Water masses and circulation pathways through the Iceland Basin during Vivaldi 1996

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Received 28 July 2003; revised 9 January 2004; accepted 5 February 2004; published 1 April 2004.

[1] Quasi-synoptic data from late 1996 spanning the subpolar North Atlantic have been used to determine the major pathways of the North Atlantic Current (NAC) at that time. High spatial resolution allows fronts to be accurately positioned on each SeaSoar section. A clearly defined front of the NAC (the Southern Branch) turns north at around 25°W and continues through the middle of the Iceland Basin as far as 60°N, 20°W. A second branch (the Northern Branch or SubArctic Front) turns north around 30°W and retroflects westward north of 54°N to re-enter the Irminger Basin and become part of the Irminger Current up the western side of the Reykjanes Ridge. A third, eastward branch turns sharply northwest at the mouth of the Rockall Trough to skirt the southwestern margin of Hatton Bank. This branch carries a tongue of saline eastern North Atlantic water (ENAW) over Hatton Bank and in consequence ENAW covers the whole of the Hatton and Rockall Banks as well as the Rockall Trough, bounded in the west by the Southern Branch. The most saline water, found in Rockall Trough, spills out into the northern Iceland Basin between Rockall and Lousy Banks. This saline, weakly stratified tongue can be traced westward to the south of Iceland continuing southwestward along the eastern flank of the Reykjanes Ridge. Subarctic Intermediate Water is carried into the Iceland Basin, creating a fresh tongue bounded east and west by the more saline ENAW over Hatton Bank and the eastern flank of the Reykjanes Ridge respectively. *INDEX TERMS:* 4223 Oceanography: General: Descriptive and regional oceanography; 4283 Oceanography: General: Water masses; 4532 Oceanography: Physical: General circulation; 4536 Oceanography: Physical: Hydrography; *KEYWORDS:* Iceland Basin, circulation pathways, North Atlantic Current, Subpolar Gyre

Citation: Pollard, R. T., J. F. Read, N. P. Holliday, and H. Leach (2004), Water masses and circulation pathways through the Iceland Basin during Vivaldi 1996, *J. Geophys. Res.*, *109*, C04004, doi:10.1029/2003JC002067.

1. Introduction

[2] It is well known that the North Atlantic Current (NAC) sweeps eastward across the Mid-Atlantic Ridge in two major branches [*Harvey and Arhan*, 1988; *Pollard et al.*, 1996; *Sy et al.*, 1992], which cross 30–35°W at ~48°N (southern branch) and 51°N (northern branch). These branches turn northward and in 1991 crossed 54°N at 22°W and 24°W respectively [*Pollard et al.*, 1996]. Less well known are the pathways of these NAC branches after they have turned north. The CONVEX survey later in 1991 showed the northward flow apparently splitting into two branches [*Bacon*, 1997; *Read*, 2001], with the major part of the flow continuing northward into the Iceland Basin just west of Hatton Bank and a smaller component turning west to recross the Reykjanes Ridge and join the Irminger Current which flows north along the western flank of the Reykjanes Ridge. *Schmitz and McCartney* [1993] showed the majority of the transport with temperatures >7°C crossing the Reykjanes Ridge and recirculating round the Irminger and Labrador Basins. In their schematic, water with T < 7°C is deflected by the Reykjanes Ridge but water with T > 7°C is not. *van Aken and Becker* [1996] reviewed work on circulation in the Iceland Basin up to 1996 and concluded that "the large-scale circulation pattern and its variability in the north-eastern North Atlantic Ocean was not well established until now". From their NANSEN Project data collected over the 5-year period 1987 to 1991, they too concluded that the majority of the transport of the NAC did not enter the northern Iceland Basin, but turned back to the west, crossing the Reykjanes Ridge south of 58°N to continue northward in the Irminger Basin.

