. 6). The composition of $ISOW_2$ is set out in Table 1. Each mixing stage could, in turn, mix with any two other water masses. This still left us with a region where the high salinity influences of ISOW and MOW are both apparent, and where at least two further water masses (LSW and EBBW) are involved. To resolve this problem we introduced a third water mass characteristic, dissolved oxygen, which was measured in the region concerned during the Discovery IGY cruises (1957-1958) and later Erika Dan and Atlantis cruises (1962-1964).

Dissolved oxygen as a water mass characteristic

Dissolved oxygen is not a conservative parameter, but we have ignored the depletion of oxygen which, in such deep water (>2200 m) has been estimated by other authors to be of the order 0.1 ml l^{-1} per 100 yr, or less (Wright, 1969; Johnston, 1977; Jenkins, 1980). A more difficult problem to resolve was the differences in standardisation of the oxygen titrations on the IGY cruises which have been discussed by Worthington (1959), McGill (1964) and Carritt and Carpenter (1966), and which have led many authors to omit these data from their considerations. Intercomparisons of data where lines of stations intersect or approach one another (Fig. 7) have led us to conclude, however, that within individual cruises data are consistent, and good agreement between cruises can be achieved by applying a factor of 1.08 to Discovery IGY cruise 1 stations and of 1.02 to Discovery IGY cruise 3 stations. For absolute values, this assumes that Erika Dan data are reliable; some confirmation of this has been found from comparisons with recent TTO data, though particularly in view of recent findings (Brewer *et al.*, 1983) it is dangerous to assume that no real changes have occurred over this period of time.

The corrected oxygen data for the limited region under study (Fig. 8) show values increasing from south-east to north-west on neutral surface 1, whilst on neutral surfaces 4 and 8 the lowest values occur fairly centrally in the eastern basin at about latitude 48°N and the area of high values retreats into the western basin as depth increases. Comparing these values with the

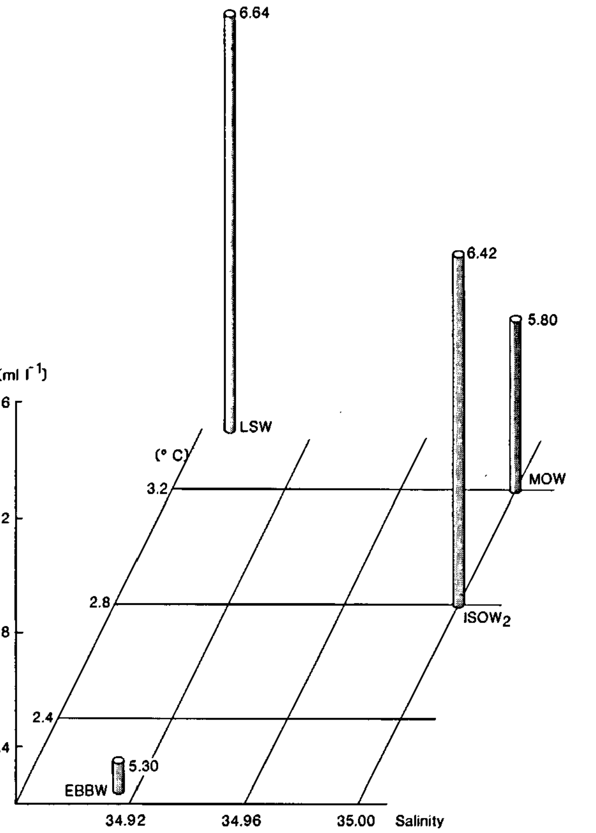

Figure 9

Dissolved oxygen values (ml l^{-1}) assigned to EBBW, LSW, ISOW$_2$ and MOW.

results of the θ-S analyses, we have assigned oxygen values to the EBBW, LSW and $ISOW_2$ which have already been defined by single values of θ and S, and we have assigned θ, S and oxygen values to MOW for this region on the basis of the observation at 2 360 m at Discovery II station 3870 (46°30′N, 7°07′W; Fig. 9). The percentage concentrations of ISOW on each neutral surface at each station throughout the area of interest were then determined either using three-point θ-S mixing diagrams with successive mixing stages of ISOW or the four-point θ-S-O_2 mixing diagram with EBBW, LSW, $ISOW_2$ and MOW. The results (Fig. 10) show close agreement with the salinity distributions (Fig. 4): apart from the Iceland-Faroe rise area, the highest percentages at any location are generally found on neutral surface 4 on which more than 40% concentrations are found within the CGFZ; the high concentrations found to the west of Hatton Bank appear to be more closely related to cyclonic circulation cells in the Iceland Basin than to the overflow into the Rockall Trough; in the south-eastern part of the region, where MOW is encountered, percentages of ISOW are generally less than 15%.

