PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Water masses and mesoscale circulation of North Rockall Trough waters during JASIN 1978

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During the Joint Air–Sea Interaction Experiment (JASIN 1978) grids of temperature and salinity profiles were worked within an area of about 150 km × 150 km to obtain details of the mesoscale circulation around the location of the experiment in the North Rockall Trough. Data were also obtained from moored current meters and from research vessel observations in the surrounding waters.

In the uppermost layers two water masses were present, North Atlantic Water from southern parts of the Rockall Trough and fresher Modified North Atlantic Water from the north and west. Beneath these an intermediate water formed by Atlantic Water in contact with Subarctic Intermediate Water was found and at greater depth distinctions could be drawn between water from the south, water with an admixture of Norwegian Sea Deep Water from the Scotland–Iceland ridges and, more sparse, water with a component of Arctic Intermediate Water from the Faroe–Shetland Channel.

The patterns of circulation were found to change little between the lower depths and 200 m. An anticyclonic eddy of fresher, colder water moved westwards across the northern half of the grid at about 1.4 km day^{-1}, the northern sector of a more saline meander expanded westwards across the southern part of the area, and smaller less well resolved circulations were found in the west. The eddy contained water of overflow origin and the meander appears to have been part of the main Atlantic to Norwegian Sea current.

When inverse analysis was applied to two of the data sets to investigate choices of reference level, zero velocity at the bottom gave the only physically realistic solution. Although the necessary process of averaging the observations to data points 45 km apart obscured the resolution of smaller features, confidence in the reference level that satisfied the inverse analysis allowed classical geostrophic analysis to be performed on the full set of stations, supporting and quantifying the earlier analysis of patterns.

The influence of the deeper circulation can be seen in the modification of the thermohaline structure in the seasonal thermocline and mixed layers. Boundaries between adjacent upper water masses were distorted by underlying convergences or fragmented by horizontal shears.

1. Introduction

The main features of ocean circulation within the northeast Atlantic arise from the relatively warm and saline water of the Atlantic Current entering the area from the west and southwest close to 50° N, where the Charlie–Gibbs Fracture Zone disrupts the Mid-Atlantic Ridge, and from the colder, fresher waters spreading southeastwards from the Labrador Sea. The oceanic polar front that separates these disparate waters is seen in the summer 1958 distribution of Dietrich (1969) to run eastward in about 52° N latitude to 25° W, where it turns northwestwards and weakens, although intermediate boundaries are probably widespread throughout the Iceland Basin. The north-going portion of the Atlantic Current water is divided into two branches by the topography of the Rockall Plateau and the banks that link it to the Scotland–Iceland ridges: one circulates north and northwestwards to form the Irminger Current south of Iceland with a lesser flow into the Norwegian Sea across the Faroe–Iceland Ridge, and the second is directed northeastward through the Rockall Trough, whence its upper waters reach the Norwegian Sea across the Wyville–Thomson Ridge.

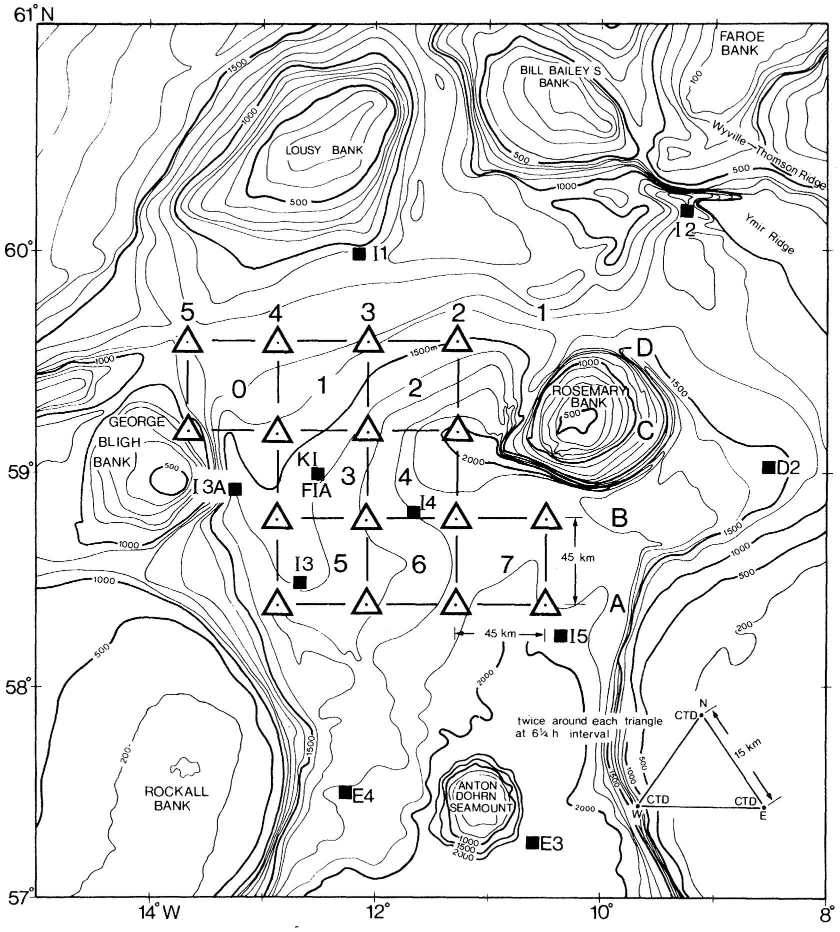

FIGURE 1. The JASIN 1978 Hydrographic Survey Area. The grid points were labelled by their vertical and horizontal coordinates as A1–A4, B1–B4, C2–C5 and to D2–D5. Current meter moorings are shown by black squares and the Fixed Intensive Array (FIA) is indicated. The boxes numbered 0–7 are those used in the inverse method calculations. Isobaths are in metres.

Net transport of water in the latter branch, though important to the heat budget of the northwest European seas, is nevertheless small by western Atlantic standards, having been assessed at about 3×10^6 m^3 s^{-1} above 500 m depth during 1964–65 (Ellett & Martin 1973). Within the Rockall Trough the water column is notably less structured than in its approaches (Ellett 1979), partly as a result of deep winter mixing in the northeast Atlantic (Meincke 1967), but also because in the south the injection of the saline Mediterranean outflow at mid-depths weakens the vertical density gradients and leads to greater mixing close to the continental slope (Ellett & Martin 1973; Pingree & Morrison 1973), in the vicinity of which much of the water enters the Trough. Below 1250 m depth the Trough is enclosed in all directions except to the south, so that the deep water movements are generally small.

In reviewing the sea areas around Britain to determine the site for the 1978 air–sea interaction study, these considerations indicated that the northern part of the Rockall Trough would provide the least variable oceanic environment, while being situated in the region most affected by the mid-latitude westerlies. It was also well suited to the logistic requirements of the ships and aircraft involved in the experiment. In the event, the intense scrutiny of the JASIN 1978 participants revealed that the oceanography of the Large-Scale Area (LSA) was by no means featureless, but this is a reflexion of the scales of resolution of both the oceanographic survey and the modern techniques employed.

During the summers of 1976 and 1977 cruises were made by the research vessels R.R.S. *Challenger*, Hr.Neth.Ms. *Tydeman* and R.R.S. *Discovery* to obtain preliminary observations, both from the ships and with moored current meters. Results from these years suggested (Pollard 1977*a*, *b*) that the main north-going current in the Rockall Trough was passing between Rockall Bank and Anton Dohrn Seamount and subsequently turning northeastwards to pass between Rosemary Bank and Anton Dohrn Seamount. The region between George Bligh Bank and Rosemary Bank (figure 1) was therefore chosen as the centre of the JASIN experiment with the aim of ensuring that observations of the upper ocean layer were not greatly distorted by advective effects.

2. Observations

To provide the necessary hydrographic background to the experiment, repeated observations were made at the sixteen positions 45 km apart shown in figure 1. These were labelled by the coordinates shown in the figure as A1–A4, B1–B4, C2–C5 and D2–D5, and the grid composed the Hydrographic Survey Area (HSA). The whole of the Rockall Trough north of 57° N latitude was designated the Large-Scale Area (LSA) and data, mostly unrepeated, were collected within it during the ten weeks of the experiment. Current meter moorings were deployed at a number of sites throughout the LSA. A brief outline of the observations will be given here, but for full details reference should be made to the summary published by the Royal Society (1979).

The HSA grid was worked chiefly by *Tydeman* and *Challenger*, but R.R.S. *Shackleton* provided data during the mid-experiment period when both these ships were absent. Two complementary plans were followed: *Challenger* and *Shackleton* obtained salinity–temperature–depth (STD) or conductivity–temperature–depth (CTD) profiles throughout the water column at the corners of triangles of 15 km side centred upon each grid point. The three profiles were repeated in sequence after about $6\frac{1}{4}$ hours had elapsed in order to reduce tidal aliasing of the data. The grid positions were mostly covered in east–west lines, and the main part of the grid was repeated four times in the course of eight weeks (surveys A–D). *Tydeman* made observations that consisted of full-depth CTD profiles at each of the twelve positions A2–A4 to D2–D4 and also made rapidly repeated ('yoyo') CTD lowerings to 150–200 m depth over the course of 1 hour at the corners of triangles of 22.5 km side. Each yoyo station was repeated after $6\frac{1}{4}$ hours. Eight of these surveys were made during the experiment, the grid being alternately worked in east–west and north–south directions.