[3] Recently, papers based on the growing data base of surface drifters [*Bower et al.*, 2002; *Fratantoni*, 2001; *Orvik and Niiler*, 2002; *Valdimarsson and Malmberg*, 1999] and deep acoustically tracked floats *Bower et al.* [2002] have examined the major circulation pathways round the SubPolar Gyre. These papers show the NAC

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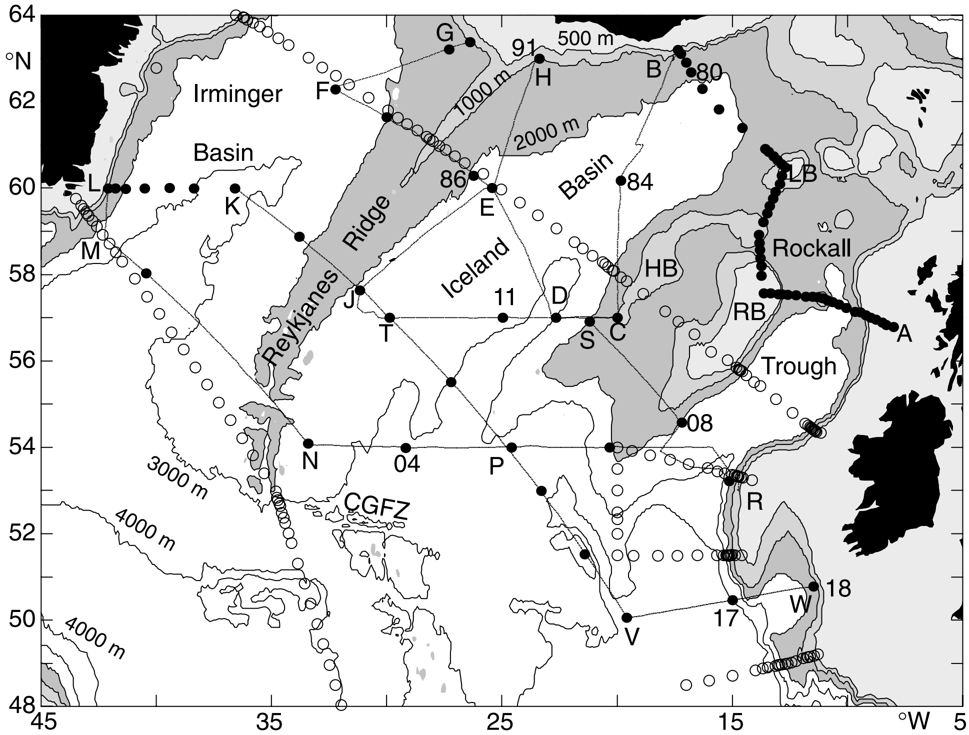

Figure 1. Station positions used in this paper. Bold dots are full depth CTDs collected on Vivaldi 1996; dots at 4 km intervals (near solid lines) are SeaSoar CTD profiles to ~400 m; open circles are Knorr 147 full depth CTD stations. Bathymetric contours are shown at 500 m and every 1000 m and depths <2000 m are shaded. Some points on the ships' tracks are labeled A-W in chronological order and selected CTDs are numbered. Abbreviated features are Lousy Bank (LB), Hatton Bank (HB), Rockall Bank (RB) and the Charlie Gibbs Fracture Zone (CGFZ).

splitting into two or more branches, with some of the flow returning to the Irminger Basin after circulating cyclonically within or around the Iceland Basin. Recent papers based on the WOCE hydrographic data through the 1990s [*Bersch*, 2002] consider how the pathways and transports have changed interannually, related to changes in the North Atlantic Oscillation (NAO), in particular the shift from a high index prior to 1995 to a low index in 1996, the year of our survey. The float and drifter data sets provide good spatial coverage of the SubPolar Gyre when several years of data are considered as a single data set but do not yet provide good spatial coverage in a single year. The hydrographic data allow year to year changes to be examined, usually with poor basin scale spatial resolution. Here we examine a hydrographic data set which covered much of the SubPolar Gyre in the space of two months.

