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Aspects of the circulation in the Rockall Trough

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Abstract

An investigation is made of the circulation and structure of the water masses in the Rockall Trough in spring, combining the results of a recent synoptic survey (May 1998) with those from a high-resolution ocean circulation model. In the near-surface layer, saline flows are carried northwards by a "Shelf Edge Current" around the eastern slopes, possibly with some branching in the northern Trough. Fresher waters from the west inflow between 52 and 53°N and partially mix with these saline flows in the southern Trough, so that waters of intermediate salinity are also swept northwards. In the southern approaches to the Trough, Labrador Sea Water (LSW) also flows strongly in from the west between 52 and 53°N, and while much of this turns south, a proportion penetrates north to join a cyclonic gyre in the Trough extending to 56.5°N. The northwestern limb of this gyre is fed by, and mixes with, more saline waters which result from overflows across the Wyville–Thomson Ridge. Furthermore, salinity and CFC data suggest episodic inflow of LSW into the central Trough. The circulation of the North East Atlantic Deep Water in the Trough follows a cyclonic pattern similar to, and lying below, that of the LSW. The Wyville–Thomson Ridge overflows in the model extend to higher densities than in the survey, are topographically steered southwestward down the Feni Ridge system, and eventually join a deep cyclonic circulation in the North East Atlantic basin. Overall, the model and the observations are in good agreement, particularly in the central Rockall Trough, and this has allowed conclusions to be drawn which are significantly more robust than those which would result from either the survey or the model alone. In particular, we have been able to infer cyclonic circulation pathways for the intermediate and deeper waters in the Rockall Trough for (we believe) the first time. The study has also contributed to an ongoing community effort to assess the realism of, and improve, our current generation of ocean circulation models. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: North East Atlantic Ocean; Rockall Trough; Circulation; Upper Ocean; Labrador Sea water; North East Atlantic deep water; Observations; Model

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1. Introduction

The Rockall Trough (marked as RT in Fig. 1) is a deep channel bounded to the west by the Rockall Bank (RB in Fig. 1, which rises to the surface at 13.5°W, 57.5°N) and it extends southwestward into deep water, and to its east is the Porcupine Bank (P in Fig. 1, shallowest near 13.5°W, 53.5°N) and the continental slopes of Ireland and Scotland. The Trough shoals from 3500–3000 m deep at it southern end (53°N), where it is open to the wider Atlantic, to 1500–1000 m at its northern end (59–60°N), where it is bounded to the north by the

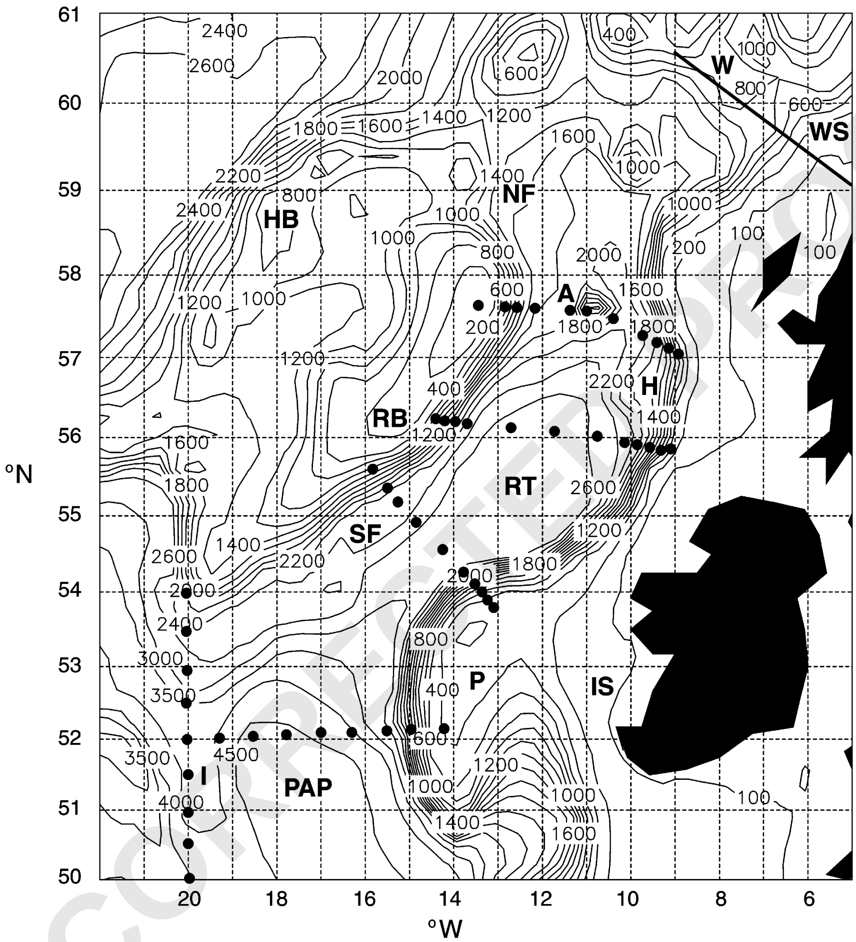


Fig. 1. Topography of the Rockall Trough and environs contoured from the model bathymetry (m), and selected CTD station positions (filled circles) from the "CHAOS" survey in May, 1998. Depth contours are shown at 100 m, every 200 m between 200 and 2600 m, 3000 m, and thereafter at 500 m intervals. The thick line between 60.6°N, 9°W and 59.1°N, 5°W represents the section across the Wyville–Thomson Ridge used for Fig. 6. The locations of the following features, referred to in the text, are also shown: Rockall Trough (RT); Rockall Bank (RB); Hatton Bank (HB); Wyville–Thomson Ridge (W); West Shetland Shelf (WS); Irish Shelf (IS); Hebrides Terrace Seamount (H); Anton Dohrn Seamount (A); Porcupine Bank (P); North and South Feni Ridge (NF and SF); Isengard Ridge (I); Porcupine Abyssal Plain (PAP).

Wyville–Thomson Ridge (W, 500–600 m deep in nature) and to the northwest by a chain of hemispherical seamounts (with connecting sills near-1200 m deep). It is potentially important in the context of understanding climate variability to elucidate the flows through the Rockall Trough, since this region provides a conduit for saline water masses of southern origin to transit northwards into the Nordic Seas where they could affect deep convection, and hence play a key role in the thermohaline overturning circulation (and heat transport) of the Atlantic Ocean (Reid, 1979; New et al., 2000).

Wintertime mixing of the near-surface layers in and around the Rockall Trough has in recent decades usually occurred to depths of 500–700 m (Ellett and Martin, 1973; Meincke, 1986; Holliday et al., 2000), but there is evidence of deeper mixing, possibly to 1000 m, in the 1930s (Ellett et al., 1986) and the 1950s (Fuglister, 1960) at least. This mixing forms relatively homogeneous upper layer waters, and these were identified as a saline Eastern North Atlantic Water (ENAW) entering the Trough from the south, and a fresher Modified North Atlantic Water entering from the northwest by Ellett et al. (1986). These are varieties of the Subpolar Mode Waters that generally circulate cyclonically in the North Atlantic, becoming progressively cooler and fresher as they do so (McCartney and Talley, 1982). The ENAW, more saline than the "North Atlantic Central Water" (NACW) in general, forms in the Bay of Biscay (Pollard et al., 1996), and moves northwards around the Porcupine Bank into the southern Rockall Trough (Ellett and Martin, 1973). It is carried at least partly by a poleward "Shelf Edge Current (SEC)" around the upper slopes of the Irish–Scottish shelves, and reaches the northern Rockall Trough and beyond (Ellett and Martin, 1973; New et al., 2000). However, the impact of fresher water masses from the west, generally termed Sub-Arctic Intermediate Water (SAIW, Ellett et al., 1986) may also be important. These upper layer water masses may often be carried by a branch of the North Atlantic Current which sweeps eastwards from the western North Atlantic before turning northwards and branching into the Trough (Pingree, 1993; McCartney and Mauritzen, 2000), mixing with the more saline ENAW as it does so (Ellett et al., 1986).

Whilst the characteristics of the SEC as it flows through the Trough are now known reasonably well, and summarised by Huthnance (1986), the upper layer circulation pathways over the deeper Trough are less certain. The SEC is associated with a high-salinity core in the upper 400 m of the water column which typically contains maximum salinities near 35.4, although these generally decrease to the north (Ellett and Martin, 1973; Hill and Mitchelson-Jacob, 1993; White and Bowyer, 1997). Flow speeds are typically 15–30 cm s^{-1} in the current, which is usually about 50 km wide, and transport estimates range is 1.2–3.0 Sv (Huthnance, 1986; Holliday et al., 2000). The continuity of the SEC has moreover recently been demonstrated by Pingree et al. (1999), who deployed a drifting buoy which was transported from 54°N on the Irish shelf (IS in Fig. 1) to 61°N on the West Shetland shelf (WS in Fig. 1). In deeper water, geostrophic estimates (Ellett and Martin, 1973; Holliday et al., 2000) on sections near 57–58°N show a significant northward flow (termed the "Rockall Trough Current") in the upper layer on the western side of the Trough. This flows to the west of the Anton Dohrn Seamount (A in Fig. 1, with a summit near 11°W, 57.5°N), although there is a southward flow on its eastern side, indicating an anticyclonic circulation around the Seamount. There is often also a narrow southward flow of MNAW on the eastern flanks of the Rockall Bank. The net transport (in the upper 500 m) of the flows over the deeper Trough was estimated as 2.7 Sv by Ellett et al. (1986). These authors also attempted a summary circulation schematic for the upper layers, using long-term temperature profiles, geostrophic velocity estimates and available current meter data. Warning that this should be treated with caution, they suggested that the southern inflows, occurring around the western side of the Porcupine Bank, divide on its northern slopes near 54°N to form a continuing SEC, and a second branch flows northwards over the deeper water of the central Trough. This latter branch forms the Rockall Trough Current before re-merging with the SEC near 58–59°N, the whole then flowing on northwards over the Wyville–Thomson Ridge into the Nordic Seas.

Below the near-surface layer, Reid (1979) conjectured that Mediterranean Overflow Water (MOW) would flow northwards as a high-salinity core in an eastern boundary undercurrent, typically at depths 1000–1200 m. The MOW core was conjectured to flow along the eastern slopes of the Rockall Trough, following a density surface rising over the Wyville–Thomson Ridge, and eventually reaching the Nordic Seas. Furthermore, Ellett et al. (1986) remark that the MOW in the Trough is identified by an oxygen minimum and by an "inflexion" in the depth profiles of salinity (forming a region of slightly enhanced salinity). The presence of the MOW in the Trough has, however, recently been called into question by McCartney and Mauritzen (2000), who found, on the basis of regional water mass distributions and geostrophic shear, that the MOW did not penetrate further northwards than about the Porcupine Bank. Also, New et al. (2000), from a modelling study, raised the possibility that the high salinities near 1000 m in the Trough could have been caused by saline waters subducted just northwards of the Wyville–Thomson Ridge, which would then flow southwards and descend on a density surface matching that of the MOW.

Deeper in the water column, the presence of Labrador Sea Water (LSW) in the Rockall Trough is unambiguous. This water mass typically occurs in the depth range 1600–1900 m, and is denoted by a marked salinity minimum (and densities near 1027.7–1027.8 kg m^{-3}). It has been clearly noted in the Trough by Ellett and Martin (1973) and Ellett et al. (1986) as far north as 57.5°N, who remarked that, since there are no exit channels in the north of the Trough deeper than 1200 m, the LSW must both inflow and outflow through the southern entrance. Furthermore, Holliday et al. (2000), analysing the LSW variability at 57.5°N and finding that this was larger than the magnitude expected from changes in the source characteristics, raised the speculation that the LSW could flow into the Trough in a series of periodic pulses. However, although it is possible to infer a weak cyclonic circulation for the deeper water masses from a geostrophic velocity section near 57°N in Ellett and Martin (1973, by assuming a level of no motion near 1000 m), none of these authors attempted to define a circulation pathway for the LSW in the Trough. Paillet et al. (1998), on the other hand, traced hydrographic parameters and deduced that the LSW would circulate anticyclonically near the southern entrance to the Trough. They indicated LSW flowing eastwards across 25°W near 51–53°N, and then turning largely southwards near 20°W, but with a secondary branch continuing on eastwards and southeastwards into the northern Bay of Biscay. However, these authors also made no attempt to suggest a circulation pathway by which the LSW might enter and circulate around the Trough.

In the north, Norwegian Sea Deep Water (NSDW) is known to flow southwards over the Wyville–Thomson Ridge and into the Rockall Trough. Although reliable estimates of the amounts which do so are not yet known, fluxes at the ridge crest may be typically 0.3–0.4 Sv (Ellett et al., 1986; van Aken and Becker, 1996), though there may be a large seasonal variability, being greatest in the summer (Dickson et al., 1986). At the general level of the ridge crest (500–600 m) in the Norwegian Sea, the NSDW has a salinity near 34.94, temperatures close to 1°C, and a density near 1028.0 kg m^{-3} (Ellett et al., 1986). This is denser than the water masses so far discussed, and therefore sinks as it moves southwards into the Trough. There is much mixing with and entrainment of the surrounding waters as it does so, and the net result is the formation of a deep salinity maximum below the LSW minimum (Ellett et al., 1986), typically between 2300 and 2500 m depth (Ellett and Martin, 1973; van Aken and Becker, 1996). Near the southern entrance to the Trough, this salinity maximum may also derive from products of NSDW which have overflowed the Iceland–Faeroe Ridge or the Faeroe Bank Channel and circulated southwards around the western flanks of the Hatton (HB in Fig. 1) and Rockall (RB) Banks (Ellett and Martin, 1973). This salinity maximum was called North East Atlantic Deep Water (NEADW) by Ellett and Martin (1973), who showed it was associated with an oxygen maximum.

Ellett and Martin (1973) also remarked that the NEADW in the Trough is associated with high levels of silicate, indicating a southern influence. Van Bennekom (1985), for instance, has shown that the deepest waters (below 3000 m) in the northeast Atlantic are rich in silicate derived from the Antarctic Bottom Water (AABW). The AABW is likely to flow northwards along the eastern side of the northeast Atlantic, following the circulation schematics for the deepest flows of Lonsdale and Hollister (1979) and Van Aken and Becker (1996). These silicate-rich waters were presumed by Ellett and Martin (1973) to be subject to a general vertical diffusion, possibly in the European Basin, mixing the high silicate values upwards into the NEADW water masses, which would then circulate into the Rockall Trough.