To provide data from the LSA, *Challenger* twice worked STD sections from the Scottish shelf to

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Rockall Bank across Anton Dohrn Seamount. *Shackleton* obtained CTD and reversing water-bottle sections at the eastern, northern and western boundaries of the LSA and R.V. *Scotia* worked water-bottle stations to the east and north of Rosemary Bank. Shorter CTD sections were made by a number of other ships. Apart from the large number of instruments in the Fixed Intensive Array (FIA), eight current meter moorings provided data at depths ranging down to 1800 m in deep water around the LSA, three of which, E1, E2 and D1 (figure 1), were in position from spring 1978.

3. Water masses

The very large set of CTD and STD profiles collected in the LSA during JASIN 1978 shows many minor water mass variations. However, the property differences are mostly very small, and even the chief division in the upper waters, between North Atlantic Water (NAW), which had entered the Rockall Trough from the south, and Modified North Atlantic Water (MNAW), which had entered from the north and northwest, is one that has only recently been formally categorized (Martin 1976). These upper Atlantic waters are aspects of the cyclonic gyre of Sub-polar Mode Water described recently by McCartney & Talley (1983), and the differences arise from the branching, noted earlier, of the North Atlantic Current to the east and west of the Rockall Plateau. The branch circulating northwards between the oceanic polar front and the Plateau is freshened and cooled by the admixture of waters from the west and modified by local processes around the marginal banks and sills. The branch passing into the Rockall Trough is subject to a lesser degree to mixing with fresher, cooler water in its upper levels (Ellett 1980) but also before entering the trough has gained salt at mid-depths from Gulf of Gibraltar Water, the product of the Mediterranean outflow (Cooper 1952). Thus the upper waters entering from the south and the northwest differed in the northern Rockall Trough during JASIN 1978 by about 0.1‰ in salinity (*ca.* 35.33 and 35.22‰) and about 1 K (*ca.* 9.3 and 8.5 °C) in temperature at the base of the upper waters, with larger salinity differences (35.10–35.30‰) close to the surface. The MNAW also exhibited more heterogeneity as a result of its varied passage over and around the northern boundaries of the trough.

In discussion of the water masses of the LSA it is implicit that existing names are applied with a local connotation and that temperature and salinity characteristics may differ considerably from those of the water types from which these varieties were derived. It is also important to note that inter-annual water mass variations are discernible in this area (Martin 1981; Ellett 1980) and comparison with other years may not be fully valid.

The properties of water reaching the LSA from the south throughout the water column, which occupied the southern and southeastern part of the HSA, are clearly shown by the envelope of temperature–salinity (T–S) characteristics for the 13 deep STD stations of the section across the Anton Dohrn Seamount, which bounded the LSA to the south. This is shown in figure 2 for the *Challenger* section of 9–10 August 1978. Variation was very small at temperatures below 10 °C with the exception of the westernmost station against Rockall Bank, which shows some influence at 4.4–5.0 °C of saline overflow from the Wyville–Thomson Ridge. The general form of this T–S envelope needs little elaboration here. Above temperatures of about 9.3 °C, NAW was found, having a thickness of 150–250 m at that time of year. Beneath it to depths of 750–850 m temperature and density gradients are weak. The characteristics within this substantial section of the water column fall parallel to the coldest extremes of the North Atlantic Central Water (NACW) envelope of Sverdrup, Johnson & Fleming (1942). It is not inconsistent with the work

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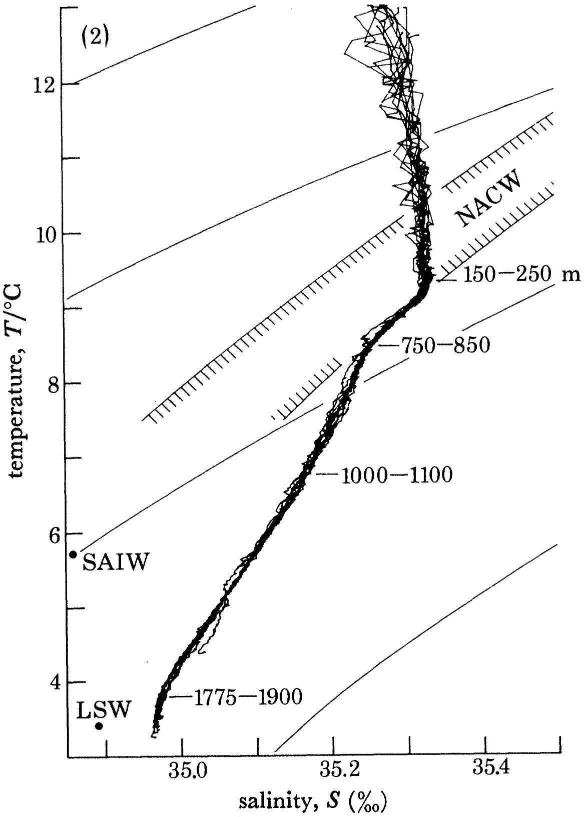
of Iselin (1939), from which the concept of the Central Water was derived, to note that the slope of this portion of the *T–S* correlation is appropriate to mixing between the lower NAW and the Subarctic Intermediate Water (SAIW) (see also figure 3) of Bubnov (1968), which is found at similar depths near the weather station *Juliett* (52° 30′ N, 20° W). SAIW affects the salinity of the upper layers of the Rockall Trough significantly in winter (Ellett 1980), and in the present context the mixed NAW–SAIW may be viewed as another 'modified' NAW. As it would be confusing to refer to it as NACW, we shall here call it Intermediate MNAW (IMNAW).



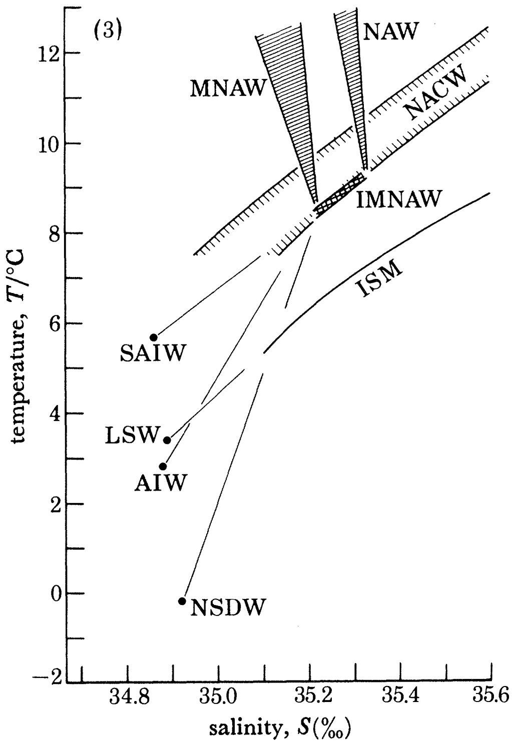


FIGURE 2. Temperature–salinity envelope for the 13 deep stations of the Anton Dohrn Seamount section, 9–10 August 1978. Depths in metres are indicated against the envelope and source characteristics of Subarctic Intermediate Water (SAIW) and Labrador Sea Water (LSW) are shown.

FIGURE 3. Schematic temperature–salinity diagram of the water masses of the JASIN area: NAW, North Atlantic Water; MNAW, Modified North Atlantic Water; IMNAW, Intermediate Modified North Atlantic Water; SAIW, Subarctic Intermediate Water; LSW, Labrador Sea Water; NSDW, Norwegian Sea Deep Water. The North Atlantic Central Water (NACW) envelope of Sverdrup *et al.* (1942) and the Intermediate Salinity Maximum (ISM) (Gulf of Gibraltar Water) of Wüst (1936) are also shown.

Below the IMNAW the *T–S* envelope of figure 2 shows a smaller decline in salinity down to 1000–1100 m (*ca.* 6.75 °C), at which level a weak salinity inflexion marked the core of the remaining influence of the Gulf of Gibraltar Water. This inflexion has characteristics that fall close to those given by Wüst (1936) for the Intermediate Salinity Maximum (see figure 3), which occurs over much of the northeast Atlantic outside the Rockall Trough, and should not be confused with inflexions that arose within the HSA in the same portion of the water column when water with a component of Norwegian Sea Deep Water (NSDW) overlaid water with a component of Labrador Sea Water (LSW), examples of which will be given subsequently.