[4] Because transports in and round the Iceland Basin are weak (order 10 Sv, where 1 Sv = 10^6 m^3 s^{-1}) and often masked by mesoscale eddies, the aim of this paper is not to quantify transports. Rather, we shall take advantage of a synoptic data set (all collected within a 2-month period) with closely spaced (4 km) CTDs to follow fronts and water mass boundaries in the surface layer and hence trace the pathways followed by branches of the NAC. Questions we seek to address include: what are the main pathways?; what is the source of saline water over the Reykjanes Ridge?; what is the source of fresher water extending to 60°N, 20°W in the Iceland Basin?; were the circulation pathways in 1996 different from those observed five years earlier during Vivaldi 1991 [*Pollard et al.*, 1996] and Convex [*Read*, 2001]?

2. Data

[5] Between 28 September and 19 November 1996 a CTD and SeaSoar survey of the SubPolar Gyre was carried out on RRS *Discovery* cruise 223 as a UK contribution to the World Ocean Circulation Experiment (WOCE). The intention was to carry out a nearly synoptic survey of the upper ocean structure and circulation of the whole of the SubPolar Gyre. The cruise, Vivaldi 1996, was a successor to Vivaldi 1991 [*Pollard et al.*, 1996], and a similar survey strategy was adopted. In order to resolve mesoscale upper ocean structure, SeaSoar [*Pollard*, 1986] was towed behind the ship at 8 knots (4 m s^{-1}), cycling between the surface and ~400 m depth. After averaging to 4 km, 2237 shallow CTD profiles resulted (Figure 1). In addition, 88 full depth CTD stations (Figure 1) were occupied (Discovery stations 12931–13018, which will be referred to by the last two digits only), 53 of them on the Ellett line across the Rockall Trough [*Holliday et al.*, 2000], which was extended to Iceland via Lousy Bank for the first time. The remainder were widely spaced (up to 300 km) across the Iceland and Irminger Basins. We have supplemented our CTDs with the 190 CTDs collected on the US WOCE cruise Knorr 147, 2 November to 3 December 1996, which overlapped

the Discovery cruise. Thus all data presented here were collected in the two month period October–November 1996.

[6] All lowered CTD data were calibrated to WOCE standards. Conservative error estimates are 0.5 dbar, 0.001°C and 0.003 for pressure, temperature and salinity respectively. SeaSoar data have higher salinity errors, up to 0.01.

[7] Figure 2 shows temperature, salinity and density in the upper 400 m along a section (FEDC in Figure 1) from the middle of the Irminger Basin (62.3°N, 32.2°W), across the Reykjanes Ridge and Iceland Basin, to the western flank of Hatton Bank (57°N, 20°W). Several features can be seen which will feature prominently in this paper:

[8] 1. At 58.4°N the salinity at all depths changes sharply (up to 0.2) over a short distance (order 10 km). Other indicators change at the same position. Temperatures beneath the mixed layer change sharply from 9°–10°C to 7°–10°C and the temperature gradient over the depth range 150–350 dbar is doubled north of 58.4°N. Salinity and density gradients also increase. The lowest mixed layer densities (<26.95 kg m^{-3}) are found just north of 58.4°N. We shall shortly identify this feature with the Southern Branch of the NAC.

[9] 2. A similar, but less pronounced, salinity step is found at 21.0°W. Mixed layer temperature and salinity are highest east of 21°W (over 11.5°C and 35.4 respectively). This feature will be identified with the Rockall Hatton Branch of the NAC.

[10] 3. Between 58.4°N and 60°N isopycnals rise in general then deepen again, reaching their shallowest at 59.2°N. Temperature and salinities are lower in this latitude band than on either side of it. We shall show that this feature relates to SubArctic Intermediate Water (SAIW) cyclonically entering and leaving the Iceland Basin.