The pathways by which these intermediate and deeper water masses enter and circulate around the Rockall Trough, however, are not well understood or described. Nonetheless, Lonsdale and Hollister (1979) have at least inferred a general cyclonic circulation for the bottom-most waters in the Trough from bedform features observed in the sediments. They reported evidence for erosive northeasterly currents at LSW and NEADW depths on the Irish slopes. These were inferred to turn westwards in the central Trough, and then flow southwestwards again, exiting the Trough around the southern extremes of the Rockall Bank. These southwesterly bottom flows were thought to occur primarily on the southeastern side of the South Feni Ridge (SF in Fig. 1), and on the lower slopes of the Rockall Bank (both near 2400 m depths at 55°), which are areas being built up by the deposition of the bottom sediments suspended from the Irish slopes. These authors also presented evidence of southerly bottom flows along the North Feni Ridge (NF in Fig. 1), indicating the presence of derivatives of NSDW which have overflowed the Wyville–Thomson Ridge.

Furthermore, Van Aken and Becker (1996) estimated geostrophic transports for the deepest waters (denser than 1027.80 kg m^{-3}) in the northeast Atlantic. They indicate 0.4 Sv of NSDW-derived waters flowing southwestwards through the western Rockall Trough, and 3.8 Sv of deeper waters (NEADW and deeper) flowing northwards along the western slopes of the Porcupine Bank. Of these, 0.9 Sv are shown as circulating cyclonically into the southern Trough (reaching only 55°N), while the remainder pass the southern entrance to the Trough in a northwesterly direction.

However, geostrophic estimates such as these are subject to the problems of the choice of an arbitrary level of no motion, and to the possibility that the flow may not be solely geostrophic in this region of complex topography and narrow currents. In addition, geostrophic estimates, ADCP and current meter measurements are likely to be contaminated by internal tides (internal oscillations of tidal period) which are known to exist around the UK and Irish continental margins (Sherwin, 1988; New, 1988), so that long periods of measurement would be needed to average out the resulting fluctuations. This appears to have been undertaken primarily only for the upper layer flows in the Shelf Edge Current (Huthnance, 1986).

In view of this limited knowledge, the main goal of the present study is therefore to gain further insight into the pathways and processes by which the various water masses move through and around the Rockall Trough. To do this we combine hydrographic and chemical observations from a recent quasi-synoptic survey of the Trough with results from a high-resolution ocean circulation model. Although the observations are sparse and represent a single "snapshot" of the flow regime, the deductions which are made are significantly strengthened by comparison with the model output. Conversely, this novel approach also provides an examination of the validity of the model and thereby contributes to an ongoing community effort to assess the realism of our current generation of ocean models. Overall, we feel that considerable synergy is demonstrated by combining the observations and the model in this way.

The paper focuses on suitable combinations of the observational and model data to deduce the flow patterns at a range of depths in and near the Rockall Trough, and is laid out in the following way. After a description of the observational survey and model (Section 2), and a preliminary comparison of the water masses (Section 3), the circulation and structure of the upper layer is examined in Section 4. This is followed by an investigation of the (model) Wyville–Thomson Ridge overflows in Section 5, and of the circulation of the Labrador Sea Water in Section 6. Section 7 then examines the deeper water masses, and finally, the results are summarised and discussed in Section 8.

2. Survey and model

The observational survey of the Rockall Trough and its neighbourhood was made in May 1998 during R.R.S Discovery Cruise 233 (CHAOS: a Chemical and Hydrographic Atlantic Ocean Survey, Smythe-Wright, 1999). The cruise commenced with a long meridional section along approximately 20°W from 20°N to Iceland, together with a zonal section to the shelf edge near 52°N. This was followed by a section across the Iceland Basin and Rockall Plateau, and then by three quasi-zonal sections of the Rockall Trough (see Fig. 1). This paper is primarily concerned with data from the sections in the Trough, which were at nominal latitudes of 57°N (actually between 57 and 57.5°N), 56 and 54°N (between 55.5 and 54°N). Data will also be drawn from the sections to the southwest of the Trough (at 20°W and 52°N) where appropriate. Full-depth CTD-Oxygen stations were made to WOCE standards at every 0.5° latitude (56 km) along 20°W, and at spacings between 5 and 40 km in the Trough, the finer spacing being coincident with the anticipated currents around the shelf-slope boundaries (see Fig. 1 for positions of the stations used in the present study). In particular, as this is relevant to our subsequent investigation, we remark that the CTD salinities were determined to an accuracy of about 0.002–0.003 (Smythe-Wright, 1999). The CTD observations were supplemented by lowered ADCP (LADCP) full-depth current measurements from the CTD frame, and by a comprehensive suite of chemical tracers including CFCs and nutrients (nitrate, phosphate and silicate) from analysis of water bottle samples. In addition, underway measurements were made of meteorological parameters, shipboard ADCP, XBTs, and surface temperature and salinity. The importance of the chemical and hydrographic parameters will become apparent during our study, which will place emphasis on these quantities as tracers to deduce the flow patterns. In contrast, geostrophic velocities will not be presented since these are subject to the problems already discussed. LADCP results will only be shown for the 20°W section, considered to be sufficiently far from shelf break topography as not to be significantly influenced by internal tides (which can propagate up to 150 km from the shelf-slope region, (New and Pingree, 1992)).

The ocean circulation model was implemented under the "DYNAMO (Dynamics of North Atlantic Models)" project, funded through the CEC MAST-II programme. Only a brief summary is given here since details can be found in the final DYNAMO scientific report (DYNAMO Group, 1997), and in Willebrand et al. (2000). The model uses an isopycnal-coordinate formulation based on the MICOM (Miami Isopycnic Coordinate Ocean Model) code (Bleck et al., 1992). It comprises a variable-density mixed layer (with Kraus-Turner dynamics) and 19 underlying layers of constant density with values of σ_0 ranging between 24.70 and 28.12 kg m^{-3}. (All subsequent densities in the present study will be values of σ_0, and given in units of kg m^{-3}.) Advection in the model is along isopycnal surfaces, and mixing is strictly controlled to be along or across the isopycnals, so that spurious (numerical) mixing is eliminated. For these reasons, and since fluid parcels in the ocean interior are expected to move approximately on constant density surfaces, the isopycnal model is well suited to the investigation of the circulation of the various water masses. The model employs an isotropic horizontal grid at a resolution of 1/3° longitude, and covers the Atlantic Ocean from 19°S to 70°N. The topography was derived from the ETOPO5 (5′ resolution) database, with the minimum ocean depth set to 75 m. A portion of the resulting bathymetry is shown in Fig. 1, and comparison with bathymetric charts shows that the major topographic features are reasonably well represented. The model was initialised from the (September) Levitus (1982) dataset (enhanced near the model's northern boundary by additional CTD data). The wind stress and heat flux used to force the model were derived from ECMWF analyses and represented mean (monthly climatological) conditions between 1986 and 1988, while the surface salinity was restored towards the Levitus (1982) climatology. In addition, relaxation zones, to simulate water mass exchanges with basins outside the model domain, were employed near the model's northern and southern boundaries, and near Gibraltar, at which layer depth and salinity (temperature and salinity for the mixed layer) were relaxed to climatological conditions in a prescribed way. The model was integrated for a period of 20 yr, and the last 5 yr of its output were averaged to produce mean seasonal climatologies. All model results shown in the present study are for the spring case (representing an average between April and June), as this covers the period of the survey.

3. Preliminary comparison at 56°N

As an initial comparison between the survey and the model, and to give confidence in using a combination of these to infer water mass characteristics and movements, we here compare the observed and modelled hydrographic structure (salinity, temperature and density, σ_0) on the 56°N section in the centre of the Trough. Fig. 2a shows that there is an upper layer in the observed salinity which is relatively uniform or well-mixed to about 400–500 m, with salinities between 35.40 and 35.46. Figs. 2c and e also show a relatively uniform upper layer in the observed temperatures and densities, this time extending a little deeper, to about 700 m. This layer has

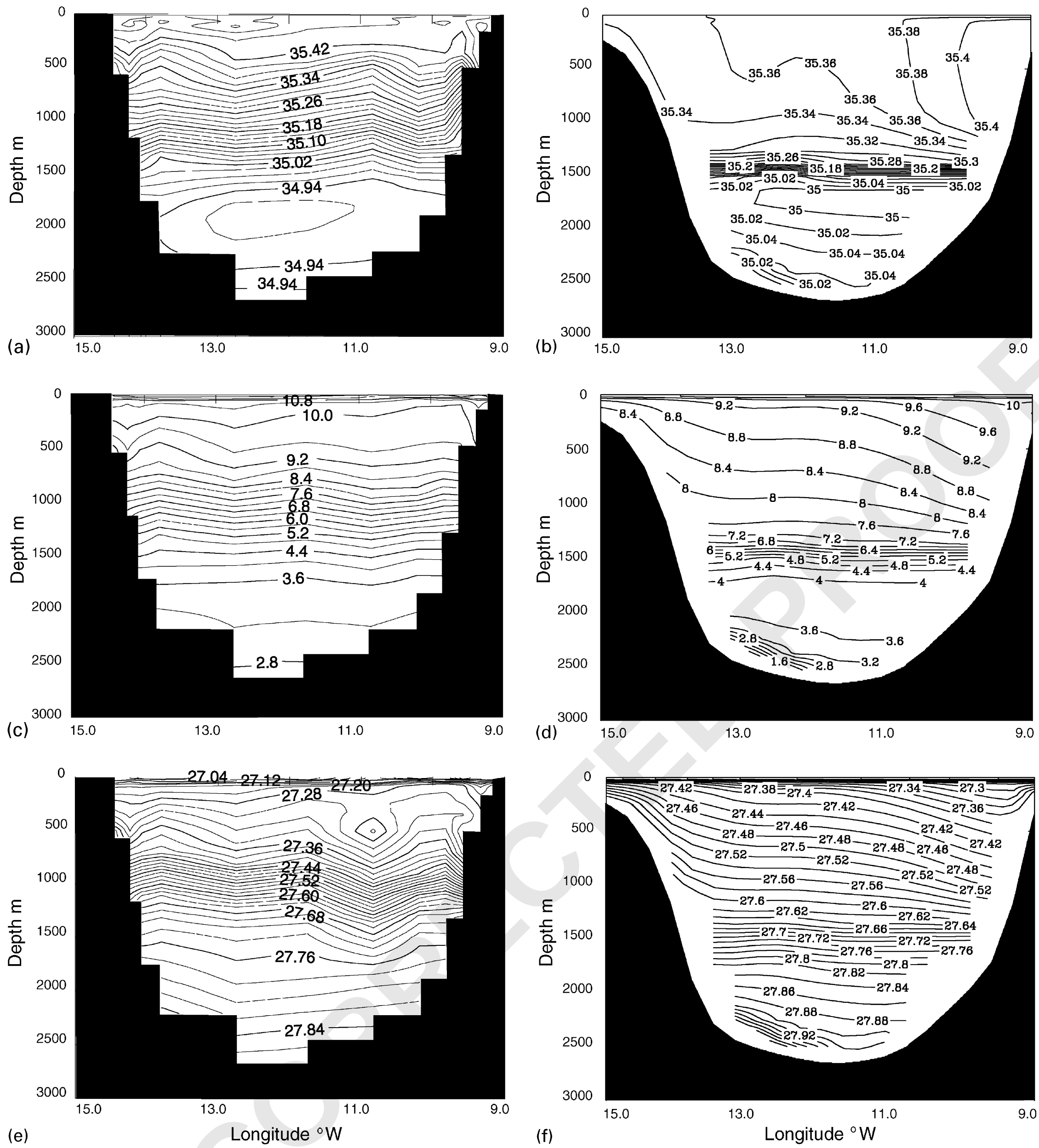


Fig. 2. Comparison of hydrographic parameters on the 56°N section. (a) Observed salinity, (b) model salinity, (c) observed temperature (°C), (d) model temperature (°C), (e) observed density (σ_0 values, $kg\,m^{-3}$) and (f) model density (σ_0 values, $kg\,m^{-3}$).

temperatures between 9 and 10.5°C and densities between 27.2 and 27.4. Below this layer, all the observed characteristics vary more rapidly to about 1500 m or so. In more detail, there is a reasonably broad halocline between 400 and 1600 m, a thermocline between 700 and 1600 m, and a more tightly defined pycnocline between about 700 and 1400 m. Below these regions of increased vertical gradients, there is then an observed salinity minimum, of less than 34.92, near 1900–2000 m depth. This is associated with temperatures of about 3.4°C (Fig. 2c) and densities between 27.78 and 27.79 (Fig. 2e). These characteristics (e.g. refer to Ellett et al., 1986) indicate the clear presence of Labrador Seawater (LSW) in the Trough. Deeper still, the observed salinity (Fig. 2a) increases slightly to form a maximum, with salinities above 34.94 near 2500 m. This water mass is associated with observed temperatures of 2.8–3.0°C and densities of 27.84–27.86, and corresponds to the North East Atlantic Deep Water (NEADW). Below this, the salinity again decreases slightly, indicating the likely presence of derivatives of the fresher Antarctic Bottom Water (AABW).

Figs. 2b, d and f show the model salinity, temperature and density, respectively, on the 56°N section in Spring, for comparison with the observations. There is a region of relatively uniform salinity and temperature down to 1200–1300 m in the model, rather deeper than in the observations. To understand the reason for this, we need to explain how the model works. All layers in the model have thicknesses which change in time and space. The uppermost layer (the "mixed layer") has density, temperature and salinity which are uniform in the vertical, but which can vary horizontally. Below this, all the other layers have constant densities. There is, however, an exchange of water between the mixed layer and the layers immediately below during the seasonal cycle as the mixed layer deepens (in winter) and shallows (in the spring and summer). Now, the density of the model mixed layer in winter (when it is deepest) is typically 27.4–27.5 $kg\,m^{-3}$ in the Rockall Trough, and its depth is typically 600–800 m (not shown). During the springtime, the mixed layer begins to warm and becomes shallower. As it rises, it passes some of its water into the layer immediately below it, in this case of density 27.52 $kg\,m^{-3}$, mixing the temperature and salinity of the two together in the process. This layer effectively has a lower interface at a density close to 27.58 $kg\,m^{-3}$, intermediate between the density of the layer in question (27.52 $kg\,m^{-3}$) and the density of the next layer down (which happens to be 27.64 $kg\,m^{-3}$ in the present model). Consequently, the temperature and salinity of the water in the winter mixed layer will actually be mixed downwards, and affect the water column, more deeply than the bottom of the model mixed layer in winter. In the present case, we would therefore expect a region of reduced vertical gradients, resulting from this mixing, in the salinity and temperature in the model down to about the level of the 27.58 $kg\,m^{-3}$ density surface. We see in Fig. 2f that this surface occurs at depths of about 1200 m. This therefore explains the existence in the model of an upper layer of reasonably uniform salinity and temperature down to about this depth, even though the actual mixed layer depth in the model is only about 600–800 m. This difference has therefore resulted from the discretisation of the model layers: with more layers, or densities chosen more appropriately for the Rockall Trough, the difference would be reduced.