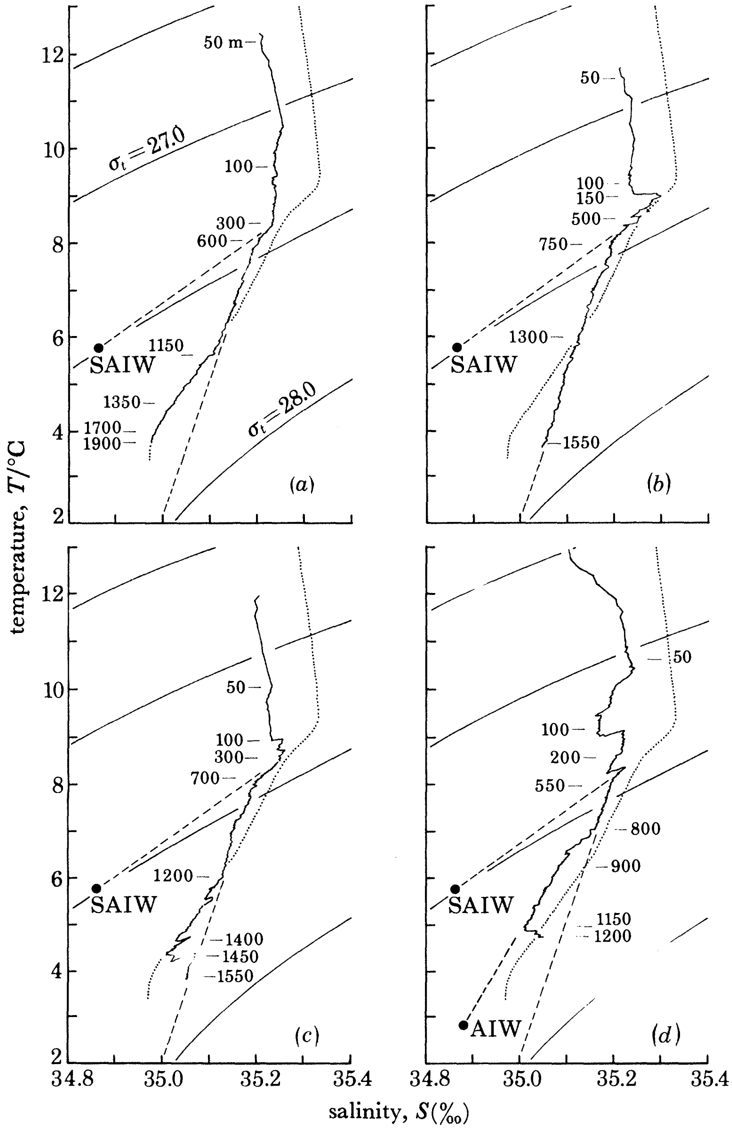


FIGURE 4. Temperature–salinity diagrams from the northern part of the HSA: (*a*) Station C2N, 22 August 1978; (*b*) Station D2E, 22 August 1978; (*c*) Station D2W, 22 August 1978; (*d*) Station D5W, 31 July 1978. Mean *T–S* characteristics from the Anton Dohrn Seamount section are shown by a dotted line. Source characteristics for Subarctic Intermediate Water (SAIW) and Arctic Intermediate Water (AIW) are shown, and dashed lines represent mixing lines from these and Norwegian Sea Deep Water. Depths beside *T–S* curves are in metres.

In the envelope of figure 2, a more definite inflexion than that at mid-depths occurs at 1775–1900 m (3.8 °C) and indicates the local characteristics of LSW (Worthington & Metcalf 1961). Below this depth the fall in salinity is reduced by the presence of water from the overflows of relatively high salinity into the northeast Atlantic across the Scotland–Iceland ridges (Lee & Ellett 1965).

Characteristics of the chief water masses influencing the LSA are summarized in figure 3, and some of these have already been discussed. The properties of NAW, MNAW and IMNAW have been chosen from the JASIN data, and those for the NACW, the Intermediate Salinity Maximum and LSW have been taken from the cited literature. For SAIW the *T–S* characteristics (5.7 °C, 34.86‰) are means of the 200 m interpolations for 14 water-bottle lowerings made at weather station *Charlie* during 5–26 May 1966, given by Husby (1968). The NSDW values (−0.2 °C, 34.92‰) are those at 600 m from the mean Norwegian Sea profiles of Mosby (1959) and are intended to represent the deepest water able to cross the Wyville–Thomson Ridge. Arctic Intermediate Water (AIW) (2.8 °C, 34.88‰), originating from the region to the north

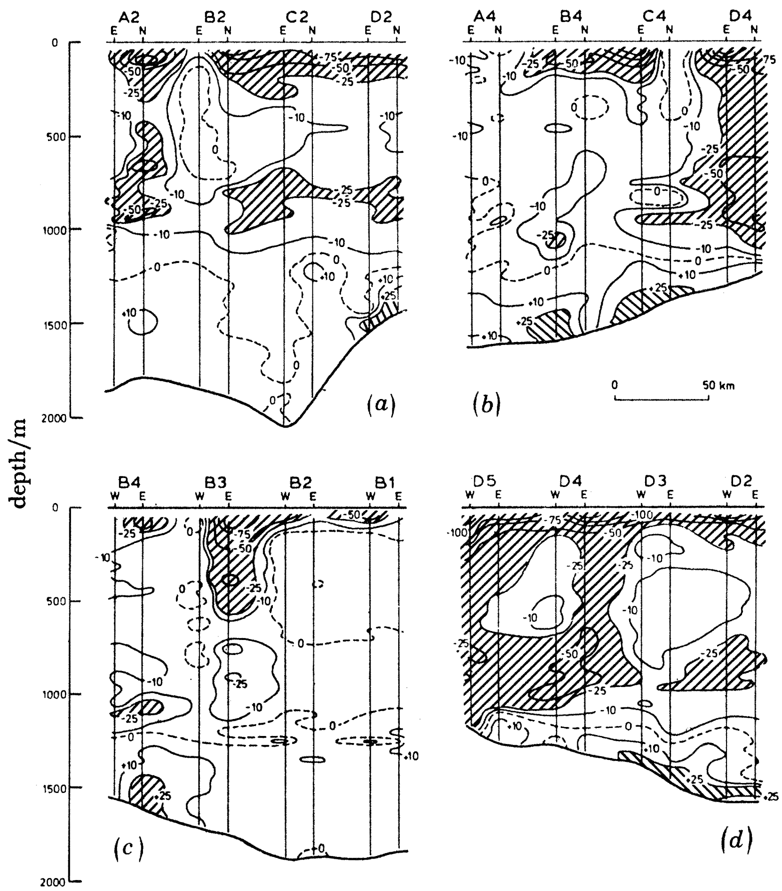


Figure 5. Sections of salinity anomaly (parts per million) from the mean temperature–salinity correlation for the Anton Dohrn Seamount section, from *Challenger* observations, 31 July to 8 August 1978: (*a*), (*b*) south–north, (*c*), (*d*) west–east. See figure 1 for station positions. Anomalies greater than 0.025‰ are hatched.

of the Faroe–Iceland Ridge, was found in undiluted form in the Faroe–Shetland Channel in 1978 (Martin 1981). The commonest mixing lines are indicated in figure 3, these being between SAIW and NAW, AIW and IMNAW, NSDW and IMNAW, and LSW and the Intermediate Salinity Maximum.

Some of these characteristics and mixing lines are shown in figures 4*a–d*, which illustrate the water masses that enter the Rockall Trough from the north. Additionally, the mean T, S correlation from the envelope of figure 2 is shown to provide a comparison with waters of southerly origin. Figure 4*a*, from station C2N (i.e. the northern apex of the triangle of stations worked at position C2) shows MNAW extending from the surface to 300 m depth. Between 300 and 600 m IMNAW indicated a trend towards SAIW, but from 650 to 1150 m the water was clearly a product of the mixing of the IMNAW and NSDW, probably in the northeastern part of the Rockall Trough. This overflow-derived water did not extend to the bottom at this station, the lower half of the water column being of southern origin, as shown by its similarity to the T–S correlation for the Anton Dohrn Seamount section below 1150 m. The latter water need not necessarily have been flowing directly from the south, but may have been circulating with the water above it as part of the water normally resident below the level of the northern sills of the trough. As noted previously, the points of inflexion in salinity where the two water masses adjoin could be confused with that due to the core of the Gibraltar water in the south of the LSA, but the lower temperature and a comparison with the reference curve clarify this.