[11] 4. Between 25°W (60°N) and 29°W, salinities below the mixed layer are higher than 35.0, outside this longitude band they are lower. Salinities over 35.1 are found on the eastern flank of the Reykjanes Ridge (whose centre line is at 27.7°W on this section) where stratification between 150–350 dbar (Figure 3c) is minimum. The source of this saline, weakly stratified water will be shown to be Eastern North Atlantic Water (ENAW).

[12] 5. In the Irminger Basin (west of 27.7°W) isopycnals rise sharply to the west in several separate bands and streaky structure tens of km wide is apparent in temperature and salinity. These indicate that the Irminger Current (flowing north on the western flank of the Reykjanes Ridge) has a banded structure, with eddies of warm, saline water from the water mass over the Ridge mixing into the Irminger Basin. We shall show that the Irminger Current comprises both water that has travelled northward along the western side of the Mid-Atlantic Ridge without entering the Iceland Basin and part of the NAC (which we shall call the Northern Branch) which enters the Iceland Basin then turns back to the west to re-enter the Irminger Basin.

[13] The critical reader will not be convinced that all the features mentioned are clearly apparent in Figure 2, but can be assured that other parameters, such as stratification and comparison of all individual T/S profiles, have all been examined to determine which features are significant. Indeed, further simplification is necessary, as it is not practical to present all vertical sections. Features similar to those described above are found on every SeaSoar section, which allows us to map vertically integrated properties in the upper layer (Figures 3a and 3b), where we have integrated from 153 to 353 dbar, i.e., ~150–350 m. The shallow limit of 150 m is chosen to lie everywhere beneath the seasonal mixed layer (cf. Figure 2). The deeper limit is dictated by the maximum depth that was nearly always achieved with SeaSoar. Figure 3c shows density difference between those levels as a measure of mean thermocline stratification.

[14] An alternative and more usual mapping that is useful is that of properties on density surfaces. We show here salinity, pressure and thickness (pressure difference between σ_0 = 27.425 and σ_0 = 27.375) on σ_0 = 27.4 kg m^{-3} (Figures 3d, 3e, 3f). The overlaid station positions show that many of the SeaSoar profiles in the southeastern half of the survey do not extend deep enough to reach this density surface, so that contouring depends on the more widely separated CTD stations. Thus better spatial resolution is found on the upper layer maps, while the isopycnic maps confirm that water mass changes that appear in the near-surface layer are horizontally aligned with T/S changes that occur on density surfaces.

3. Discussion

3.1. Pathways and Transports

[15] On each sub-figure of Figure 3 are overlaid 4 bold lines, two solid and two dashed. These mark the pathways inferred from the property contours on the two figures, all the SeaSoar sections (cf. Figure 2) and transports. The use of transports requires some explanation before we examine the pathways one by one. Simply contouring a property does not ensure that there is significant transport along that contour. Therefore although we shall not attempt to fully quantify or map transports in this paper, we do need to develop some feel for where the major transports are located. We have therefore calculated geostrophic transport in the upper 1400 m of the water column, assuming that 1400 m is a level of no motion. We shall call this the baroclinic transport. This depth is a reasonable choice for a level of no motion over much of the Iceland and Rockall Basins [*Read*, 2001; *van Aken and Becker*, 1996], but is a bad choice in a few regions. Southeast of Iceland and on the eastern flank of the Reykjanes Ridge, in particular, there is significant southwestward flow at 1400 m [*Bower et al.*, 2002] linked to the Iceland Scotland Overflow Water (ISOW). Nevertheless, the baroclinic transport is a useful guide to where there are strongly sloping isopycnals, frontal jets and significant transport. In Figure 4, therefore, we show major features of the baroclinic transports from all CTDs. Each solid arrow shows the baroclinic transport in Sv associated with a pair of CTDs, or with several adjacent CTD pairs spanned by a thin line. In most cases, only transports summing to 4 or more Sv are shown, and some larger values have been omitted where they cancel with adjacent near-equal and opposite transports, indicative of mesoscale features. A few values smaller than 4 Sv have been shown where they mark a significant feature. Occasionally the values have been adjusted by one or two Sv, to obtain the observed net baroclinic transport along a line where several weaker features have been omitted. For