GEOSTROPHIC TRANSPORTS

We have calculated geostrophic currents across 12 sections (Fig. 11), each section having been worked by one ship on one cruise (Tab. 2). After consideration of the reference levels selected by previous workers for geostrophic computations in this region (*see*, for example, Worthington, 1976; and Ivers, 1975) we have somewhat arbitrarily selected the depth of the 10% ISOW surface (above its core) as a reference level

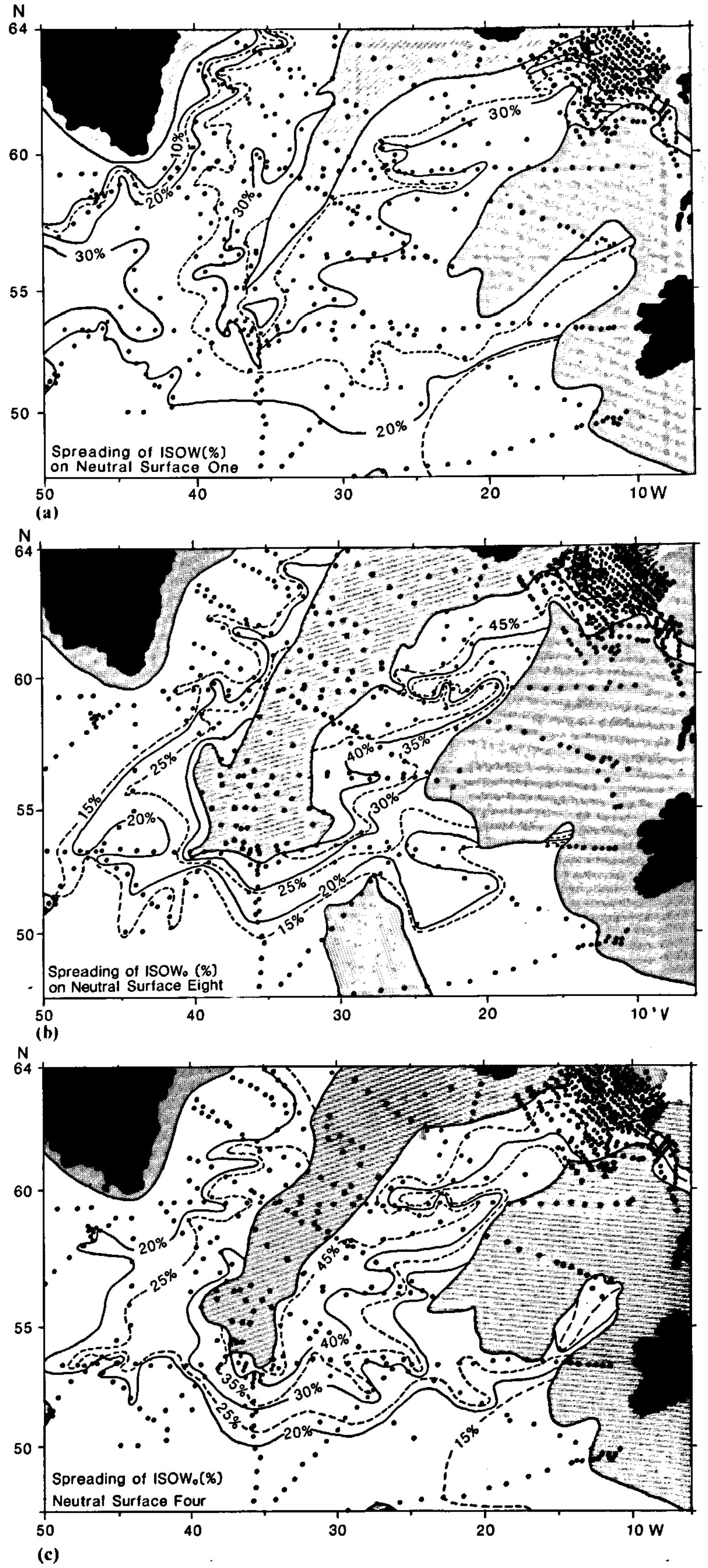

Figure 10

Spreading of ISOW (%) on neutral surfaces:
a) neutral surface 1; b) neutral surface 4; c) neutral surface 8.