The model therefore has an "upper layer" of reduced vertical gradients in temperature and salinity which is deeper (extending to about 1200 m) than the actual depth of the model mixed layer (600–800 m), and deeper than the mixing depths inferred from the observations (400–700 m). This upper layer in the model has salinities of typically 35.34–35.4, temperatures between 7.5 and 10.0°C, and densities between 27.3 and 27.5, somewhat fresher, colder, and denser than in the observations, but in accord with what might be expected if the upper layer in the observations were to be mixed to about the same depth (i.e. entraining fresher, colder, denser waters from greater depths). Below the upper layer in the model there is a tightly confined region of sharp gradients in all the shown characteristics (between 1300 and 1700 m approximately). Below this, a salinity minimum is apparent between 1700 and 1900 m in which the salinities are below 35.00, the temperatures are between 3.8 and 4.2°C, and the densities are in the range 27.78–27.84. This is the model Labrador Sea Water (LSW), and its characteristics are in good agreement with the corresponding water mass in the observations (though slightly saltier, warmer, and denser). Deeper still, the model salinities increase slightly to in excess of 35.04 between 2300 and 2500 m, and this maximum reflects the model North East Atlantic Deep Water (NEADW), with corresponding temperatures between 3.2 and 3.6°C and densities between 27.88 and 27.90. These characteristics are also in reasonable agreement with those of the corresponding water mass in the observations. However, there is a small region on the western side of the deepest Trough (12–13°W) in which the model densities again increase markedly, exceeding 28.00 at the bottom, and here the salinities have decreased markedly to below 34.98, and the temperatures have decreased to 1–2°C. This indicates an additional water mass not apparent in the observations. These properties are, however, close to those in the Norwegian Sea at the level of the Wyville–Thomson Ridge as already mentioned (densities near 28.0, salinities near 34.94, and temperatures near 1°C), and indicate the presence of Norwegian Sea Deep Water (NSDW) flowing southwards through the Trough in the model. This results from overflows across the Wyville–Thomson Ridge, as shown below.

4. Upper layer circulation and characteristics

The observed upper layer salinities on the 57°N, 56°N, 54°N and 52°N sections are shown to 500 m depth in Fig. 3. In all sections, the upper well-mixed layer is typically 400–500 m deep. At 52°N (Fig. 3d), the upper layer salinities are relatively high, ranging between 35.50 and 35.58, with the highest occurring in the feature near 18.5°W (possible reasons for this are considered in Section 8). At 54°N, however, the upper layer is generally markedly fresher, with salinities between 35.44 and 35.50. Here, the most saline water (above 35.50) occurs between 200 and 400 m depth at 13.5°W, and is taken as representing the northward flow of saline water in the Shelf Edge Current (SEC) around the northwestern Porcupine Bank. The generally lower salinities at 54°N, as compared with those at 52°N, indicate the possible inflow of fresher waters either from the west or north, and the small-scale patchiness in the upper layer suggests a region of mixing between these water masses.

At 56°N, the upper layer has salinities similar to, but slightly fresher than, those at 54°N, ranging between 35.41 and 35.48, presumably because of continued mixing with the fresher waters. There are also two identifiable local salinity maxima in the upper 200–300 m, one near the Scottish shelf edge at 9.5°W, and a second between 12.5 and 13.0°W. At 57°N, the upper layer salinities occupy almost the same range (35.40–35.46) as at 56°N, and again, two salinity maxima are present, one near the Scottish shelf, and one just to the west of the Anton Dohrn Seamount (ADS, with a summit about 600 m deep near 11°W). The salinity maxima near the eastern slopes in these sections indicate the continued presence of the SEC, while the more westward maxima indicate a secondary northward pathway for the saline water masses, which we identify with the Rockall Trough Current (RTC).

To further investigate the possibility of relatively fresh flows from the west impacting upon the southern approaches to the Rockall Trough, Fig. 4a shows the observed upper layer salinity

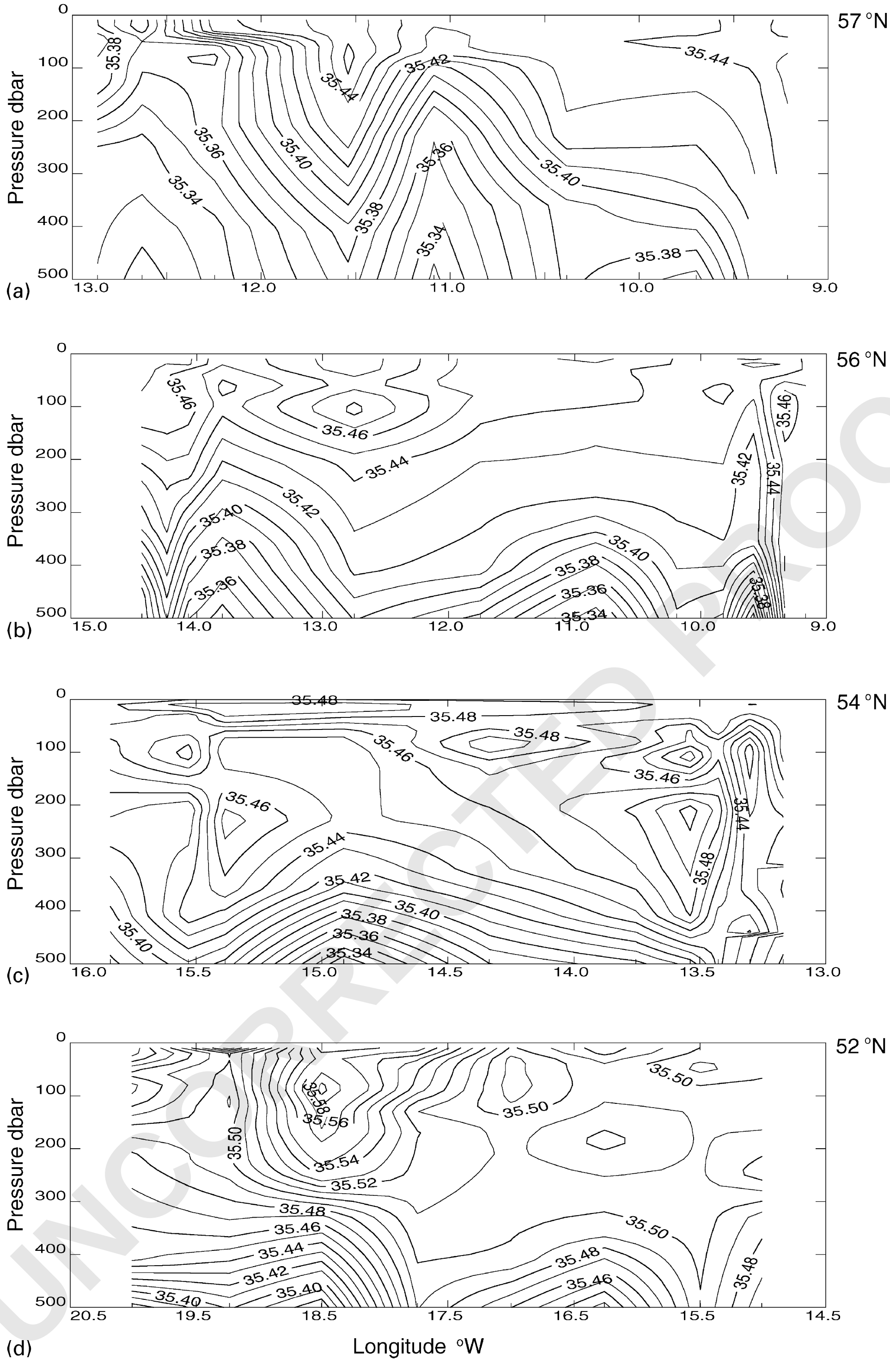


Fig. 3. Observed upper layer salinities along the sections (a) 57°N, (b) 56°N, (c) 54°N and (d) 52°N.

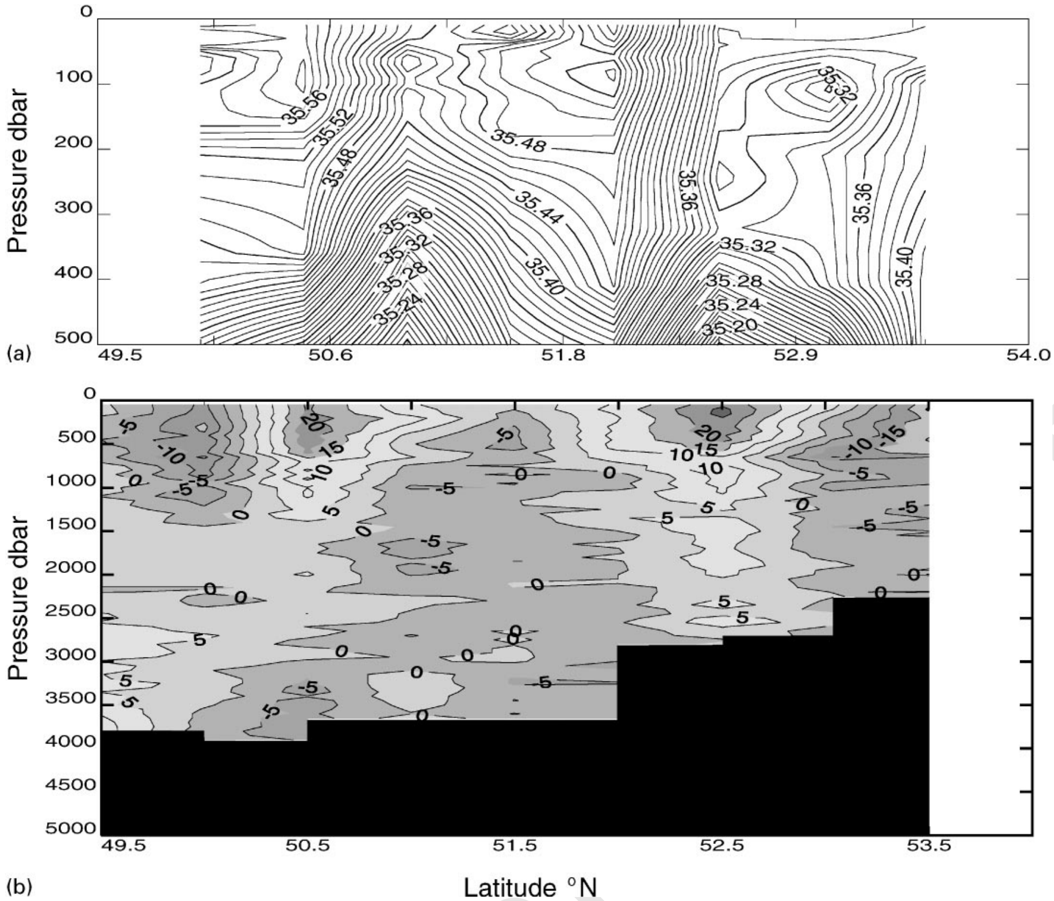


Fig. 4. Observed structure along the 20°W section. (a) Upper layer salinity (contours every 0.01 units) and (b) LADCP currents (positive eastward, cm s^{-1}).

between 50 and 53.5° along 20°W. A pronounced upper layer front is evident near 52.5°N, with relatively high salinities to the south, between 35.45 and 35.55, and much fresher waters to the north, with salinities typically between 35.30 and 35.40. Fig. 4b shows the corresponding LADCP velocities (east–west component) at 20°W. We see that the upper layer flow (above 500 m) is predominantly eastwards through this section, with strong jets reaching above 20 cm s^{-1} separated by weaker westward counterflows reaching typically 10 cm s^{-1}. The salinity front near 52.5°N is associated with the strongest of these eastward flowing regions, indicating a significant influx of relatively fresh waters here (on the northern side of the front). Although we cannot definitely know which of the eastward flow regions are associated with eddies, and which correspond to genuine current branches extending significantly to the east, the deeper current structure seems to indicate that the eastward flow near 50.5°N is part of a near-symmetric upper ocean eddy (in the top 1500 m) with a balancing counterflow near 50°N, while the eastward flow at 52.5°N, penetrating significantly to the full depth, is more likely to be a major current branch. This is consistent with, and provides a likely explanation for, the fresher waters at 54°N as compared with those at 52°N, as discussed above.

Turning now to the model, Fig. 5 presents the current and salinity structure at 204 m (one of the depths used in the interpolation of the model output to a standard set of levels, and taken as representative of the upper layer). The patterns are consistent with, and support, our interpretation of the observations. Firstly, we note a strong eastward flow (being a branch of the model's North Atlantic Current) which crosses 20°W near 54°N, and this is associated with a pronounced front with fresher water on its northern side, paralleling the observed structures near 52.5°N. After being joined by a second fresh flow from the north near 16–18°W, this eastward flow clearly produces a major inflow of fresh water masses along 54°N which sweep in towards the northern Porcupine Bank, and then, turning to the northeast, continue on into the Rockall Trough. We also note the presence of a large eddy, centred on 17°W, 52.5°N, which is quasi-stationary (topographically locked) and produces alternating bands of east–west flow at 20°W which are similar to the observed structures between 49.5 and 51°N on 20°W.