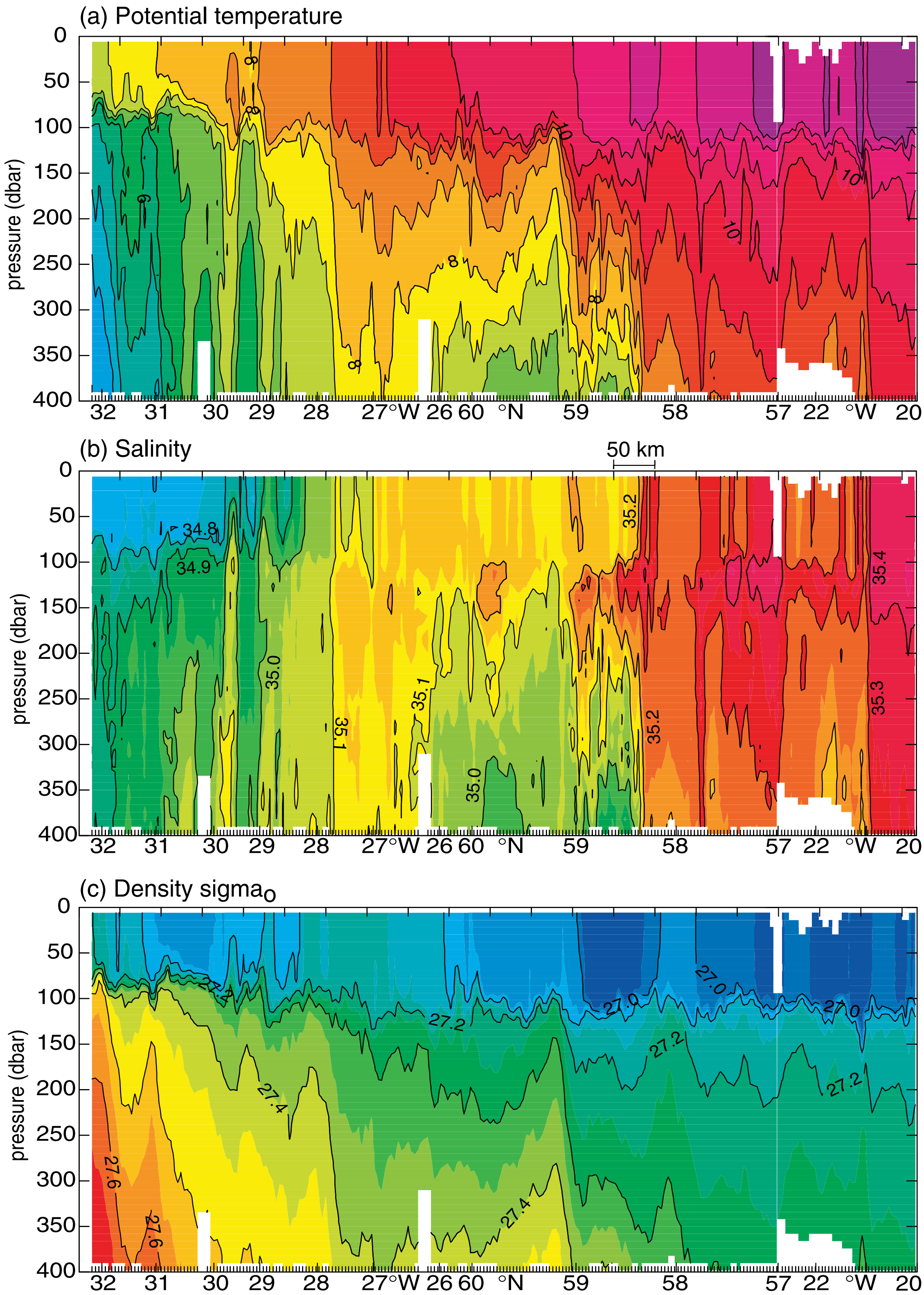

Figure 2. SeaSoar CTD sections of (a) potential temperature, (b) salinity, (c) density σ_0 along the line FEDC (Figure 1) from the middle of the Irminger Basin to Hatton Bank. Tick marks on the upper axis of each figure are at 50 km intervals. Positions along the line in latitude or longitude are marked along the lower axes.