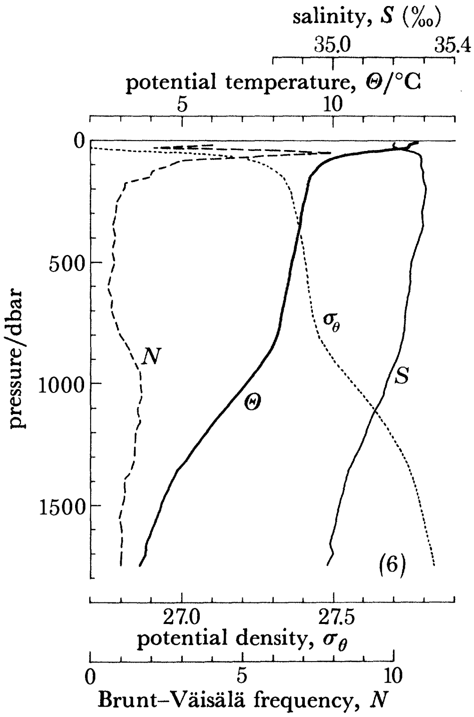
Figure 4*b*, from D2E, illustrates a station where more saline IMNAW was found beneath a shallow (150 m) upper MNAW layer, and where the lower part of the water column was a direct mixture with NSDW from 750 m to the bottom. An adjoining station, D2W (figure 4*c*), shows an example that falls between the two preceding examples. Here the water column reverts from 'overflow' to 'southern' type at 1200 m, but returns to overflow characteristics with a marked salinity inversion at about 1450 m.

Figure 4*d* shows one of the least saline profiles observed. It was taken at station D5W, between George Bligh Bank and Lousy Bank, and its most interesting feature is the water below 800 m. At this depth the T–S correlation departs from the IMNAW–NSDW mixing line to fall upon one that in the diagram joins water of IMNAW and AIW characteristics. Although AIW has not previously been observed in the Rockall Trough, and nutrient observations for positive identification are lacking, these two water masses occur one above the other to the north of the Iceland–Faroe Ridge and in the Faroe–Shetland Channel, but to a smaller thickness. Martin (1981) has shown that AIW influence was at a maximum in the latter during 1978 and it seems possible that the D5W water, which retains a 60% AIW content at its base, represents an overflow of this water across the Wyville–Thomson Ridge. As the AIW is less dense than the NSDW overflow, it may be postulated that the former circulated around the northern wall of the Rockall Trough before reaching George Bligh Bank. In view of the distribution of AIW found by Dooley & Meincke (1981) during the 1973 ICES Overflow Expedition, a route into the trough by way of the sills between George Bligh Bank, Lousy Bank and Bill Baileys Bank seems less likely, although the fact that this water was only encountered at stations B4, C5, D5 and D4N raises this possibility.

The horizontal distribution of these water masses was generally similar throughout the JASIN experiment. 'Southern' water was found in the south and east of the HSA; in the north, MNAW and IMNAW occupied the upper water column, mostly with a mixed overflow water beneath; at the stations farthest to the northwest AIW appeared at depth during the first three *Challenger* surveys. The largest water-mass change propagating into the HSA was at the deepest levels, where the strength of the component of NSDW overflow from the Wyville–Thomson Ridge increased in the northeast between the second and third surveys.

4. Structure

An example of the variations across the HSA is given in figure 5, which shows two north–south and two east–west sections across the area during 31 July to 8 August. The sections are in terms of salinity anomaly from the mean T–S correlation for the Anton Dohrn Seamount section, salinity at observed temperatures at 50 m depth intervals at each of the stations being compared with salinity at the same temperature upon the reference curve. Thus negative values show fresher water than upon the Anton Dohrn Seamount section and positive values, more saline water. Figure 5*a* is towards the east side of the HSA, and except in the upper layers and a mid-water portion of station A2N, conditions were within $\pm 0.025‰$ of the reference curve. Towards the west (figure 5*b*), fresher water existed at D4 down to 1200 m with more saline water below. This is a reflexion of the way in which the mixing line between IMNAW and NSDW intersects



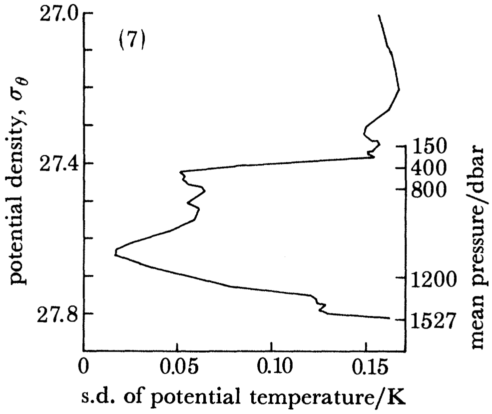


FIGURE 6. An example of the vertical profiles of potential temperature, *T*, salinity, *S*, potential density, σ_θ, and Brunt–Väisälä frequency, *N*, from the mean of six lowerings made at station B3, during 25–26 August 1978.

FIGURE 7. Standard deviation (s.d.) of potential temperature on σ_θ surfaces from Hr. Neth. Ms. *Tydeman* observations for the second half of the experiment (from Van Aken 1981).

the reference *T–S* curve at mid-depths (see figure 4*b*, for example), and shows the influence of Wyville–Thomson Ridge overflow throughout much of the water column in the northwest of the HSA. Figure 5*c* crosses the southern half of the HSA and shows water of largely southerly origin except at station B3E, where fresher water intrudes; figure 5*d* shows overflow-influenced water along the northern boundary of the area.

Although salinity anomalies below 150 m depth are never greater overall than $\pm 0.05‰$ in these diagrams, it can be seen that there are a number of vertical discontinuities that stretch either throughout the water column or through a large part of it. In such frontal zones there was much small-scale structure of the type seen in the *T–S* plots of figures 4*a–d*, which the use of data extracted at 50 m depth intervals has suppressed. The general form of the vertical profiles is illustrated by the examples of figure 6, which gives profiles of potential temperature (Θ), salinity (S), potential density (σ_θ) and Brunt–Väisälä frequency (N) for the means of six STD lowerings at a station (B3) near the centre of the HSA. In this example the seasonal thermocline reached to about 150 dbar† and the main thermocline was found between 800 and 1400 dbar.

† bar = 10^5 Pa.

The weak gradients in the layer between these have their origin partly in the small density differences between the two water masses (NAW and SAIW) that form the IMNAW occupying this part of the water column, and partly in the further weakening of these differences by the deep winter mixing of the northeast Atlantic (Meincke 1967). Van Aken (1981) has studied the small-scale structure of the HSA in detail, and finds that the horizontal temperature variation upon the density surfaces (the thermoclinicity) was large, particularly in the upper and lower parts of the water column. Figure 7 shows the standard deviation of potential temperature on σ_θ surfaces obtained at intervals of $0.01\sigma_\theta$ for all *Tydeman* CTD profiles taken during the second half of JASIN 1978. It illustrates the contrast between the intermediate depths and the upper and lower layers in this respect. It should be noted that comparison of mean vertical profiles for the same set of stations showed that the variations in thermoclinicity differed from those in density gradient, in that the upper region of high thermoclinicity extended below the base of the seasonal thermocline and the minimum occurred towards the mid-depth of the permanent thermocline. Where frontal zones occurred between adjoining water masses, interleaving cold and warm intrusions were found (Van Aken 1981) that were inversely proportional in vertical length scale to the Brunt–Väisälä frequency, and mostly 1–2 km in horizontal extent. The intrusions were very close to isopycnal and arose from differential advection along density surfaces, the density stratification being left unchanged at larger scales. A statistical analysis (Van Aken 1982) indicates that warm, salty intrusions had a slight density deficit and cold, fresh intrusions a small density excess, agreeing with models of Stern (1967) and Toole & Georgi (1981) in which salt-finger convection is the driving mechanism for frontal interleaving and hence allows cross-frontal transport of heat and salt.

Away from frontal zones, irregular small-scale structure was present to a lesser degree (see figure 4*b*, for example). Analysis (Van Aken 1981) indicated that this arose from deformation of the mean profile by internal waves in the manner described by Johnson *et al.* (1978).

5. Mesoscale circulation

Although records from nine current meter moorings are available from the LSA during JASIN 1978 (Collins & Pollard 1982) it became apparent at an early stage of analysis that these were insufficient to resolve the circulation of the area without the hydrographic survey data. Examination of the latter in terms of the salinity anomaly method (Edwards *et al.* 1979) showed that, despite the small contrasts in properties, eddies and meanders had existed at depth across the HSA, and it was important to determine the development of these, and their effect on the uppermost layers, during the experiment.