In addition to the inflow of fresh waters (with salinities less than 35.30) from the west along 54°N, there is also a pronounced model Shelf Edge Current (SEC) in Fig. 5, carrying the most saline waters polewards around the continental margins. This is seen as a strong northward current between 11 and 12°W, 50 and 52°N, which then splits, partly following around the western slopes of the Porcupine Bank, and partly crossing the topographic saddle point between the Porcupine Bank and the Irish Shelf at 12°W. These flows, of salinities between 35.42 and 35.50,

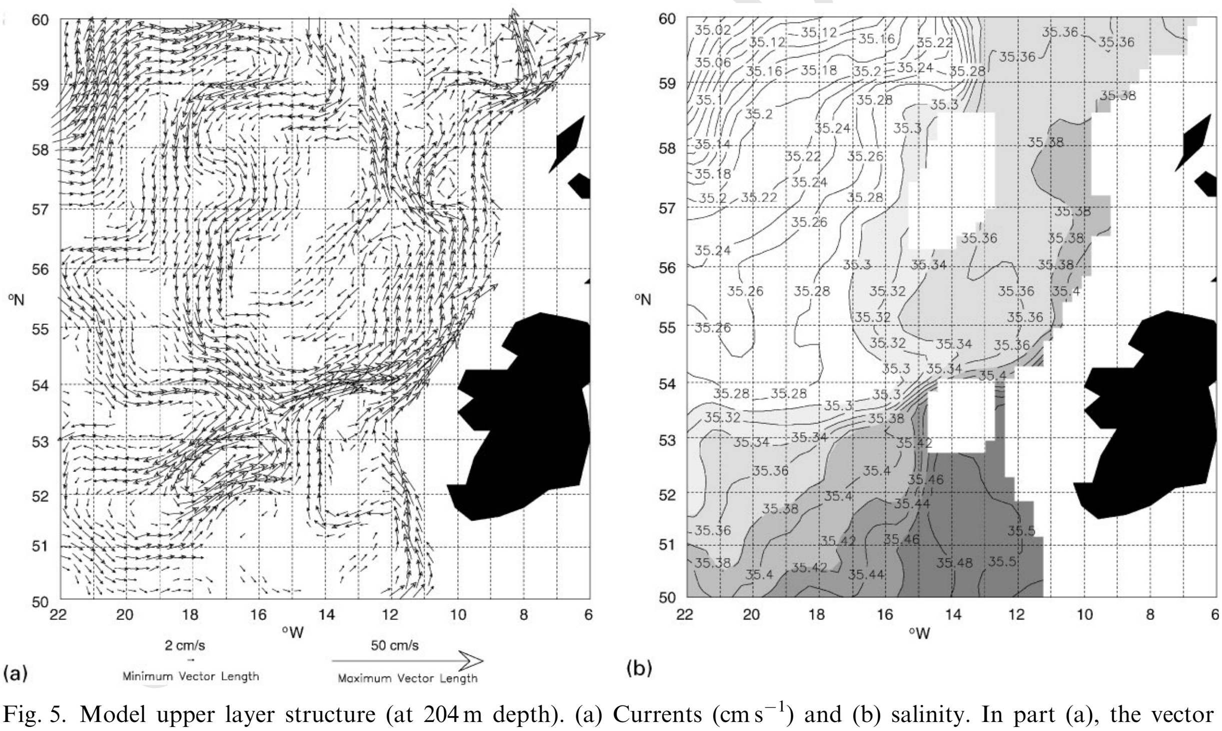


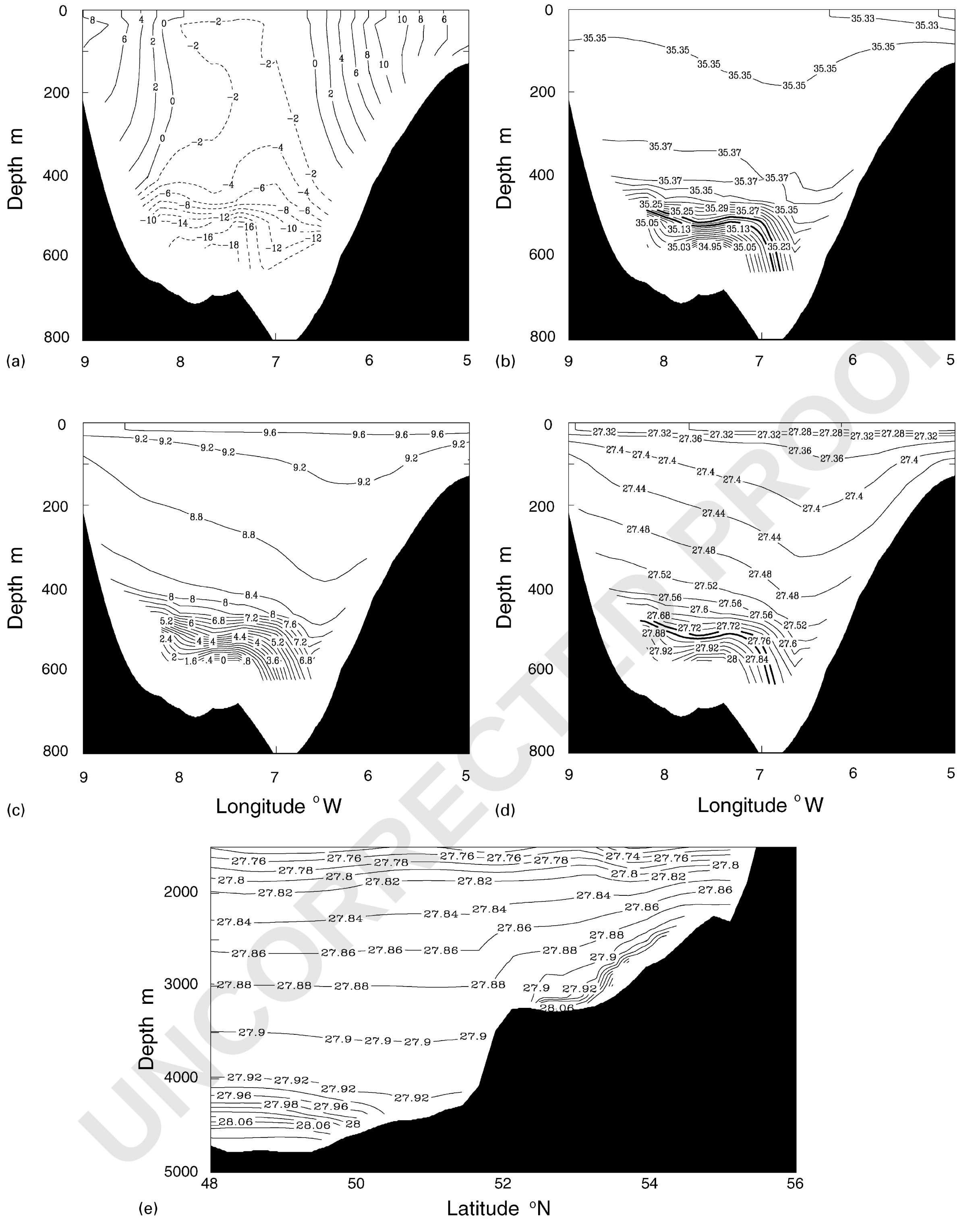
Fig. 5. Model upper layer structure (at 204 m depth). (a) Currents ($cm\,s^{-1}$) and (b) salinity. In part (a), the vector arrows show the velocities at the arrow centres.

then meet, and partially mix with, the fresher waters flowing in from the west on the northern Porcupine Bank, to form a broad northward flow of intermediate salinity through the Rockall Trough which typically (e.g. at 56°N) extends between the central Trough and the Scottish shelf. However, by 57°N, the northward flow has separated into two separate components, as inferred for the observations, with one branch flowing around the western side of the Anton Dohrn Seamount (ADS), and one following the Scottish slopes. North of the ADS, these two flows then re-merge (although part of the western branch flows northwestwards and escapes into the Iceland Basin), so that a strong SEC is in evidence flowing northeastwards along the Hebrides Shelf (58–59.5°N) and towards the Wyville–Thomson Ridge (at 60°N). Note also that the highest model salinities in the Rockall Trough, close to 35.40, are those in the SEC running around the Irish–Scottish slopes, and Fig. 2b shows that the high salinity core in the SEC at 56°N extends to 800 m or so. These characteristics are in good agreement with those reported for the SEC in the Rockall Trough by Hill and Mitchelson-Jacob (1993).

5. Wyville–Thomson Ridge overflows

The southward flows from the Nordic seas which cross the Wyville–Thomson Ridge (WTR) are relatively dense and descend rapidly into the northern Trough, mixing with and affecting the ambient water masses there. In order to understand the structure of the deeper water masses in the Trough, we therefore firstly investigate the characteristics of these overflows. For this, we employ the model output, since the present survey did not extend as far north as the WTR. Fig. 6a shows the east–west velocities over the WTR (the north–south velocities by comparison being almost negligible, and typically between $\pm 2\,\mathrm{cm\,s^{-1}}$). The section is aligned northwest–southeast between 60.6 and 59.1°N (see Fig. 1), so that any westward flows are moving into the northern Rockall Trough. A well-defined SEC (with a maximum eastward speed in excess of $10\,\mathrm{cm\,s^{-1}}$) is present in the upper 300 m on the West Shetland Shelf (5–6.5°W). There are, however, strong westward flows at all depths below about 500 m along the entire length of the ridge. These flows reach $18\,\mathrm{cm\,s^{-1}}$ at and below 600 m. Fig. 6b reveals that the salinities are reasonably uniform to about 400 m, but below this depth they decrease markedly to fresher than 34.95. Fig. 6c shows that, while the upper layer is about 8–9.5°C, the temperatures also rapidly decrease below 400 m, so that the deepest, freshest waters overflowing the WTR have temperatures in the range 0–2°C. Finally, Fig. 6d shows that the density also increases reasonably steadily down to 400 m across the section, but below this there is a sharp pycnocline in which the densities rapidly increase to over 28.04. The deepest, densest water masses on this section represent model Norwegian Sea Deep Water (NSDW) which spills over the WTR, and its characteristics agree reasonably well with those reported by Ellett et al. (1986) for NSDW near the WTR (densities of 28.0, salinities near 34.94, and temperatures close to 1°C). The characteristics of the model NSDW on this section are also close to those of the densest water in the 56°N section (Fig. 2, densities of 28.0, salinities near

Fig. 6. Model structures across the Wyville–Thomson Ridge (from 9°W, 60.6°N to 5°W, 59.1°N, see Fig. 1), showing (a) eastward currents ($\mathrm{cm\,s^{-1}}$), (b) salinity (bold lines mark the 35.21 and 35.17 contours), (c) temperature (°C) and (d) density (σ_0 values, $\mathrm{kg\,m^{-3}}$; bold lines mark the 27.76 and 27.80 contours). Part (e) presents the model density field at 16°W (σ_0 values, $\mathrm{kg\,m^{-3}}$).


(a)
(b)
(c)
(d)
(e)
Depth m
0
200
400
600
800
9
8
7
6
5
Longitude °W
2000
3000
4000
5000
48
50
52
54
56
Latitude °N

34.98, and temperatures between 1 and 2°C), thus confirming that the NSDW flows southwards to at least 56°N in the model.

Although the densest flows which spill into the Rockall Trough across the WTR represent almost pure NSDW, significant overflows of dense water also occur at all densities in excess of about 27.5–27.6 kg m^{-3}. These are clearly derivatives of the NSDW, being mixed to various degrees with the overlying lighter waters. We will refer to these generically as the WTR overflows in the following.

While Ellett et al. (1986) report that the overflow of NSDW across the WTR may be of the order of 0.3 Sv, van Aken and Becker (1996) give an estimate of 0.4 Sv, for waters with densities greater than 27.8 kg m^{-3}. The present model has overflows which are rather stronger than this, and measure (again for densities greater than 27.8) some 2.1 Sv. The reason for this is that the model WTR is typically some 100–150 m too deep, being 600–800 m deep (Fig. 6), as opposed to the 500–650 m in nature. This itself results from the resolution of the model being only 1/3° horizontally, or about 20 km here. The model topography was defined from the ETOPO5 database (which has a resolution of 5 min) as the mean depth of all the database values within each model grid cell. This effectively averages the topography over about a 20 km square. For the Wyville–Thomson Ridge, which is a knife-edge which varies greatly on a 10 km length-scale, this will necessarily result in a deeper representation in the model, as shown.

Whilst the relative freshness of the NSDW as it crosses the WTR is clear in Fig. 6 as compared with the upper layer salinities (derived from the North Atlantic waters), we note in Figs. 6b and d that the positions of the 27.76 and 27.80 density contours closely match the positions of the 35.21 and 35.17 salinity contours (compare the bold contours). This indicates that the salinity on the 27.78 density surface (used to define the model LSW) at the WTR is also close to these values, and is significantly higher than that derived from the LSW on the same density surface in the central Trough (e.g. about 35.00 at 56°N, Fig. 2). We therefore expect the WTR overflows, known to pass through the Trough on the western side, to provide a source of relatively high salinity water (of salinities near 35.18–35.20) which could mix with the LSW water mass in the northwestern portion of the Trough (as will be seen to be the case below).

Finally, to illustrate the positioning (in relation to the topography) and vertical migration of these dense flows as they move further down the Trough, Fig. 6e presents a density section at 16°W. The dense WTR overflows are apparent between 53°N and 54.5°N at depths near 3000 m, and take the form of a lens of water (with densities at and higher than 27.92) flowing westwards. Coriolis force acts to push this flow towards the right (northwards) so that it is banked up with the topography on its right-hand side as shown. The topographic high at 55°N is the South Feni Ridge (SF in Fig. 1), so that the flow is following the downslope side of the Ridge system. These dense water masses are also apparent in the deep Porcupine Abyssal Plain (PAP in Fig. 1) at latitudes south of 52°N and at depths below 4000 m, where they partake in a general cyclonic circulation in the deep ocean (investigated further below).

6. Labrador Sea Water

Labrador Sea Water (LSW) is characterised in the central Trough in both the model and the observations by a minimum in salinity centred at densities near 27.78–27.80, temperatures between 3.2 and 4.0°C, and at depths between 1700 and 2200 m. It can be traced in the model (not shown) from its source in the Labrador Sea (40°W, 56–57°N) by examining the salinity on the 27.78 density surface. The salinity on this surface is freshest at the source (below 34.92) and gradually increases (through mixing) with distance eastwards. A similar eastward increase is apparent in observations, but the situation is compounded by the temporal variability of Labrador Sea source water. In the present study we define LSW in the observations by the salinity minimum near 2000 m depth, as this best describes the core of the water mass. For the model, the depth and characteristics of the water mass defined by such a minimum salinity would depend on the method used for the vertical interpolation from the discrete layers of constant density. We therefore choose instead the 27.78 density surface to define the model LSW, which in any case closely approximates the salinity minimum surface.