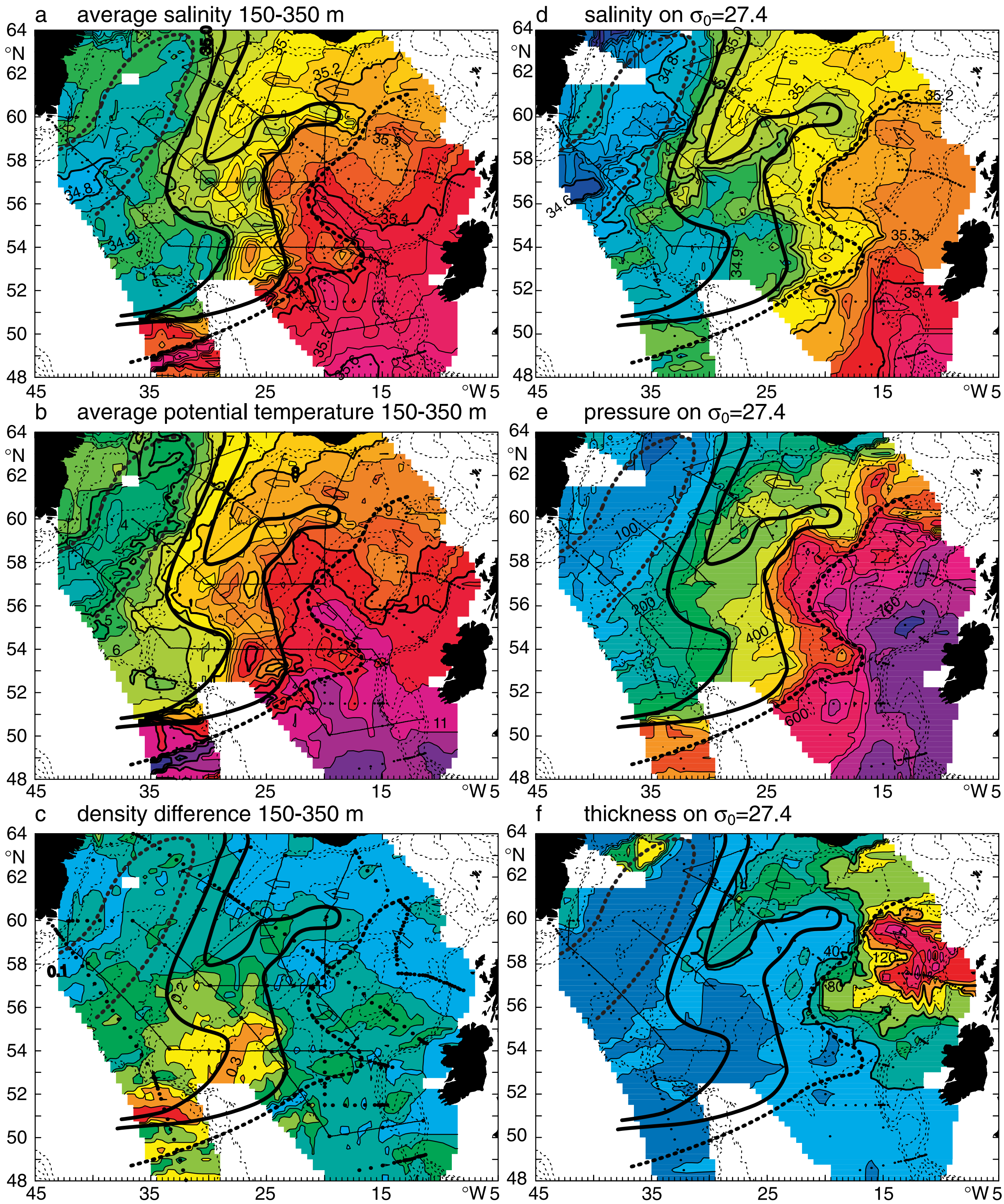

Figure 3. Maps of (a) potential temperature and (b) salinity, where the parameters have been vertically integrated from 153 to 353 dbar in pressure; (c) density difference between 353 dbar and 153 dbar; (d) salinity, (e) pressure and (f) thickness (pressure difference between σ_0 = 27.425 and σ_0 = 27.375) on the density surface σ_0 = 27.4. Station positions