Fortunately, these mesoscale features proved to have a large degree of coherence with depth, and patterns observed at 1000 or 1200 dbar were very similar to those at 500 dbar, and were traceable in the layers beneath the seasonal thermocline. In addition, the same features appeared from plots of a number of parameters, for example depth of a density surface, salinity upon a density surface or density upon a pressure surface. As will be discussed, the broad features of the HSA were a cold anticyclonic eddy, which moved westwards across the northern half, an anticyclonic meander of warmer water, which occupied much of the southern portion of the HSA, and several smaller cyclonic circulations, which were less readily resolved. The eddy moved westwards at a mean speed of 1.4 km day^{-1} (Kruseman & Prangsma 1983), and this value has been used to produce distributions corrected to particular days during the four main

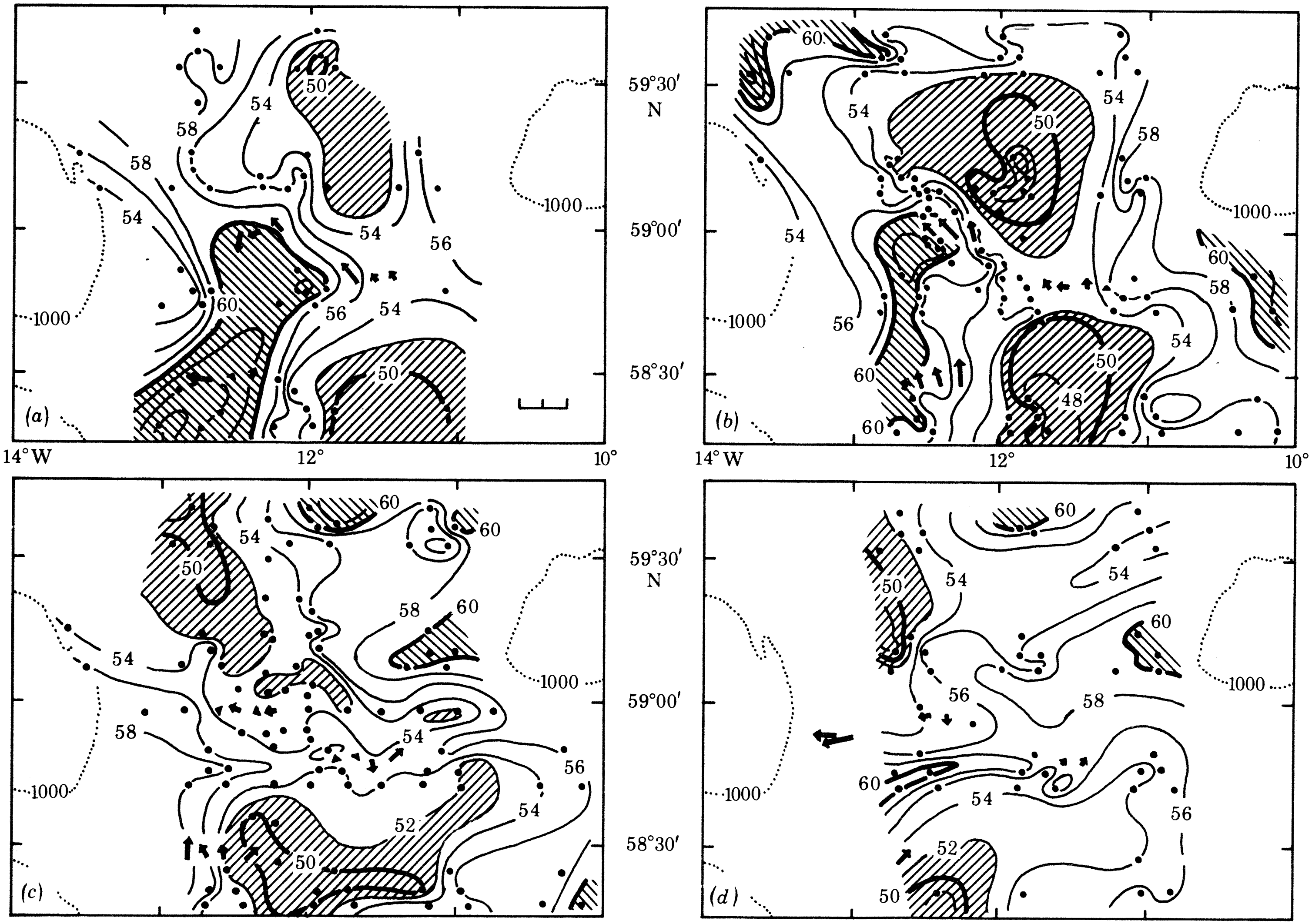


FIGURE 8. Density (σ_t) on the 1000 dbar surface during four periods of the experiment: (*a*) 19 July, (*b*) 29 July, (*c*) 18 August, (*d*) 28 August. Isopleths are labelled as $(\sigma_t - 27) \times 100$. Positions of data have been adjusted to the days shown by assuming a constant westward drift across the area of 1.4km day^{-1}. Noon current vectors from 500 to 600 m at five-day intervals are shown for moorings K1, I3 and I4. Dotted lines show 1000 m isobaths. (Adapted from Kruseman & Prangsma (1983).)

survey periods. Circulation above 1000 m is largely controlled by the depth of the main thermocline, centred upon this depth, owing to the weak stratification between about 200 and 800 m (see figure 6). Density (σ_t) distributions upon the 1000 dbar surface provide a measure of this and are shown in figures 8*a–d*, with station positions adjusted to compensate for the mean westerly drift. The figures also include filtered noon current vectors at five-day intervals similarly adjusted for position, taken from instruments at depths of 500–600 m from moorings K1, I4 and either I3 or I3A (Collins & Pollard 1982).

In the first two diagrams (figures 8*a*, *b*) the complete anticyclonic northern eddy can be seen, its diameter being about 100 km, and, in the southeast, part of another anticyclonic circulation appears. Examination of *T–S* characteristics shows that the northern eddy contained significant proportions of NSDW in the mid-depth and lower water column and had probably originated either from near mooring I2 (figure 1), where Wyville–Thomson Ridge overflow entrains upper water as it enters the Rockall Trough (Ellett & Edwards 1978), or from the sill between Lousy Bank and Bill Baileys Bank, where *Shackleton* observations in July 1978 showed a weak southerly flow (Gould 1980). The southeastern circulation contained water similar to that found on the Anton Dohrn Seamount section, which suggests that this circulation was part of a meander of the main northeastward current of the Rockall Trough. This current was observed to pass from the east of Rockall Bank to the south of Rosemary Bank during the previous summer (Pollard 1977*a*, *b*), and the mooring at E4 (figure 1) showed north to northeast currents east of Rockall Bank for most of the JASIN 1978 experiment (Collins & Pollard 1982). Some water from the west side of the meander appears to have travelled north towards the northerly eddy and then recirculated westwards and southwards cyclonically.

After an interval of 20 days (figure 8*c*) the centre of the northern eddy had moved to the western side of the HSA and the southerly meander had expanded across the southern half of the grid. In the centre of the area, interaction between these two features had produced an eastward-pointing tongue of relatively low density water drawn from the eddy and a ridge of higher density water drawn from the cyclonic recirculation in the southwest shown in figure 8*b*. In the north and northeast higher values during this survey are connected with increased overflow influence at this time.

The final diagram (figure 8*d*) shows the eddy receding from the northwest of the HSA, a rise in density along the central ridge and little change in the meander.

The general coherence of the patterns in these figures is reassuring, as is the good agreement of the 500–600 m current meter vectors. Analysis at other levels confirms that the broad features of mesoscale circulation between 200 and 1000 dbar, where vertical density gradients are very weak, are represented by these figures. However, the problem remains of obtaining a quantitative description of the circulation. Difficulties arise in applying classical geostrophic analysis because of the difficulty in selecting for pairs of stations reference levels that could be unequivocally justified from the survey data. A solution has been found in the application of the inverse analysis technique of Wunsch (1978) to the data sets for the second and third *Challenger* surveys (Pollard 1982*b*). In this technique independent mass conservation equations are written for as many sets of observations as possible, and are subsequently solved to obtain the reference velocities. As there are usually fewer equations than unknowns, the sums of squares of the reference velocities are minimized to obtain a unique solution. For the *Challenger* surveys means were taken of the sets of six observations around each grid triangle, geostrophic shears were calculated for adjacent pairs of stations, and conservation equations were constructed for the