Fig. 7a examines the flows on the LSW density surface in the model, which is typically 1600–1800 m deep in this region. There is a strong cyclonic gyre in the central Rockall Trough with flow speeds up to 7 cm s^{-1}, which is fed from the south-west by an inflow along 54°N, and from the north by overflows from the WTR along 12°W. The inflow of relatively fresh LSW from the west along 54°N occurs almost directly below the inflowing surface waters described above and impacts upon the northwestern Porcupine Bank. Although much of it turns to the southwest, exiting through 52°N between 18 and 20°W, and through 20°W between 52 and 53°N, some also moves

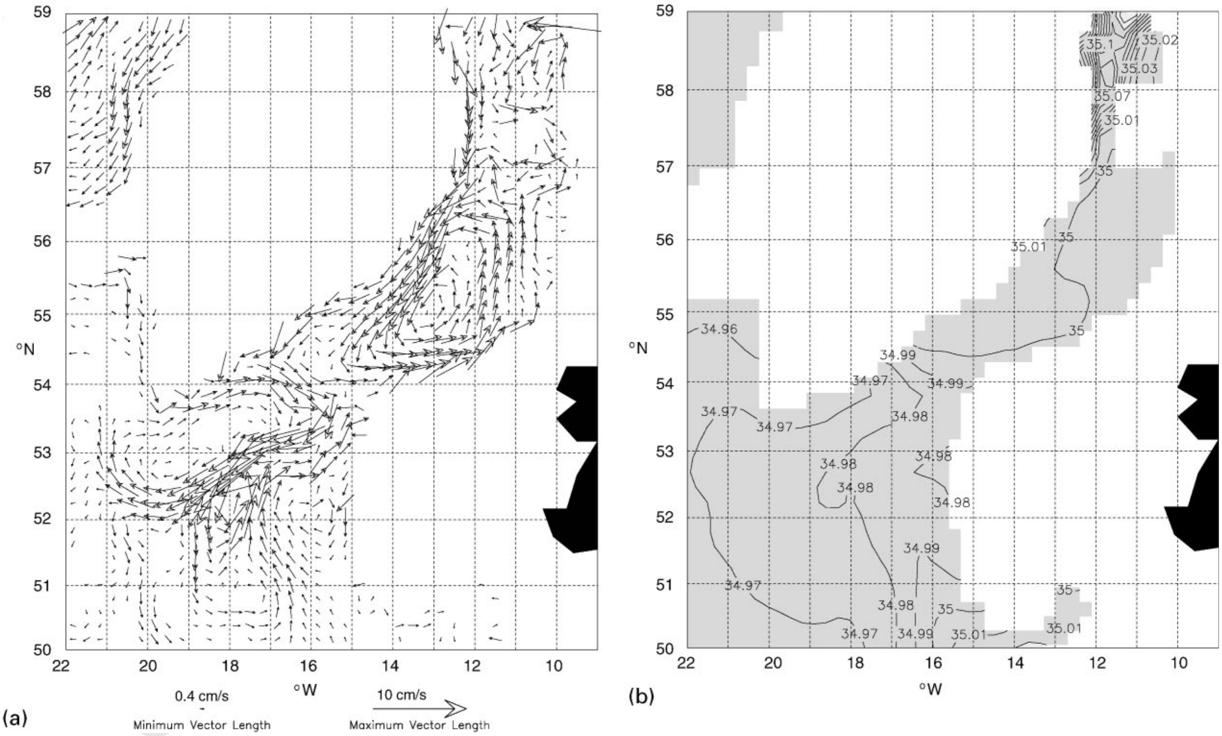


Fig. 7. Model structure on the Labrador Sea Water surface (corresponding to a density of 27.78). (a) Currents (cm s^{-1}) and (b) salinity (contours every 0.01). In part (a), the vector arrows show the velocities at the arrow centres.

northwards into the Trough and feeds the central gyre. The central gyre is also quasi-barotropic and is situated below a similar cyclonic feature seen in the surface layer, but here the flows on the western side are intensified (5 versus 2 cm s^{-1} at 56°N), and those on the eastern side diminished (3 versus 5 cm s^{-1} at 56°N) compared with those in the surface layer. While the southern limb of the central gyre is close upon the (steep) northern Porcupine Bank, the northward flowing eastern limb moves away from the shelf slope and follows along 11–12°W, approximately above the 2500 m contour (which detaches from the shelf slope around the Hebrides Terrace Seamount, H in Fig. 1, and the contiguous Fan systems between 56 and 57°N). The northern limb of the gyre also mirrors the 2500 m depth contour, turning to the west along 56.5°N and then back towards the southwest at 12.5°W. The WTR overflow waters move southwards between 12 and 13°W, following the course of the North Feni Ridge between 57 and 59°N, and join and mix with the waters circulating in the central gyre near 56.5°N. These combined waters then flow southwestwards along the southeastern side of the Rockall Bank to 14.5°W, 55.2°N, which is the northern limit of the South Feni Ridge. Here the current splits to form two continuing southwestward branches. One of these branches follows the southeastern side of the Feni Ridge to about 54.5°N, where it turns eastwards to form the southern limb of the central gyre. The second branch follows a more inshore route down the steep slopes of the Rockall Bank. This branch extends southwestwards to 17°W, 54.5°N, where it meets with the inflowing LSW, which turns it eastwards. Evidence for this splitting of the deep flows is provided by the sedimentary bedforms analysed by Lonsdale and Hollister (1979).

The model salinity pattern on this surface, Fig. 7b, is entirely consistent with the circulation pattern and the characteristics of the two inflowing water masses. The freshest waters (34.97) are seen in the LSW inflow along 54°N, and these partially turn back to the southwest towards 52°N, 19°W with salinities near 34.98 (slightly increased through mixing with the other water masses). There is a minor salinity front near the entrance to the Trough (15–17°W, 54°N) associated with this partial retroflection of the LSW inflow. However, a part of the LSW inflow does find its way into the central Trough (in Fig. 7a), and this is seen as the freshest water in the Trough (with salinity below 35.00) moving eastwards along 54.5°N, and then northwards between 11 and 12°W in the central cyclonic gyre. As expected, the influence of the more saline WTR overflow waters (with salinity up to 35.20 on this density surface at the WTR) is marked in the northwestern region of the Trough, and is associated with the southward movement of these water masses down 12°W. The large gradients apparent here indicate the likelihood of strong lateral mixing between the WTR overflows and the fresher LSW water mass. We may also explain the slight increase in salinity on this density surface in the central Trough (35.00) compared to that at 20°W (34.97) as being due to this mixing with the WTR overflow waters.

We now investigate the flow of the LSW core waters as revealed by the observations. Since the LADCP profiles and geostrophic velocities are likely to be of limited use for the reasons already discussed, we turn instead to the hydrographic and chemical tracer measurements. Fig. 8 presents the salinity at the LSW salinity minimum derived from the CTD stations. While the CTDs provide an adequate representation of flow variations in the across-section directions, there are areas, (such as the entrance to the southern Trough between the 20°W, 52°N and 54°N sections) where the data coverage is too sparse for unambiguous interpretation of the flow field. In these regions we have been guided by the model circulation pattern, and the tendency of flows to be steered by the topography, to help our interpretation.

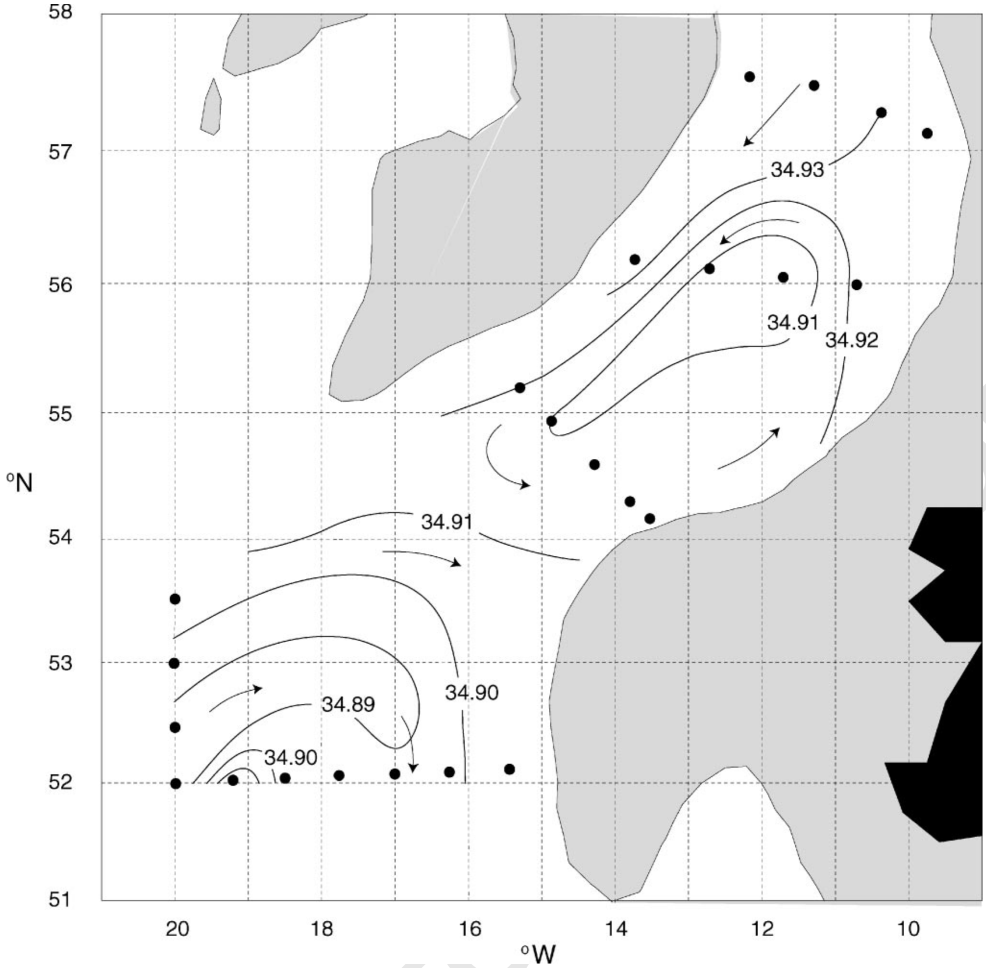


Fig. 8. Observed salinity structure on the salinity minimum surface corresponding to Labrador Sea Water. The CTD station positions are shown by the filled circles, and the arrows indicate the inferred circulation pathways. Only those CTD stations at which an appropriate salinity minimum was found are shown, and the bathymetry shallower than1000 m is denoted by the grey shading.

In Fig. 8 we see that the lowest salinities on the LSW surface in the study area occur outside the southern entrance to the Trough. The lowest values, less than 34.89, occur between 52 and 53°N on 20°W, and indicate that this is the core of the LSW inflow to the region. This is directly below the inflowing surface waters inferred earlier, and Fig. 4b shows eastward flows of about 5 cm s^{-1} at the LSW depths. Only slightly higher salinities (just above 34.89) are observed near 17°W on the 52°N section, which indicates that this is the main outflow region. Assuming the flows would largely follow the depth contours between 20°W and 52°N, we therefore expect the freshest (purest) LSW to inflow through 20°W in a (north-) eastward direction, and then to largely turn to the south, to exit through 52°N near 17°W as shown. The model is in qualitative agreement with this general anticyclonic circulation, although the inflow and outflow are in slightly different positions.

In the Trough, salinities are higher, being close to 34.91 or above. As in the model, the highest salinities (above 34.93) occur in the northwestern region (12–13°W on the 57°N section) and we take this as evidence of southward flowing water from the WTR overflow. As this flows southwestwards down the western side of the Trough, its salinity decreases (reaching 34.92 on the western side of the 54°N section), consistent with lateral mixing with the fresher water masses in the central Trough. (Note that vertical mixing in this boundary current could only result in increasing salinity with distance travelled, since the LSW is defined by the salinity minimum. Hence the mixing here must be predominantly lateral.) The freshest water in the Trough occurs in the centre of the 56°N section (near 11.7°W), where values of 34.905 are attained. Slightly higher values are seen at the neighbouring CTD station to the west (34.907 at 12.7°W), and it seems reasonable to assume that these low values are connected to the minimum salinity, 34.910, observed towards the western side of the 54°N section (at 14.9°W), giving the 34.91 contour as shown. This is consistent with cyclonic circulation, with the slow increase in the salinity of the fresh core with distance travelled around the gyre being further evidence of lateral mixing with the saline boundary current along the western margin.

On the southeastern side of the 54°N section in Fig. 8, salinities are just above 34.91 (actually 34.913–34.914), higher than the values observed in the southern approaches to the Trough, but fresher than the water masses in the boundary current on the western side of the Trough. It therefore seems that these intermediate salinities result from the mixing of the water of salinity 34.92 in the western boundary current (on the 54°N section) either with fresher waters which flow in from the southern approaches, or with the fresh core in the central Trough. Either way, some of the waters on the western side of the 54°N section must turn southwards and then eastwards, probably along near 54°N, to form the southern limb of a cyclonic gyre in the central Trough (as in the model).

It is also apparent that at least some of the freshest LSW in the southern approaches is entering or has entered the Trough, but how this occurs is not completely clear. The inflow could take the form of a more or less continuous advection of fresher water from the southern approaches which mixes with the slightly more saline waters in the Trough. However, assuming that the low salinities on the 56°N section are derived from the LSW outside the southern entrance to the Trough, and noting that the lowest salinities on the 54°N section are higher than the lowest salinities at 56°N, we are led to the interesting possibility that there must have occurred an episodic inflow of LSW into the Trough at some time prior to the survey.