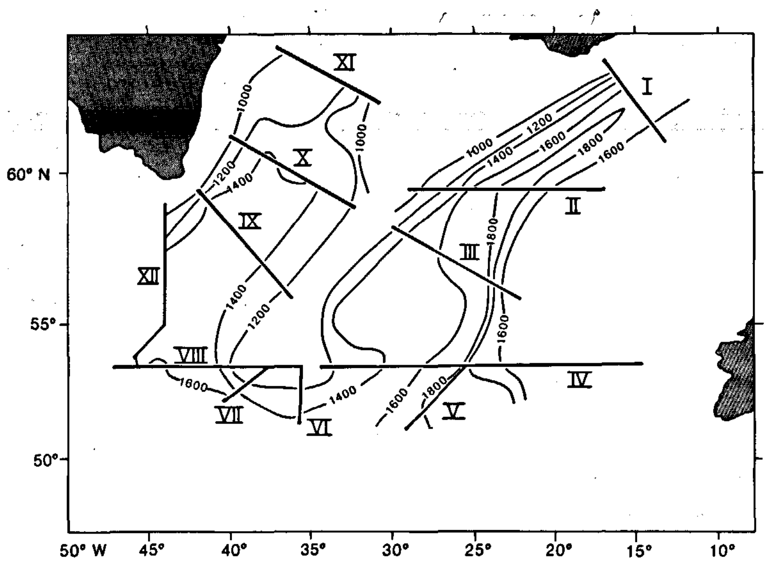

Figure 11
Sections used for geostrophic current calculations and depth (m) of selected reference level of no motion.

Table 2
Sections used for geostrophic calculations.

Section	Ship	Dates
I	Chain	October 1960
II	Erika Dan	April 1962
III	Hudson	February 1967
IV	Erica Dan	January 1962
V	Atlantis	Jan./Feb. 1964
VI	Atlantis	April 1964
VII	Erika Dan	April 1962
VIII	Erika Dan	February 1962
IX	Erika Dan	April 1962
X	Hudson	February 1967
XI	Hudson	March 1967
XII	Erika Dan	March 1962

Table 3
Volume Transport (Sv) through a composite section from Greenland to Porcupine Bank (transport north-eastwards positive).*

Part of section	Above ZL	Below ZL	Total
Greenland-Reykjanes Ridge	—0.2	—7.4	—7.6
Reykjanes R.-Rockall Plateau	—3.5	—3.6	—7.1
Rockall Pl.-Porcupine Bank	+15.3	—1.2	+14.1
TOTAL	+11.6	—12.2	—0.6

* 1 Sv = 10^6 m^3 s^{-1}.

of no motion in order to determine absolute current velocities across these sections. Total transports were computed in a composite section from Greenland to the Porcupine Bank, comprising sections X, III and the eastern part of IV, and the total flux (Tab. 3) is sufficiently close to zero to support our choice of reference level.

Total transports of deep water beneath the reference level were computed using a "balancing within the error" scheme to preserve continuity, errors having been estimated to be about $\pm 20\%$ (*see* Theodorou, 1983). The results (Fig. 12) show inputs of 4.5 Sv between Faroe Bank and Iceland, 1.0 Sv into Rockall Trough from the north, 5.0 Sv through the Denmark Strait, 1.5 Sv from the south-east and 1.0 Sv entrained from above (LSW) which is indicated schematically to occur in the CGFZ. Of these 13 Sv, 10 Sv flow south-westward in the western boundary undercurrent and 1.5 Sv enters the interior of each of the eastern and western basins. The main features agree well with those presented by Worthington (1976) for deep ($\theta < 4$°C) circulation in the North Atlantic, but here we present considerably more detail of the pattern in the eastern North Atlantic.