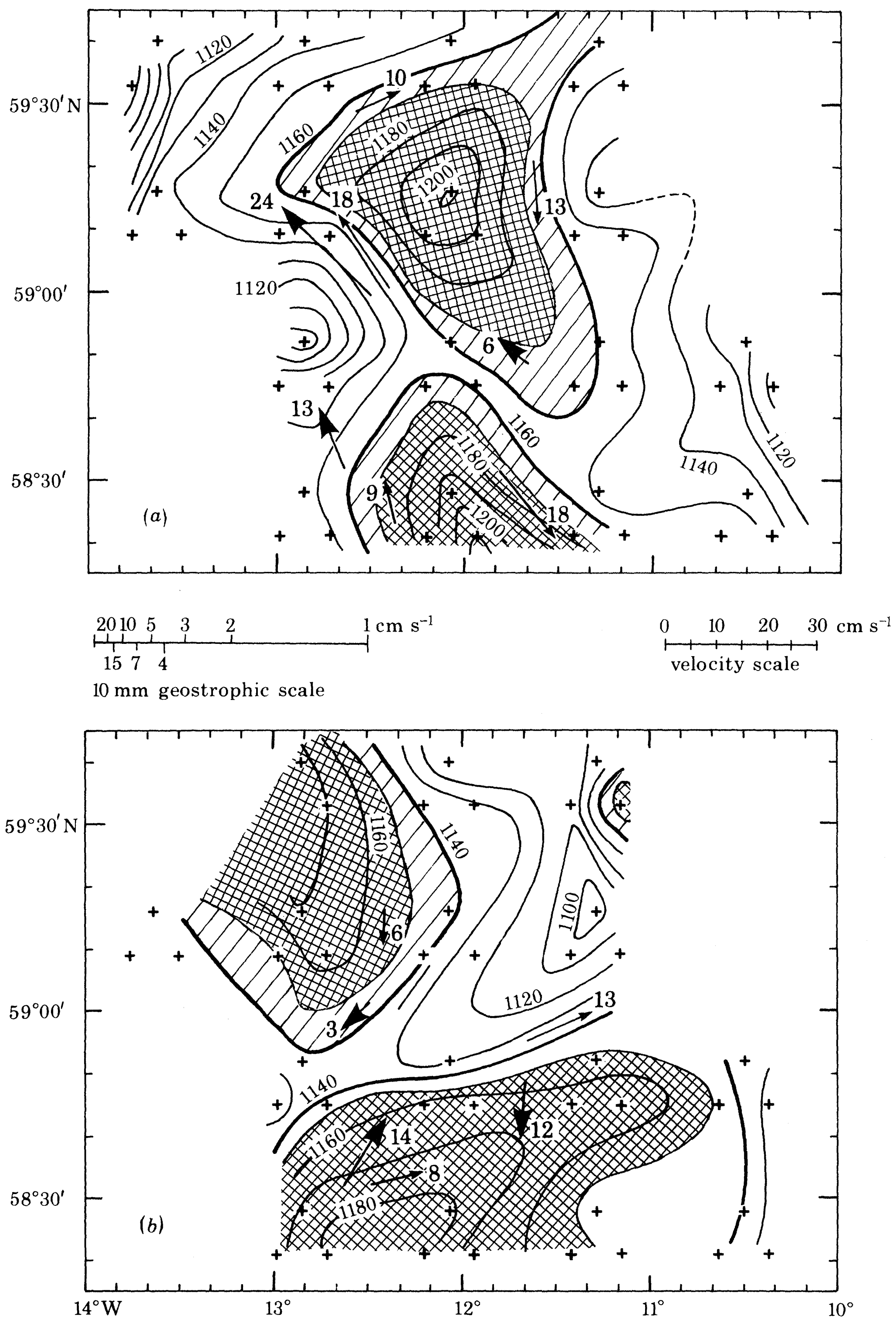


FIGURE 9. Dynamic heights (dynamic mm) at 200 dbar adjusted to a level of no motion at the bottom. Light arrows show estimated geostrophic velocities and heavy arrows show 200 m current observations. From Pollard (1982*b*). (*a*) Survey B, 31 July to 11 August 1978. (*b*) Survey C, 20–29 August 1978.

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45 km × 45 km square boxes numbered 0 to 7 in figure 1. Solutions were derived for reference levels at 500 dbar, 1000 dbar and the bottom, and, as discussed by Pollard (1982*b*), the most physically realistic results were found with the bottom as reference level and with reference velocities insignificantly different from zero (less than 1 cm s^{-1}). The inferred correlations confirmed the main features of figure 8, but the 45 km × 45 km boxes were rather too large for

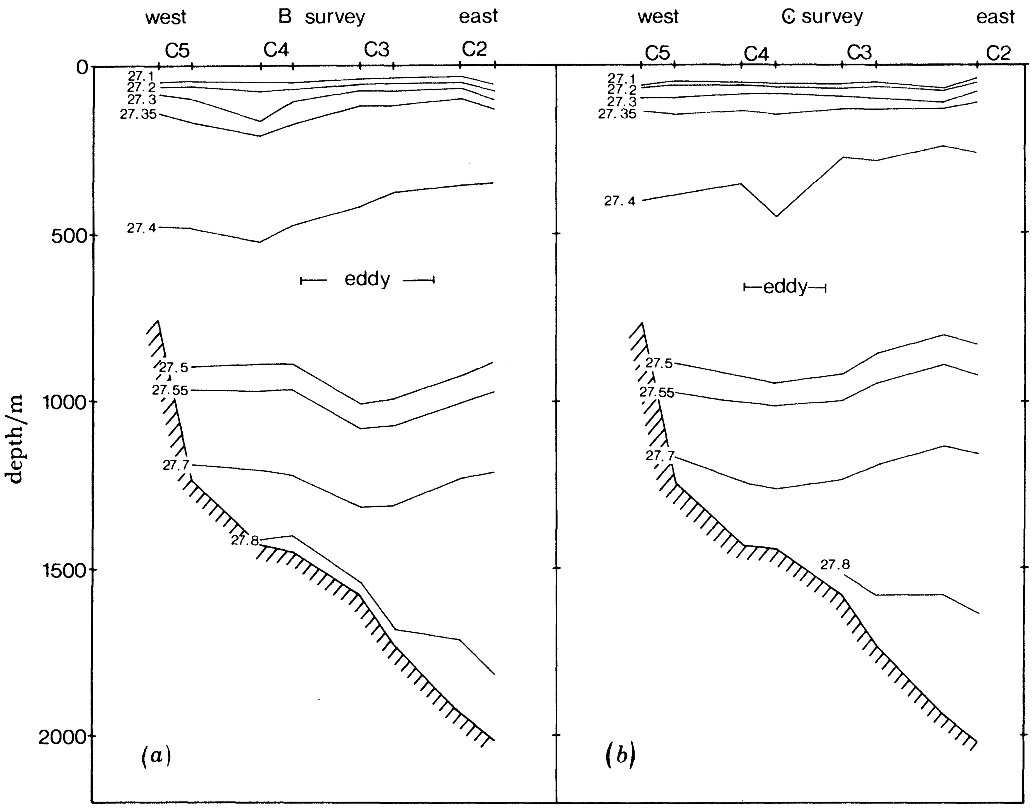

FIGURE 10. West–east sections of density (σ_θ) at stations C2–C5, from Pollard (1982): (*a*) 2–4 August 1978; (*b*) 22–24 August 1978.

the resolution of details of the velocity field. However, given confidence in the use of the bottom as a reference level, it was possible to improve spatial resolution by taking the mean of each pair of stations at the apices of the triangles and calculating dynamic heights relative to the bottom. Zero bottom velocities were achieved by adjusting the dynamic heights at the bottom of the shallower stations to the values of the adjacent deeper stations. Figures 9*a*, *b* show the dynamic topographies at 200 dbar obtained by this procedure, quantifying the features seen in the 1000 dbar σ_t contours of figures 8*b*, *c*. Pollard (1982*b*) examines the observed and geostrophic currents and concludes that features with scales of about 30 km or more are resolved by the hydrographic surveys and are consistent with the current meter observations, but smaller features can only be examined qualitatively.

6. Upper layers

Having described the mesoscale circulation features determined by the hydrographic surveys, we may examine the effects these had upon the upper layers of the HSA. Figure 10, from Pollard (1982*a*), shows the depression of the main thermocline, which controlled the northern eddy, but demonstrates a reversed baroclinicity in the upper layers. During survey B (figure 10*a*) the $\sigma_\theta = 27.3$ isopycnal was domed from 160 to 70 dbar in the centre of the eddy, for example, and on sections drawn for stations B1–B4 during the same survey Van Aken & Prangsma (1981) show that a reversal of baroclinicity occurred at about 100 m, in agreement with a maximum in the northward current component at 100 m at moorings W1 and W2 at the FIA during 30 July to 18 August.

Kruseman & Prangsma (1983) have constructed charts of salinity upon the 27.3 σ_t surface using *Tydeman*, *Challenger* and R.V. *Atlantis* II data and restricting the time span of each to the minimum needed for reasonable coverage of the HSA. These are given here as figures 11 *a–h* and should be compared with the deeper circulation as seen in figures 8 *a–d*. On this surface, at the base of the seasonal thermocline, the form of the salinity distribution over the area is essentially simpler than at depth, two water masses only being involved, NAW in the south and MNAW in the north. The diagrams are able to show how the basic situation of a decreasing northward salinity gradient was distorted by the deeper circulations.

Initially, the primary features were two tongues, one of salinity greater than 35.25(‰) extending to the northwest from the NAW east of the FIA (59° N, 12° 30′ W), the other, fresher (salinity less than 35.25 ‰), extending from the northwest of the HSA across the FIA (figure 11 *a*). The fresher tongue weakened at the end of July (figures 11 *b*, *c*) and became fragmented by early August (figure 11 *d*). In contrast, the more saline tongue developed, as water was drawn into the confluence zone at the FIA, southwest of the northern eddy, and the clockwise advection of the tongue around the eddy is apparent in figures 11 *c*, *d*. A detailed cross section of the saline tongue near the FIA is described by Pollard (1982*a*) and is also shown by Pollard *et al.* (this symposium, figure 5).