The circulation pattern suggested above, and the idea of episodic inflow events, are strongly supported by the CFC-11 observations in Fig. 9. The CFCs (Chlorofluorocarbons) have entered the ocean from the atmosphere, and as a result of the atmospheric CFC time history, showing generally increasing values, waters which have been more recently in contact with the atmosphere have higher CFC values. As the water masses move away from their source region, the CFC concentrations are further modified by mixing. Since LSW is one of the youngest water masses in the Eastern North Atlantic, it is expected that its CFC content will be high, but that this will decrease with spreading distance as it mixes with older, lower CFC-value, water masses. This is confirmed in Fig. 9, where the highest CFC concentrations below 1000 m, with values up to in excess of 2.8 $\mathrm{p\,mol\,l^{-1}}$, occur on the 20°W section between 52 and 53.5°N (Fig. 9a). These high concentrations are at depths between 1200 and 2000 m and correspond to the main LSW inflow to our study area as inferred from Fig. 8. The second highest CFC values in Fig. 9, near 2.2 $\mathrm{p\,mol\,l^{-1}}$,

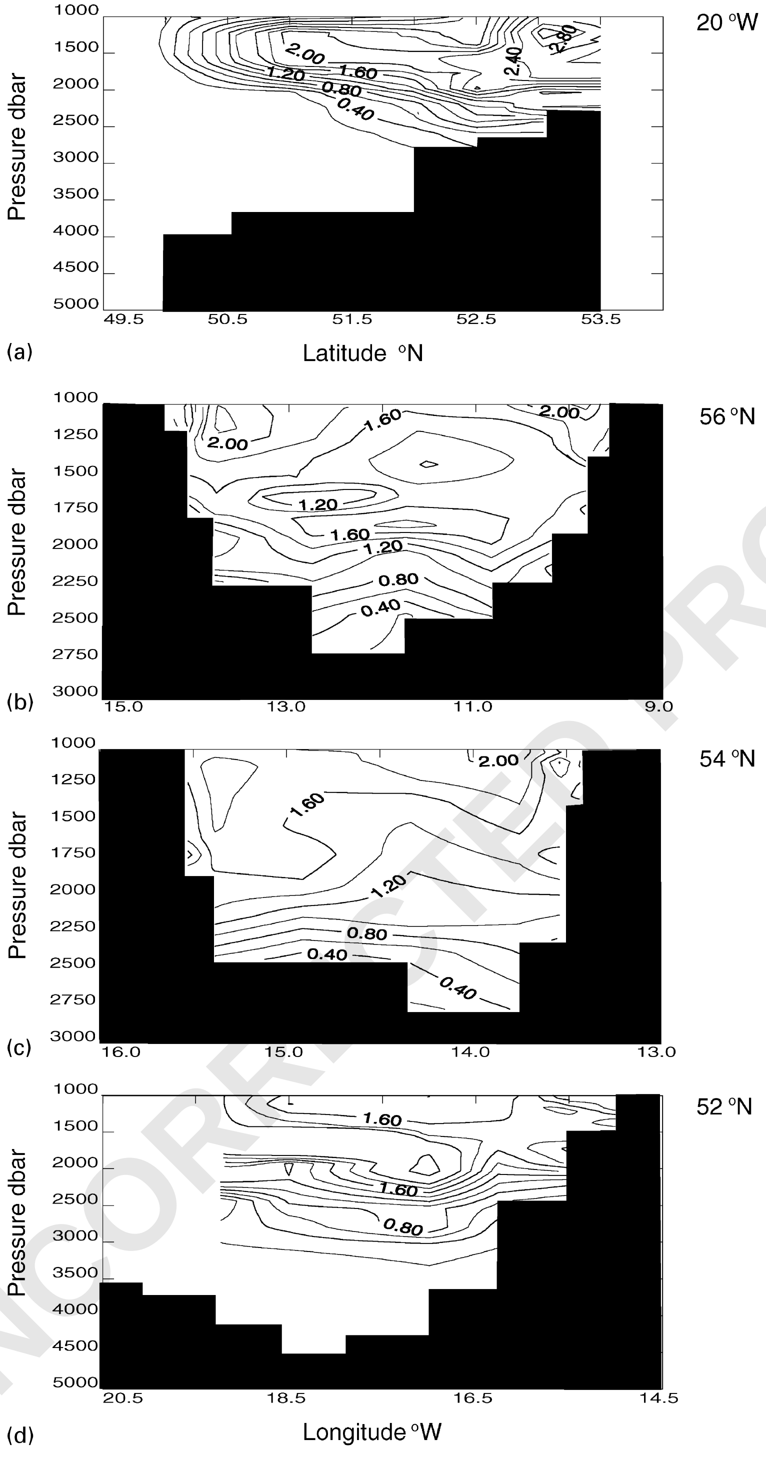


Fig. 9. Observed CFC-11 concentrations ($\mathrm{p\,mol\,l^{-1}}$) below 1000 m depth on the sections (a) 20°W, (b) 56°N, (c) 54°N and (d) 52°N. Contours every $0.2\,\mathrm{p\,mol\,l^{-1}}$.

occur at a similar depth at 17°W on the 52°N section (Fig. 9d), and again indicate that this is the main outflow pathway for the LSW (supporting the deductions from the salinity pattern in Fig. 8).

Fig. 9 also shows that a proportion of the LSW penetrates into the Trough. At 56°N (Fig. 9b), relatively high CFC values, exceeding 1.8 p mol l^{-1}, occur in a thin band near 1900 m (the approximate depth of the LSW core) in the centre of the Trough. The position of this feature corresponds exactly with the lowest salinities on the LSW surface (Fig. 8), and it is therefore indeed likely that this water derives from the purer LSW in the southern approaches to the Trough. Moving to the 54°N section (Fig. 9c), we again see a region of enhanced CFC concentrations near LSW depths (centred near 1800 m) towards the western side of the section (14.7–15.4°W). Here the maximum values are lower than at 56°N, being close to 1.6 p mol l^{-1}. Again the high CFC core coincides exactly with the lowest salinity seen along this section on the LSW surface. The reduction in the CFC values in the LSW core between the centre of the 56°N section and the western portion of the 54°N section concurs with our inference of a cyclonic circulation in the central Trough, with southwestward movement down the western side of the Trough leading to reduced CFC values through lateral mixing with the ambient (lower-CFC) waters. Furthermore, we remark that the highest CFC values at the LSW depths on the 56°N section are higher than anywhere at similar depths on the 54°N section, and that this strongly reinforces the idea that an episodic inflow of the LSW has taken place.

Finally, we attribute the relatively high CFC values (up to 2.2 p mol l^{-1}) near the western side (13–14°W) of the 56°N section, between 1000 and 1400 m depth, as due to the lighter waters (relatively recently formed in the Nordic Seas) which overflow the WTR and descend into the Trough. As they move southward, their CFC concentration declines, probably through lateral mixing with the ambient water masses, as evidenced by the maximum values on the western side of the 54°N section (between 1000 and 1500 m depths) being only about 1.8 p mol l^{-1}.

7. Deep circulation and characteristics

North East Atlantic Deep Water (NEADW) can be identified in the Trough by its salinity maximum near 2500 m. Unfortunately, the salinity at this maximum (in the present survey) is almost uniform, varying only between 34.941 and 34.947. These variations are so small (and not much larger than the accuracy with which the measurements can be made) that they cannot be reliably contoured. However, the variations of silicate (which in the absence of mixing should act as a conserved tracer) on this surface are much larger and can usefully be employed to this end.

Fig. 10 shows silicate concentrations on the sections at 52°N, 54°N, 56°N and 57°N. At 52°N, values are low in the upper and intermediate water masses, but increase relatively rapidly from about 15 μmol l^{-1} at 2200 m, to 40 μmol l^{-1} at 3300 m, and exceed 45 μmol l^{-1} in the deepest regions (below 3800 m). This marked contrast is due to the presence of relatively fresh, silicate-rich water derived from Antarctic Bottom Water (AABW) occupying the deepest ocean and underlying the NEADW, which is saltier but relatively low in silicate. The pronounced vertical silicate gradient in the 2000–3500 m depth range results from the mixing together of these two water masses. The proportion of the water masses changes from being mostly NEADW higher in

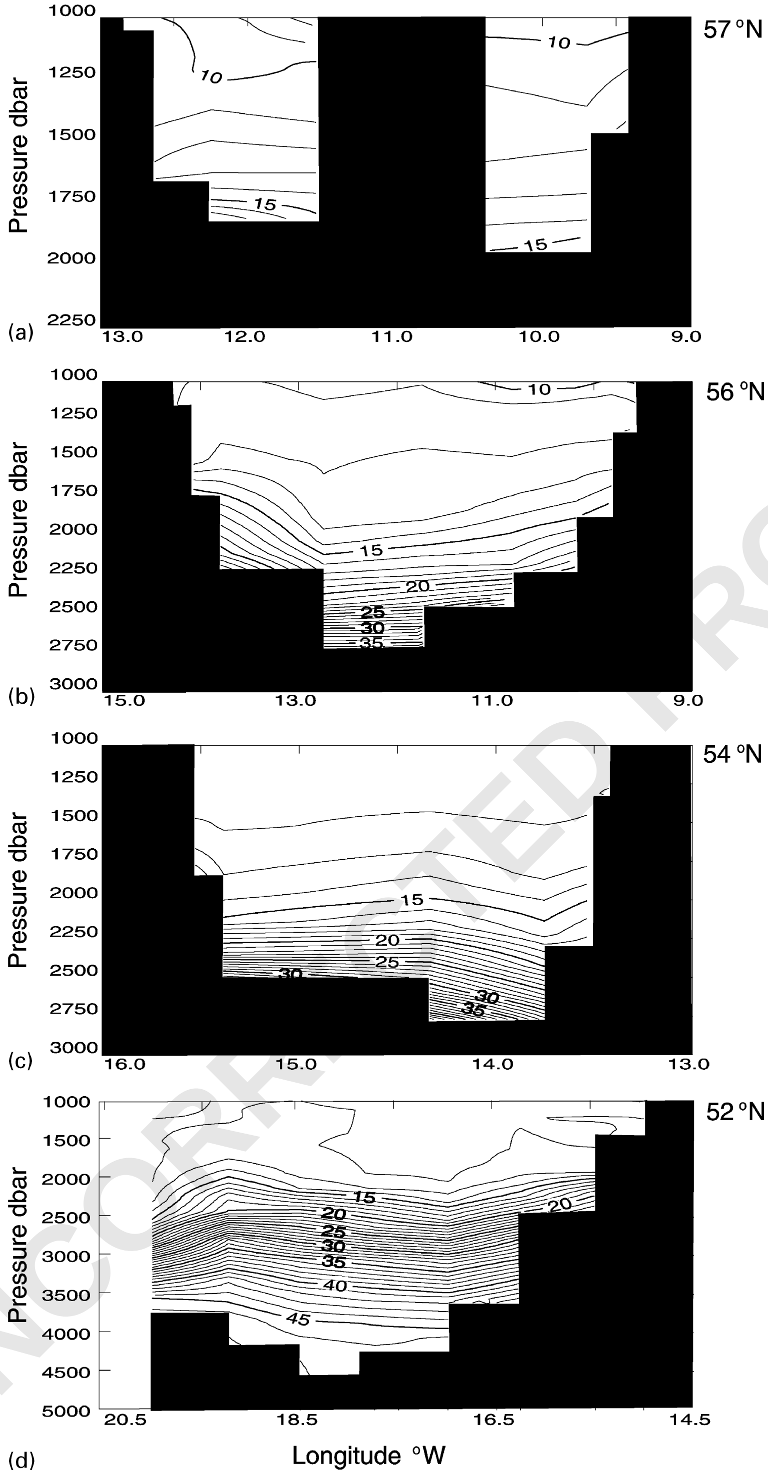


Fig. 10. Observed silicate concentrations (μmol l^{-1}) below 1000 m depth on the sections (a) 57°N, (b) 56°N, (c) 54°N and (d) 52°N.

the water column (2000–2500 m, with silicate values of typically 15–20 μmol l^{-1}), to mostly AABW derived (with silicates of 40 μmol l^{-1} or over) below 3300 m.

Further northwards into the Trough, silicate values increase with depth on every section, but the highest (deepest) values decrease northwards as the depth of the ocean floor decreases. Thus in the 54°N section, values generally increase from about 20 μmol l^{-1} at 2300 m depth to 40 μmol l^{-1} at 2850 m, whilst at 56°N, values are still near 20 μmol l^{-1} at 2300 m, but only increase to 35 μmol l^{-1} at 2700 m since this is the deepest water in this section. At 57°N, the highest values only just exceed 17 μmol l^{-1} in the deepest waters, but these are less than 2000 m deep. Thus the influence of the AABW on the deepest waters becomes progressively less with distance to the north, but a significant component derived from the AABW clearly extends to at least 56°N. It is unlikely that the deepest waters are directly connected between the various sections. For instance, if the deepest waters are to circulate from the 54°N section to the 57°N section and back again in some circulation pattern, this would imply that the bottom waters, on moving north, would ascend from 2800 m deep to less than 2000 m, together with large decreases in density (from about 27.88–27.80 kg m^{-3}, not shown) and silicate, with the reverse occurring on the southward return path. Indeed, although vertical mixing in the Trough may allow some measure of upward penetration of the AABW derivatives, we would expect the circulation of these deeper waters to occur primarily on surfaces of nearly constant density or other properties, and that these would show only relatively small-scale changes in depth.

For the NEADW, we therefore choose the surface of maximum salinity to identify the core of this water mass, and remark that this varies only between 2320 and 2530 m in the Trough. Fig. 11 then presents the silicate values on this surface, and we immediately infer an overall circulation pattern that is broadly consistent with that for the LSW. The lowest values, less than 23 μmol l^{-1}, occur near 20°W, 52°N, while the second lowest, near 24 μmol l^{-1}, occur at 17°W along 52°N. It has been conjectured (Ellett and Martin, 1973; Ellett et al., 1986) that the NEADW in the southern Rockall Trough area could be formed (at least partially) by overflows of (saline) water masses from the Nordic Seas which cross the Iceland–Scotland ridges and circulate southwards down the western side of the Hatton and Rockall Banks. Furthermore, van Bennekom (1985) has shown that the deep waters in the Nordic Seas are relatively low in silicate (typically less than 15 μmol l^{-1} even at great depth). Expecting the silicate values in the cores of these flows to gradually increase with downstream distance (by lateral mixing), the pattern in the southern approaches to the Trough in Fig. 11 clearly indicates an inflow from the west through 20°W near 52°N, and that this then turns southwards to exit through 52°N near 17°W. These flow patterns are remarkably similar to those for the LSW somewhat higher in the water column. In other words, the flows appear, to a first approximation, to be quasi-barotropic between these depths, an observation which is supported by the LADCP velocity field on 20°W near 52.5°N in Fig. 4b. This also shows that the eastward flows of the NEADW are strong, and reach approximately 5 cm s^{-1}, at this location.

In the central Trough, we again infer a cyclonic gyre, more or less directly below that for the LSW. The lowest values, less than 25 μmol l^{-1}, occur on the northwestern side of the gyre, and are taken to result from vertical mixing with the overlying lower silicate waters from the Nordic Seas which progress southwards over the WTR and through the 57°N section (where the lowest values are only 17 μmol l^{-1}). At 57°N, the NEADW salinity maximum is not present, and the deepest waters have densities near 27.80 kg m^{-3}, and salinities between 34.94 and 34.96 (not shown).