Finally, using the geostrophic calculations together with the computed percentages of ISOW present in each of the sections, we present (Fig. 13) a schematic circulation pattern for this water alone. Total inputs

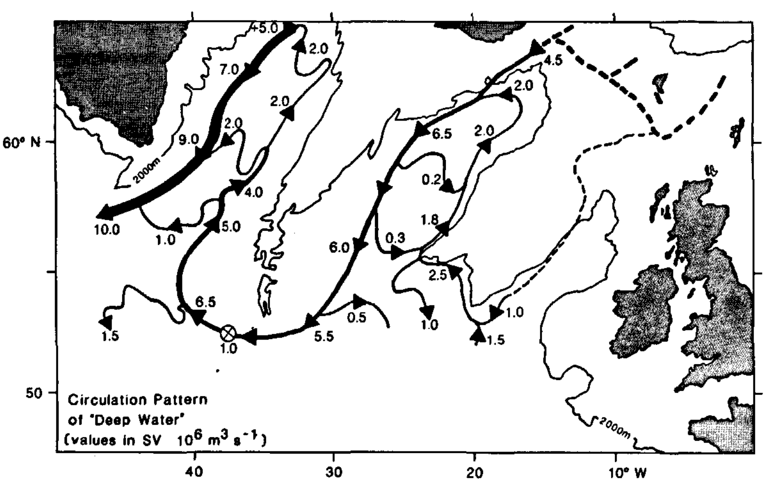

Figure 12
Circulation pattern of deep water (below the reference level in Fig. 11) (values in Sv=10^6 m^3 s^{-1}).

are 1.8 Sv (1.5 Sv between Faroe Bank and Iceland and 0.3 Sv over the Wyville-Thomson Ridge). These values are in close agreement with those presented by Meincke (1983) based on combined current measurements and water mass analyses over the Greenland-Scotland ridge using data since 1973. They are, however, somewhat higher than those suggested by McCartney and Talley (1984) who estimate from water mass conversion rates that the total outflow of cold dense water from the Norwegian Sea (including that through the Denmark Strait) is only 1.7 Sv. After some re-circulation in the eastern basin we show all of the 1.8 Sv inflow to pass through the CGFZ into the western basin where 1.2 Sv joins the western boundary undercurrent and 0.6 Sv enters the interior of this basin.

that seasonal and year-to-year variations each accounted for only a small part (about 10%) of the total variance. Further, this study has mainly used observations at discrete depth intervals made with sampling bottles and reversing thermometers, and considerable interpolation has been necessary to identify patterns on particular surfaces. The water mass analyses have required restrictive assumptions about the numbers of water masses interacting in any particular area and have required each of these water masses to be specified by single values of temperature and of salinity (and where used of dissolved oxygen). Geostrophic current calculations involve a number of simplifying assumptions, but that of a motionless reference level is likely to be the least realistic. It is possible that some features found, such as the deep cyclonic circulation in the

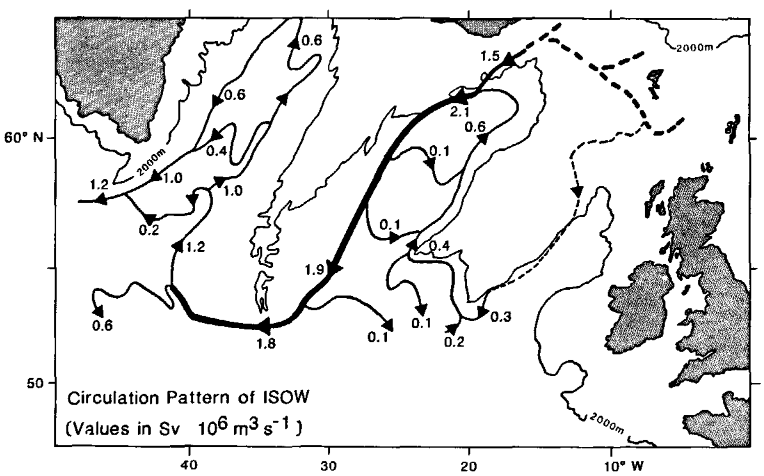

Figure 13
Circulation pattern of ISOW (values in $Sv = 10^6\ m^3\ s^{-1}$).

CONCLUDING REMARKS

This study is based on data collected over a period of 20 years, and assumes that steady state conditions have existed over this period of time. The non-synopticity of this data, and the possibility that there may be both seasonal and year-to-year variations in the circulation pattern being investigated which would distort this analysis, must not be overlooked. Shor *et al.* (1980) found that monthly discharges to the west below 2 000 m through the northern valley of the CGFZ, estimated from direct current measurements between October 1975 and June 1976, varied between 0 and 4.7 Sv. On the other hand Harvey (1980) examining values of the salinity maximum in 101 profiles at Ocean Weather Station C in the CGFZ between 1964 and 1973 found

Iceland Basin, result from the non-synoptic character of the data base. Nevertheless, a picture has been obtained which is not only internally consistent, but which while being in general agreement with earlier studies adds considerable quantitative detail to them.

Acknowledgements

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