As the eddy propagated westward during August, fresher water from the north filled the northeast quarter of the HSA, and the saline tongue moved westwards and fragmented. It remains discernible in figures 11 *e–g*, however, and its temperature signature in the mixed layer is clearly apparent in the mixed-layer temperature plots of Guymer *et al.* (this symposium). The eddy advection of heat in the surface layer is discussed by Prangsma *et al.* (this symposium). We conclude that the mesoscale velocity fields had a strong influence on the upper ocean and mixed layer by advective redistribution of the thermohaline structure.

7. Conclusions

Despite an initially daunting appearance of complexity, it has proved possible to outline the sub-surface mesoscale changes that occurred in the northern Rockall Trough during JASIN 1978 in terms of the interaction between a westward-moving eddy of fresher water in the north of the area and a meander of higher salinity water across the south of the HSA.

It has been suggested earlier that the meander was part of the main current that passes from the Atlantic towards the Norwegian Sea through the Rockall Trough, and this origin is supported by its content of water similar to that found in the south of the LSA on the Anton

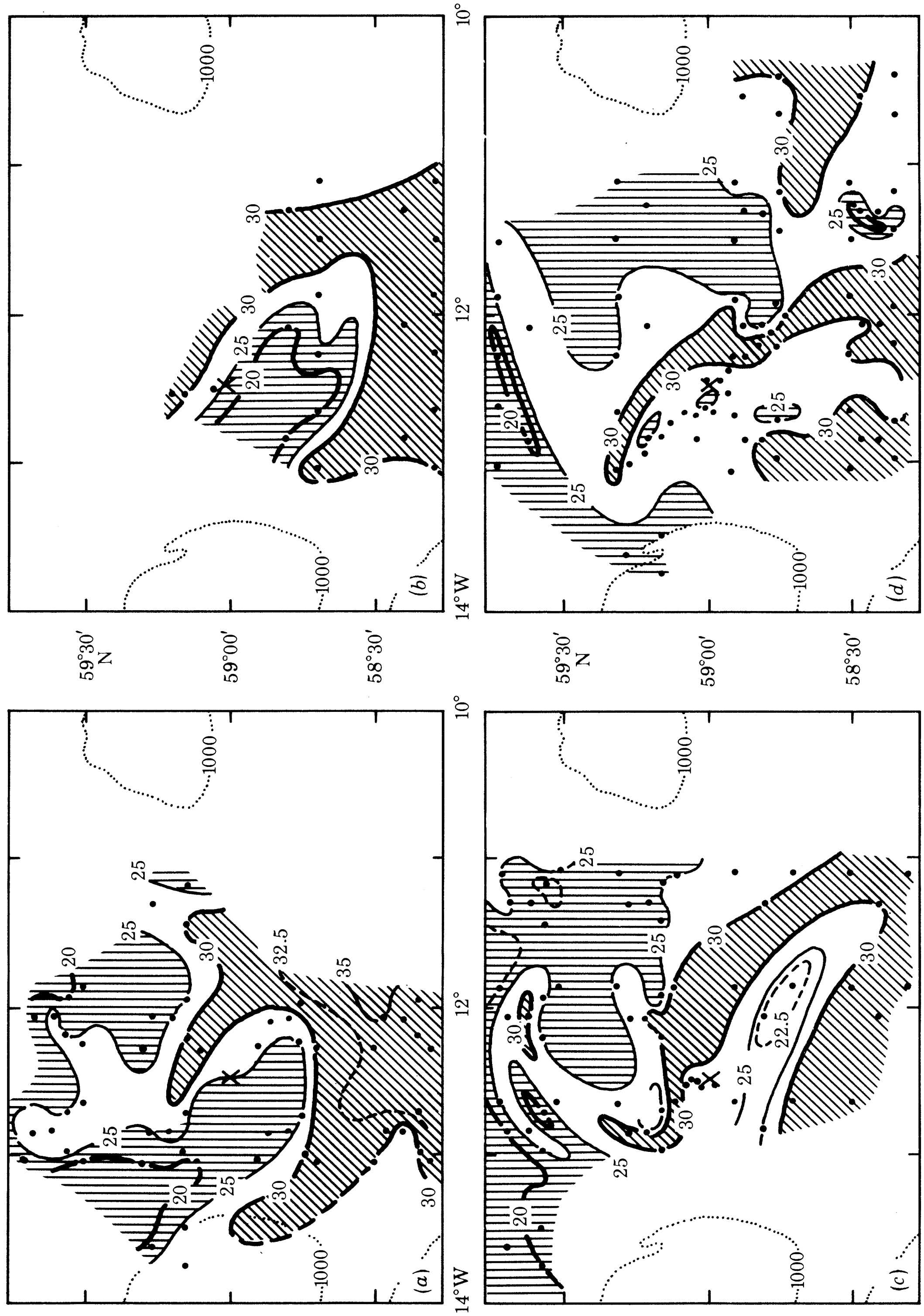

FIGURE 11 (a–d). For description see opposite.

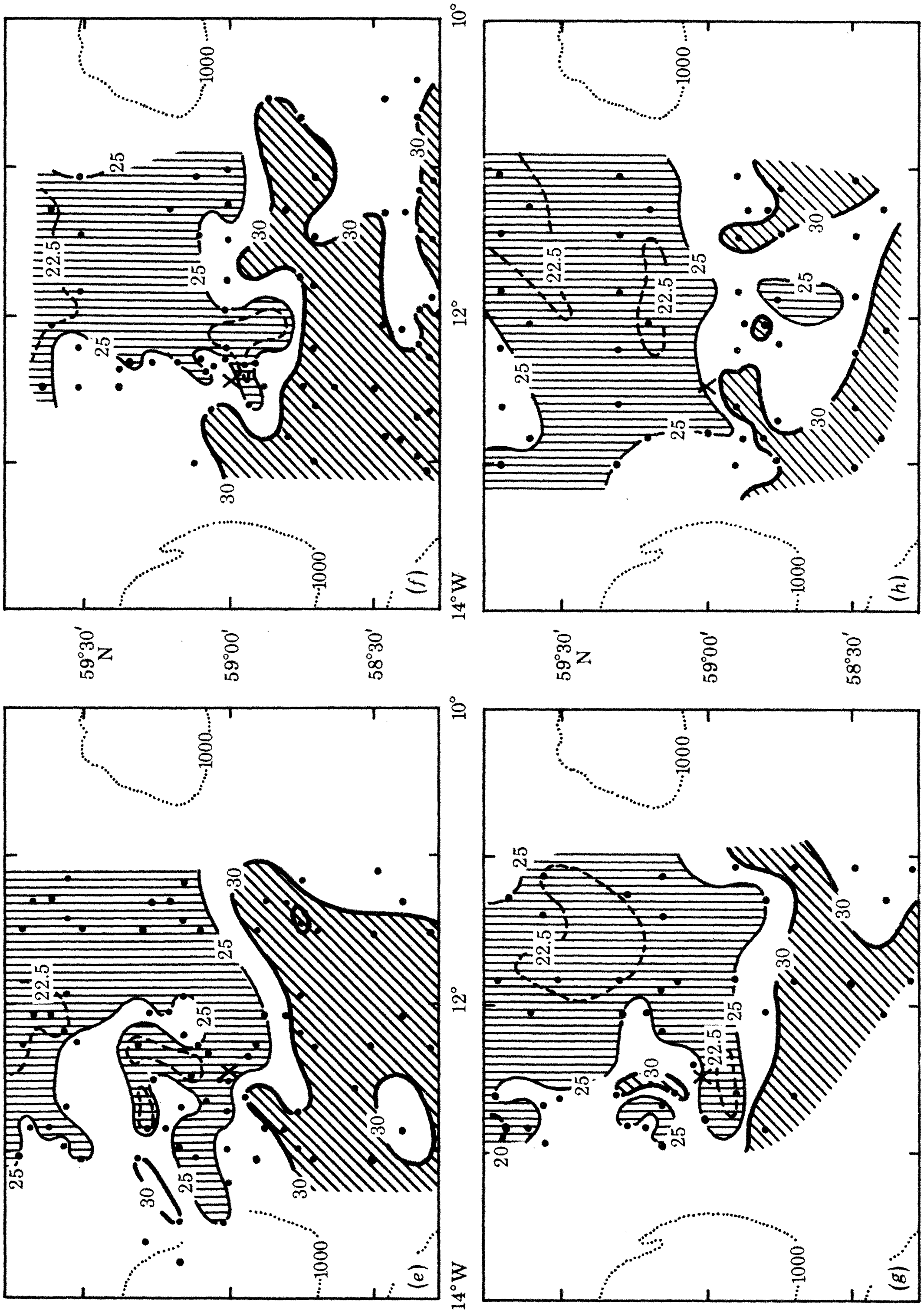

FIGURE 11. Salinity on the 27.3 σ_t surface for eight periods of the experiment: (*a*) 17–24 July, (*b*) 26–28 July, (*c*) 29 July–3 August, (*d*) 4–13 August, (*e*) 20–26 August, (*f*) 27 August to 1 September, (*g*) 2–7 September, (*h*) 8–14 September. Isohalines are labelled as $(S-35)\times 100$. The Fixed Intensive Array is marked by a cross in each diagram. Dotted lines show 1000 m isobaths. (Adapted from Kruseman & Prangsma (1983).)