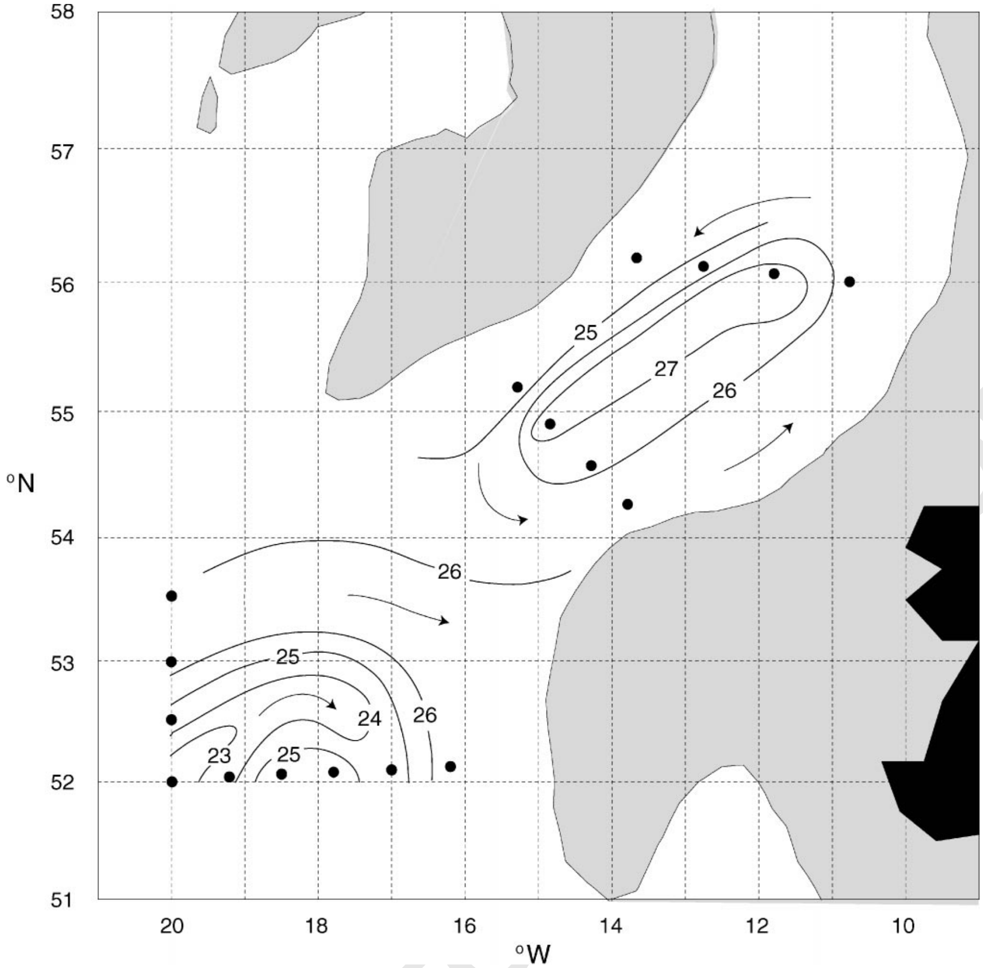


Fig. 11. Observed silicate structure (μmol l^{-1}) on the salinity maximum surface corresponding to North East Atlantic Deep Water. The CTD station positions are shown by the filled circles, and the arrows indicate the inferred circulation pathways. Only those CTD stations at which an appropriate salinity maximum was found are shown, and the bathymetry shallower than 1000 m is denoted by the grey shading.

Consequently, while the deepest flows at 57°N are not dense enough to directly affect (by advection and lateral mixing along density surfaces) the NEADW waters in the central Trough (of densities between 27.84 and 27.86 kg m^{-3}, see Fig. 2), we anticipate vertical mixing on the northwestern side of the gyre in a rapidly flowing boundary current. Since the NEADW surface is near the bottom here, such mixing would result in the lowering of the silicate values by mixing from above the NEADW surface. Furthermore, such mixing would be expected to inject salinities near the observed values (34.94–34.95) onto this surface, and could therefore act as a source of the NEADW salinity maximum in the central Trough.

On the southeastern side of the cyclonic gyre, higher silicate values, between 25 and 26 μmol l^{-1}, are observed. It seems likely that (as for the LSW surface) these intermediate values could result from the low-silicate southwestward flow on the western side of the gyre turning eastwards along approximately 54°N to form the southern limb of the gyre, mixing with higher silicate waters either from the southern approaches or from the centre of the gyre, and then turning northeastwards along the Irish slopes. In either case, the existence of a salinity maximum in the central Trough near 2400–2500 m, together with the observation that the salinities in this maximum show very little spatial variation over all the CTD stations shown in Fig. 11, supports a connection on this surface (either through advection or mixing or both) between the southern approaches (i.e. the 52°N and 20°W sections) and the central Trough.

Finally, we cannot definitely say what has caused the high silicate concentrations, above 27 $\mu mol\,l^{-1}$, in the centre of the cyclonic gyre in the central Trough, but possibilities would include either upward mixing from the silicate-rich deeper waters below, or that the episodic LSW inflow events could have extended to these depths, and advected higher silicate waters (over 26.5 $\mu mol\,l^{-1}$ at 53.5°N, 20°W in the present survey) from the south. This latter hypothesis is supported by noting that the positions of the highest silicates in the central Trough closely coincide with the positions of the lowest salinities and highest CFCs on the LSW surface.

Turning now to the model, Fig. 12a presents the circulation pattern on the density surface 27.88, corresponding to the NEADW core (at depths in the model between 2100 and 2300 m in the Trough). The flow pattern is remarkably similar to that inferred from the silicate observations (and to that for the LSW surface) in the central Trough, but there are differences in the southern approaches. In the central Trough, a pronounced cyclonic gyre lies directly beneath the circulation pattern on the LSW surface, and this has a southern boundary near 54°N. Flow speeds in the gyre are typically 5 $cm\,s^{-1}$, but reach 7 $cm\,s^{-1}$ in places. The gyre is largely fed from the north by a southward flow down the western flanks of the Trough, carrying overflow waters from the WTR. As for the LSW circulation, this flow also splits at the northern side of the South Feni Ridge, near 15°W, 55°N, forming one branch which flows down the southeastern side of the Ridge before recirculating in the central gyre, and one branch continuing down the steep slopes of the Rockall Bank. In the southern approaches to the Trough, however, there is a general cyclonic flow, in contrast to the anticyclonic flow inferred for the observations. In the model, there is a northwestward flow along the deeper slopes of the Porcupine Bank. Although part of this turns northeastwards near 52.5°N, 17°W to flow in the Rockall Trough, providing a southern source to the central gyre, most of the flow turns southwestwards between 52 and 53°N, and thereafter northwestwards following the deeper topography of the southwestern limits of the Rockall and Hatton Banks. We also note the presence of a cyclonic gyre in the northern Porcupine Abyssal Plain (PAP in Fig. 1) between 50 and 53°N, 16–19°W.

It is now instructive to examine in Fig. 12b the model circulation on the density surface 27.92. This surface forms part of the densest outflows over the WTR, and descends from 500–600 m deep at the WTR (Fig. 6d), to 2400 m at 56°N (Fig. 2f), 3000 m at 16°W, 54°N (Fig. 6e), and eventually to 4000 m south of 51°N in the PAP (Fig. 6e). There is a strong southwestward flow of these water masses along the western side of the deepest parts of the Trough, with flow speeds up to 7 $cm\,s^{-1}$. These carry water from the WTR overflow along the eastern (downslope) side of the North Feni Ridge between 59 and 57°N, then around the eastern side of the Rockall Bank, and on down the eastern side of the South Feni Ridge (see Fig. 6e) to about 54°N, with some recirculation into a weakened and smaller (as compared with those on the NEADW and LSW surfaces) central cyclonic gyre. At 54°N the dense overflows are turned to the south, and then to the west near 53°N, by the topographic "elbow" in the South Feni Ridge. The flow is then turned southwest

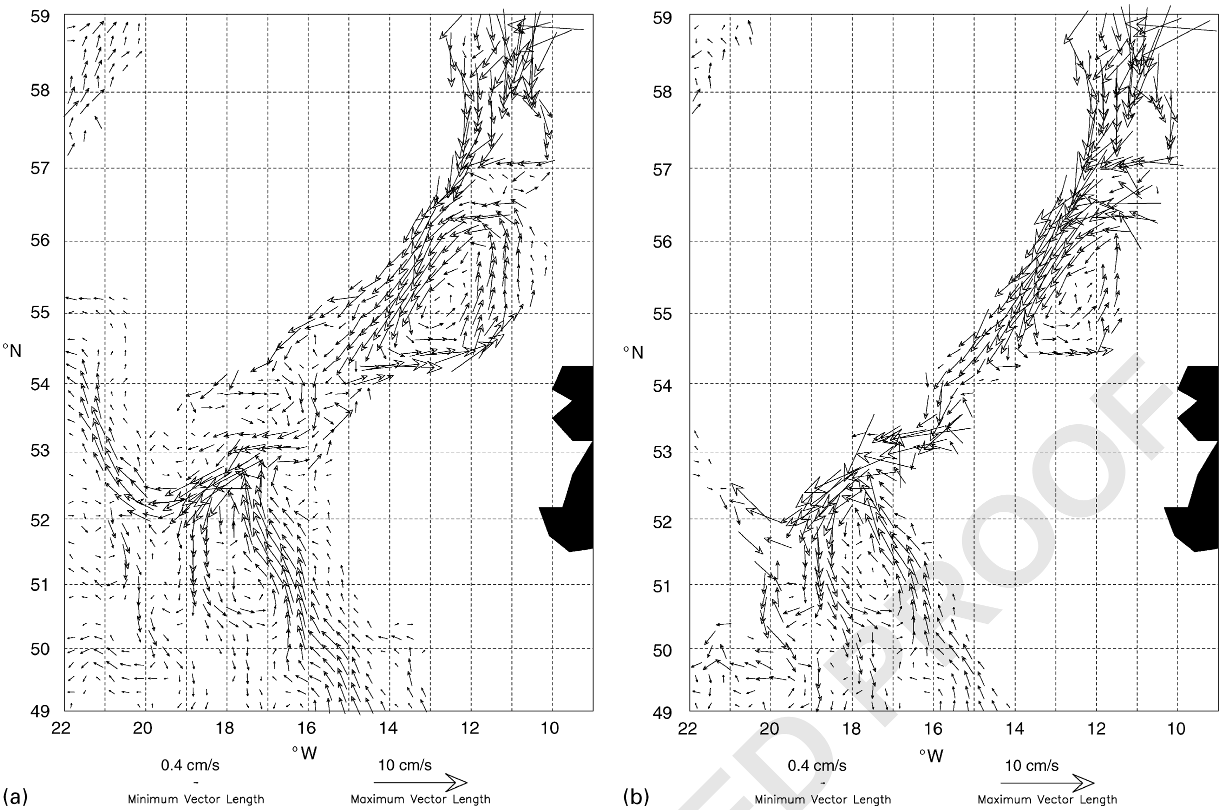


Fig. 12. Model currents ($cm\,s^{-1}$) on the density surfaces (a) 27.88, corresponding to North East Atlantic Deep Water, and (b) 27.92, corresponding to the dense overflows from the Wyville–Thomson Ridge. The vector arrows show the velocities at the arrow centres.

between 53 and 52°N following the (downslope side of the) southern end of the South Feni Ridge. At 19°W, 52°N, the current is largely turned to the south to flow down the Isengard Ridge (I in Fig. 1) to 19°W, 50.5°N, although part also escapes westward through a gap in the Isengard Ridge near 52°N. The dense flow down the Isengard Ridge is then turned partially eastwards near 50°N (presumably by the seamount system there), and then northward on meeting the Porcupine Bank topography and its associated boundary current near 16–17°W. This forms a deep cyclonic gyre in the PAP, with flow speeds of typically 3–5 $cm\,s^{-1}$, and which underlies that on the lighter NEADW surface. Overall, the flows on this dense surface are clearly strongly controlled by the topography, and appear to drive, at least partially, similar flow features seen on the NEADW surface and, to a lesser extent, on the LSW surface (e.g. the southwestward flow through 52–53°N, 16–20°W being a good example).

8. Summary and discussion

In the present study, we have investigated the circulation and structure of the water masses in the Rockall Trough in the spring, combining the results of a recent (May 1998) quasi-synoptic survey with those from a high (1/3° longitude) resolution ocean circulation model. Overall, the model is encouragingly consistent with the inferences made from the observations, and this has allowed conclusions to be drawn which are significantly more robust than those which would result from either the survey or the model alone.

In the upper, relatively well-mixed, layer the observed salinities are highest on the 52°N section, but become generally fresher further north into the Trough. There are also cores of high salinity both near the Irish–Scottish slopes and further west over the deeper waters in the central Trough, indicating the Shelf Edge Current (SEC) and the Rockall Trough Current respectively. The general freshening to the north implies the likelihood of mixing with fresher water masses, and these appear to be supplied by eastward flow through the 20°W section. This section shows the eastward inflow of fresh (fresher than on 52°N) water in several bands. Although we cannot be certain which of these features represent recirculating eddies and which represent genuine current branches, it seems most likely that the eastward flow between 52 and 53°N, co-located with the inferred inflow of the deeper water masses, is primarily responsible for the import of the fresher upper-layer water to the region.

We also note the presence of a relatively fresh upper ocean feature (with salinity below 35.50) near 17°W, 52°N (in Fig. 3d), and remark that this is co-located with the inferred southward outflows (through 52°N) of the deeper water masses. This fresh feature could therefore also indicate a partial turning to the south of the (fresh) upper layer flows which inflow near 52.5°N, 20°W. Furthermore, this retroflection of the upper layer flows could act to "trap" the observed high salinity (over 35.58) feature (derived from waters of a more southerly origin) near 18.5°W, 52°N (Fig. 3d), although large eddies have also been reported in this region (Ellett et al., 1986; Pollard et al., 1996) and may offer an alternative explanation for this feature.

The model clearly shows both the northward flow of saline waters through 52°N (carried by the SEC), and a relatively fresh inflow from the west along 54°N (being a branch from the model's North Atlantic Current). Part of this inflow turns southwestwards (as is possibly the case in the observations), but mostly transports fresher waters eastwards into the southern Rockall Trough, where they partially mix with the more saline waters carried by the SEC before continuing northwards through the Trough. The model also shows the SEC carrying a high salinity core northwards through the region, as well as the possibility of the branching of the northward flows in the central Trough. The model therefore strongly supports the inferences from the observations.

Our results also strengthen the findings of McCartney and Mauritzen (2000, from observations) that, in the upper ocean, the North Atlantic Current sweeps into the Porcupine Bank region from the west or southwest, and then bifurcates near 53°N to send one branch northeastwards through the Rockall Trough. Our study furthermore supports the circulation schematic of Ellett et al. (1986), which indicates that the northward flow through the Trough is instead derived primarily from a southern source and carried by a Shelf Edge Current (SEC) into the southern Trough.

The model upper layer salinities are generally lower by about 0.05–0.08 than in the present observations, but the model salinities in the SEC core show the same trend as in the observations, falling by about 0.04 between the southern Trough (54°N) and further north (57°N). The generally lower model salinities appear to result from the model mixed layer being deeper (600–800 m, see preceding discussion) than in the observations (400–700 m), thereby mixing the near-surface waters with the fresher water masses deeper down. However, there is historical evidence that winter mixed layer depths in the Rockall Trough may have been deeper at certain times in the past (as already described), so that the upper layer salinities may also have been less at those times. Indeed the variability of the upper layer salinity in the Trough at 57.5°N has been investigated by Holliday et al. (2000) and shown to vary by up to ±0.08 over the past 23 yr. Moreover, these authors showed that the climatological mean salinity in the upper layer (at 200 m say) on the 57.5°N section is about 35.35, slightly fresher even than the present model. Consequently, the model upper layer salinities lie generally within the range of variability expected in nature. We also note that the model currents in the SEC near 57°N have been compared with observed currents by New et al. (2000). While the model current (because of the approximately 20 km resolution in the model) was found to be too weak and too broad (both by a factor of about two), the transport (above 500 m) in the SEC agreed well with estimates from observations, being 1.6 Sv as opposed to 1.5–1.8 Sv.

We also remark in passing that a core of high salinity water, indicative of Mediterranean Outflow Water (MOW) flowing northwards in an eastern boundary undercurrent, was seen in the present survey near the continental slope only on the 52°N section (between depths of 750–1000 m, not shown). The fate of this water mass, and whether or not it was able on this occasion to penetrate into the Rockall Trough, requires a more detailed study which will be undertaken separately.

There is remarkably good agreement between the model and the observations for the circulation on and structure of the Labrador Sea Water (LSW) surface. Both show the main inflow of the freshest LSW through 20°W, between 52 and 54°N (co-located with the inflowing surface waters), and that this then turns primarily to the south, but with some also entering the central Trough where a strong cyclonic gyre is present. Both also show the southward flow of more saline water down the western side of the Trough, indicating overflows from the Wyville–Thomson Ridge (WTR). This more saline water mixes with the LSW, and is the likely reason for the generally increased salinity of the LSW inside the Trough as compared with that in the southern approaches to the Trough. Finally, both the model and the observations show that LSW penetrates the Trough to about 56.5°N, with a core circulating in a pattern which approximately follows above the 2500 m depth contour, highlighting the effect of topography on steering these flows.

The survey has also given us the insight that there could be episodic inflow events of LSW into the Rockall Trough (supporting the hypothesis of Holliday et al., 2000, from the LSW salinity variability near 57.5°N). This was shown by the local salinity minima on the LSW surface in the central Trough, and the coincident maxima of CFC-11. Without such inflows, lateral (isopycnal) mixing would gradually remove the extrema in these quantities. We speculate that such events could result from the unsteadiness of large-scale eddies in the southern approaches to the Trough, allowing the intermittent inflow of the LSW. These eddies are present in the model, but are too steady to allow such episodic inflows (possibly because the model resolution is too coarse). Similar eddy-like features have also been observed in nature in this region, as referred to earlier.

One other possible explanation of the salinity minimum in the central Trough which should be considered is that this could result from long-term changes in the source characteristics of the LSW. Read and Gould (1992), Lazier (1995), and Dickson et al. (1996) have shown, for instance, that the LSW at its source in the Labrador Sea has undergone two pronounced cooling and freshening events (associated with increased convection depths), between 1972 and 1980, and from

1986 onwards, separated by a more saline period in between. These cooler, fresher waters travel (in part) eastwards across the North Atlantic, although estimates of the timescales to reach the Rockall Trough vary widely, between 5 and 20 yr (Read and Gould, 1992; Cunningham and Haine, 1995; Sy et al., 1997). If the longer estimates are correct, then it may be plausible that the fresh waters in the central Trough result from the 1972–1980 fresh period, and the fresh waters circulating in the southern approaches result from the period after 1986. However, atmospheric CFC concentrations were steadily increasing during the above periods, so if this were the case, we would expect the water to become progressively older, with lower CFC concentrations, further northwards into the Trough. The present CFC pattern, with an identifiable maximum in the central Trough, therefore counts against this, and argues for a more recent "episodic" inflow.

We note that the LSW salinities observed in the present survey in and near the Rockall Trough (less than or close to 34.90) are markedly fresher (by 0.03–0.05) than those reported in 1991 (Read and Gould, 1992) and than a mean over recent decades (Paillet et al., 1998), and almost certainly indicate the presence in the Trough of some of the fresher LSW source waters described above (probably those which were produced after 1986). A further point is that while the model LSW salinities are about 0.07–0.08 higher than those of the present survey, differences with earlier surveys would therefore not be so large.

Considering now the deep and near-bottom flows in the Trough, we have shown the existence of a salinity maximum, near 2500 m deep, extending to 56°N. This reveals the presence of the North East Atlantic Deep Water (NEADW). However, high silicate values in the deepest levels of the Trough, indicative of Antarctic Bottom Water permeating into the Trough from the south, are also in evidence up to at least 56°N, and these partially mix onto the NEADW layer. We have been able to use the observed silicate distribution on the NEADW (salinity maximum) surface to infer the deep flow patterns, and these closely follow the flows on the overlying LSW surface. This reveals a quasi-barotropic nature to the deeper flow fields, which is also borne out in the LADCP section at 20°W and, largely, by the model results. The circulation (inferred from the observations) on this surface consists of an inflow from the west (through 20°W, 52°N) which is largely turned to the south in the southern approaches to the Trough, exiting through 52°N at 17°W, and a cyclonic gyre in the central Trough. In the southern approaches, the core of low silicate values sweeping in from the west offers support to the hypothesis of Ellett and Martin (1973) that the NEADW in this region has resulted from the Iceland–Scotland overflow waters (low in silicate, van Bennekom, 1985) which transit southwards down the western flanks of the Hatton and Rockall Banks. In the model, the cyclonic gyre in the central Trough is directly and strongly fed by a northern source (as a result of advection on the appropriate density surface from the WTR overflows), and more weakly fed from the south. In the observations, the influence of the northern WTR overflow waters is still apparent, but there is no direct advective connection (since the deepest waters on the 57°N section are not dense enough). Instead, vertical mixing in the boundary current in the northwestern region of the central gyre appears to inject lower silicate waters onto the NEADW surface there. There is also the possibility that the central gyre in the observations is fed by waters from the south.

The observed eastward inflow of the NEADW through 20°W occurs near 52°N, and is co-located with the inflow of the overlying LSW. We also note that this is the latitude of the Charlie Gibbs Fracture Zone (CGFZ), a deep channel in the Mid-Atlantic Ridge, through which the LSW is supposed to flow. It is therefore tempting to think of the LSW as a dynamically "active" inflow, which could (in the present case) be moving rapidly into the eastern basin through the CGFZ following a quasi-zonal pathway near 52°N (conserving its potential vorticity), and sweeping up and carrying along the underlying NEADW as it does so. This may not always be the case though, and could depend on the flow rate of the LSW through the CGFZ (which could be relatively large at present following the recent (i.e. since 1986) freshening and increased depths of convection in the Labrador Sea). On the other hand, the model has relatively weak inflows of LSW from the west, and relatively strong outflows from the Rockall Trough of the NEADW and denser waters. These dense outflows reach the deepest waters in the Porcupine Abyssal Plain (PAP), and (because of their relative density), take part in a cyclonic circulation with topography on their right-hand side. When viewed from a broader perspective (not shown), the model produces outflows from the Nordic Seas at densities near and above 27.9 kg m^{-3} through the Faeroe Bank Channel into the northern Iceland Basin, and through the Rockall Trough into the PAP, and these appear to act as sources of dense water at great depth which drive a cyclonic circulation around the whole of the eastern basin of the North Atlantic. It appears that this (strong) deep cyclonic gyre affects the model circulation on the overlying NEADW surface (and to a lesser extent that on the LSW surface), driving it in a cyclonic direction in the southern approaches to the Trough, in contrast to the anticyclonic circulation of the NEADW in the observations (which could be following underneath a strong inflow of the LSW).

There is, however, good evidence from the bottom bedforms of a general cyclonic circulation around the deeper topography of the North East Atlantic basin (Lonsdale and Hollister, 1979), and this is furthermore supported by the geostrophic estimates of the deep circulation by van Aken and Becker (1996). In particular, these papers both reveal a deep northward flow along the western side of the Porcupine Bank, and northwestward flow around the southwestern extremities of the Rockall and Hatton Banks, thus strongly supporting the deep circulation patterns in the model. (Furthermore, if these deep circulation pathways are correct, together with the inferred circulation of the LSW in the present study (supported by Paillet et al., 1998), then there must be flow reversals between the intermediate and deepest waters in this region).

In more general terms, the present study, showing a cyclonic gyre in the central Rockall Trough on both the LSW and NEADW surfaces, is in good qualitative agreement with the inferences about the bottom-most flows of Lonsdale and Hollister (1979) from their analysis of the sedimentary bedform features. Even details such as the inferred splitting of the bottom currents at the northern end of the South Feni Ridge are convincingly reproduced in the model. However, whereas Lonsdale and Hollister (1979) were only able to infer the circulation patterns for the flows contiguous to the sea-bed, we have been able to show that the cyclonic nature of the flow in the central Trough extends to cover at least the deeper and intermediate water mass regimes (the NEADW and the LSW). We have furthermore shown, for the first time (we believe), the circulation pathways for the Labrador Sea Water and North East Atlantic Deep Water in the Trough.

Although there has been generally good agreement between the model and the observations, and the model has significantly helped with our interpretation of the observations, we have also gained useful insights into how the model representation could be improved. Firstly, we have already remarked that the usage of more layers (or different choices for the layer densities) would be likely to give a better representation of the model upper layer structure in the Rockall Trough (which extends too deeply as a relatively uniform layer in the model). Secondly, it is apparent that the southwestward outflows of the deepest water masses from the Rockall Trough are likely to be too rapid and too dense in the model (and this could overly affect the circulation patterns of the NEADW and the LSW in the southern approaches to the Trough, as described above). This could be improved in two ways. Firstly, we have already shown that the overflows of the dense waters (heavier than 27.80 kg m^{-3}) across the WTR are too large (about 2.1 Sv) as compared with most recent estimates (0.3–0.4 Sv), and this results from the WTR topography being about 100–150 m too deep. This itself is an artifact of the model resolution, which effectively led to a smoothing of the topography over the model grid cells, 20 km^2. A higher resolution model would therefore have a better representation of the WTR topography, a shallower ridge, and a weaker, more realistic, overflow. Alternatively, it would be possible to manually adjust the topographic dataset used by the model to represent the ridge more realistically. This, however, was not known as a key issue before the model was implemented.

It also seems likely that there is insufficient vertical (diapycnal) mixing in the model to adequately represent the entrainment process as the NSDW waters spill over the WTR and into the Rockall Trough. In nature this is accompanied by strongly enhanced vertical mixing, mixing the densest NSDW waters with the lighter ambient waters, and leading to a reduction in the maximum densities in the overflow with distance downstream. In the model, waters with densities in excess of 28.0 extend all the way from the WTR to the PAP, but are not evidenced in the observations, implying the likelihood of too little mixing in the model. The vertical mixing in the model was defined by setting the diapycnal diffusivity as $K = 10^{-7}/N/\ m^2\ s^{-1}$ where N is the buoyancy frequency. This replicates average mixing rates in the deep ocean, but has now been shown to provide insufficient mixing in regions where there are other dense overflows such as the Denmark Strait (Willebrand et al., 2000). However, this is not really a model problem, since the model mixes at just the rate that is specified. It really points instead to an insufficient knowledge of what the vertical mixing rates should be as the WTR overflow waters descend into the Trough, and how these should be effectively parameterised in the model. There is thus a definite requirement for detailed observational studies to measure these rates, and to understand the mechanisms involved, if our present generation of ocean models are to adequately represent this process.

On the other hand, although the present survey did not detect overflows as dense as those in the model, there could be significant decadal-timescale variability associated with the cycling of the North Atlantic Oscillation (NAO) index (essentially the pressure difference between Iceland and the Azores). It is known (Dickson et al., 1996; Dickson, 1997), for example, that when the NAO is high, as it has been throughout most of the 1990s, then wintertime convection in the Nordic Seas is shallow, so that the volumes of dense NSDW produced are low. In this case, the interface between the NSDW and the lighter waters in the Nordic Seas would be expected to sink, as the NSDW outflows from the Nordic basins and is not replenished sufficiently quickly. Consequently, the overflows of dense NSDW across the WTR would be expected to be low or non-existent. However, at low NAO states, with anomalously high production of the NSDW, it is plausible that the interface could rise sufficiently (i.e. above the depth of the WTR sill) so that large volumes of dense NSDW could spill southwards into the Rockall Trough. Thus the deepest flow patterns in the model could more closely represent those occurring near such low NAO states rather than those in the 1990s.

In summary, we feel that the present study has provided valuable insights into the circulation patterns of the Rockall Trough, and a particular strength has been the investigation and comparison of a recent survey and a high-resolution ocean model. Overall, the model and the observations are in good agreement, particularly in the central Rockall Trough, and this has allowed conclusions to be drawn which are significantly more robust than those which would result from either the survey or the model alone. In particular, we have been able to infer the circulation pathways of the intermediate and deeper waters for (we believe) the first time. The study has furthermore illustrated the complexity and variability of the likely flows in this area, of potential interest for the offshore production of oil and gas, the fisheries and defence industries, and for navigation. It has also contributed to an ongoing community effort to assess the realism of, and improve, our current generation of ocean circulation models.

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