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Dohrn Seamount section. Similar water was approaching the Wyville–Thomson Ridge across the southern portion of a section run northwards along 9° W longitude by *Shackleton* in July 1978 (Gould 1980) and close to the continental slope on sections worked by *Scotia* during April, August and September 1978 (Dooley & Martin 1980), but a connection with the meander may have been indirect, particularly as observations of a separate and remarkably steady current over the continental slope west of the Hebrides were obtained in the following year (Ellett *et al.* 1980). The results of the inverse analysis suggested to Pollard (1981) that the southeastward flow from the meander near stations A2 and A3 (figure 1) may have reversed immediately to the east of the HSA to form an anticyclonic circulation around Rosemary Bank. This is supported by southward currents recorded at mooring D2 from mid-July to late August, and by the section data from *Scotia*, but there is insufficient evidence to indicate whether this flow subsequently continued southward or turned northeastward to augment the slope current flow towards the Norwegian Sea.

What has here been termed the cyclonic recirculation to the west of the meander appears to be a branch from it of water that returns southwards upon encountering shoaling bottom topography and the waters resident in the northwest of the trough.

There are two possible sources for the northern eddy. Its content of IMNAW–NSDW must have originated from overflow across the Scotland–Iceland ridges, but could have come from either the Wyville–Thomson Ridge or the Faroe Bank Channel. In July *Shackleton* observed a southern flow of overflow water from the Faroe Bank Channel entering the Rockall Trough against the western flank of Bill Baileys Bank, but Gould (1980) suggests that this was circulating around the topography. Because the overflow characteristics were continuous to the bottom at most stations in the eddy in depths below the Bill Baileys Bank–Lousy Bank sill of 1200 m, it seems probable that the eddy was formed of overflow from the Wyville–Thomson Ridge, which had entrained IMNAW from the vicinity of mooring I2, towards which the overflow is directed by topography (Ellett & Edwards 1978). The 100 km scale of the eddy would be appropriate to an origin in this area, and its track to the HSA would have followed the sedimentary Feni Ridge, the formation of which has been ascribed to Norwegian Sea overflow (Jones *et al.* 1970). Current meter records from mid-depth at I2 show a flow into the Trough throughout the experiment except for brief periods in mid-July and mid-August (Collins & Pollard 1982).

The use of the inverse method (Pollard 1982*d*) led to the conclusion that a zero reference level at the bottom was preferable to others higher in the water-column, and this enabled quantitative estimates to be made of the velocity fields. Because the 45 km grid was somewhat coarse for the resolution of some of the smaller features, the bottom zero reference level was adopted for conventional dynamic height calculations from the individual triangle stations, and this adequately resolved the main features. It will be seen that the origin suggested above for the eddy supports the choice of the bottom as the best approximation to a level of no motion. Although there is evidence of episodic bottom flows (Zenk 1980), zero reference levels in the middle or upper water column would have been unrealistic in relation to water with T–S correlations similar to that of figure 4*b*.

At the base of the seasonal thermocline and in the mixed layer it has been possible to show the effect of the deeper circulation upon the upper waters, where fronts originating in boundaries between NAW and MNAW were intensified during some periods by the underlying confluences and at other times distorted and fragmented by shears. Despite the small range of temperature and salinity across the area, boundaries were found to persist over horizontal scales that the hydrographic grid was sometimes unable to resolve. In general, however, it appears that the hydrographic surveys, current meter data and sections from the LSA have together been able to provide a coherent description of the mesoscale circulation during the two months of the JASIN 1978 experiment.

This work involved many of our colleagues, the Captains, Officers and crews of our research ships and contributions of data from other JASIN investigators, all of whom we can only thank collectively. S.M.B.A. and I.O.S. Wormley current meter moorings were funded by the U.K. Department of Energy, and we thank the NATO Scientific Fund and the U.S. Office of Naval Research for assistance with data workshop sessions.

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Discussion

R. T. Pollard. (*Institute of Oceanographic Sciences, Brook Road, Wormley, Godalming, Surrey GUG 5UB, U.K.*). Where did the fresh water in the mixed layer (35.12‰ in *Tydeman* survey 8) originate? On the annual timescale, could the advection of water of different salinity in the surface layer, followed by winter convection, account for the interannual salinity changes you mentioned?

D. J. Ellett. It is not possible to say more about the origin of the low salinity water found in the northwest of the HSA other than that it seems to have entered the Rockall Trough from the Iceland Basin. Surface samples taken by U.K. weather ships for the Fisheries Laboratory, Lowestoft, show salinities of less than 35.2‰ to the west of Rockall Bank in August and September 1978, and although northeast Atlantic surface values were rising from levels that in 1975–6 were probably their lowest this century (Ellett 1980), they appear to be at least 0.1‰ below those of the summer 1958 surface distribution of Dietrich (1969).

As regards interannual salinity variations in the area, changes of 0.15‰ occurred between the winters of 1968 and 1976 in water mixed to at least 400 m. The evidence of sub-surface data from weather stations *Juliett* (52° 30′ N, 20° W) and *India* (59° N, 19° W) is of increasing SAIW presence centred upon 400 m depth to the south and west of the Rockall Trough during these years (Ellett 1980), and it is likely that it was this water, rather than the surface layer alone, that had the greatest influence in decreasing salinity in the upper levels of the Rockall Trough.

P. Kruseman. During surveys 1 and 2 and during surveys 6 and 7 inflow of water with a salinity below 35.1‰ is found in the surface layer. As discussed in the paper this water originates in the area to the east of Iceland. Inflow through the Faroe–Shetland Channel is the most likely route to the JASIN area but inflow out of the Icelandic Basin can not be excluded.

I assume that during winter convection this low salinity water is the cause of the modification of NAW to MNAW. In that case differences in advection of low salinity water in the surface layer will cause the variability in the salinity of the MNAW.

J. G. Harvey (*University of East Anglia, Norwich, U.K.*). What is the distinction between the two cold low-salinity water masses (AIW and LSW) that Mr Ellett has identified?

D. J. Ellett. LSW is the low salinity water mass formed in winter between southern Greenland and Labrador (Lazier 1973, 1980). This spreads eastward and provides a salinity minimum and dissolved oxygen maximum at depths of 1800–2000 m to the west of Europe. Confusion arises because some early workers have referred to this water as Arctic Intermediate water.

In recent years the latter name has been applied exclusively to water found in the southern Norwegian Sea and formed by winter convection in the region between the Iceland–Faroe Ridge and the Oceanic Polar Front east of Iceland. Meincke (1978) shows its flow from here to the Faroe–Shetland Channel, where it occurs immediately above NSDW at depths above 600 m. Its presence in the Faroe–Shetland Channel shows long-term variations and was at a maximum in 1978 (Martin 1981). Because of this, because of depth considerations, and because any MNAW and LSW entering from the west would not be expected to mix directly, but would be separated by an SAIW salinity minimum, it appears that AI water was responsible for T–S correlations like those of figure 4*d*.

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J. D. Woods (*Institut für Meereskunde, Düsternbrooker Weg* 20, *D*-2300 *Kiel, F.R.G.*). Mr Ellett referred to the possibility that double diffusive convection contributed to the vertical mixing inferred, in the classical manner, from the JASIN T–S plots. Was there any more direct evidence to support this conjecture? Or, if not, does the indirect evidence allow one to estimate the rate of water-mass conversion by double diffusive convection in this region?

H. M. Van Aken. The evidence for double diffusive convection was indirect. Both from statistical analysis of temperature inversions and from cross-spectral analysis of temperature and salinity in vertical wavenumber space it appeared that warm, salty intrusions had a density deficit while cold, fresh intrusions had a density excess. This agrees with the situation in salt-finger driven intrusions in frontal zones. But since models of that type of intrusions are scarce, not well tested and sometimes contradictary it is not yet possible to estimate the rate of water-mass conversion by double diffusive processes.

J. A. Businger (*Department of Atmospheric Sciences, University of Washington, Seattle, Washington* 98195, *U.S.A.*). Mr Ellett referred to an eddy in the central area and a meander in the south. From the maps shown, it is not clear what the difference is between the two. Can he clarify this?

D. J. Ellett. The term 'eddy' was used for the closed circulation crossing the northern and central HSA during the experiment. At first sight we thought the southern feature to be the northern half of a similar closed 'eddy', but we were convinced by the warmer and more saline characteristics that it represented a contiguous part of the main northeastward flow of the Rockall Trough and have therefore referred to it as a meander.

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