are shown as dots and bathymetry is dashed. For Figures 3d, 3e, and 3f, only stations which had data on the σ_0 = 27.4 surface are shown. Bold solid and dashed lines show inferred major pathways, discussed in the text.

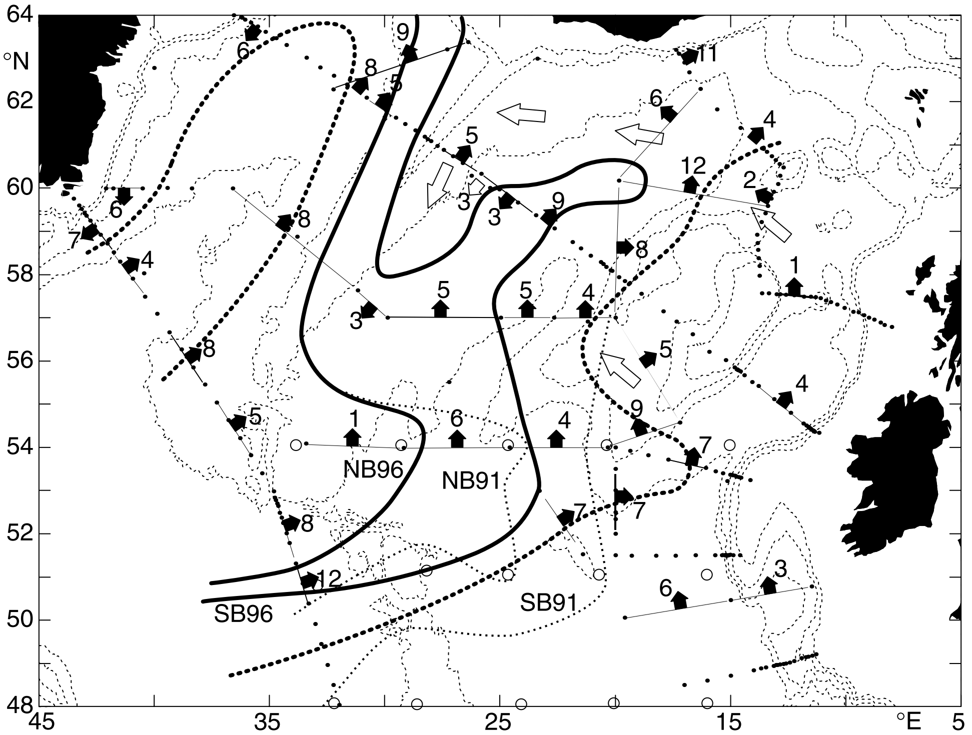

Figure 4. Numbered arrows show baroclinic transport (defined here as the transport in the top 1400 m relative to zero at 1400 m) in Sv for adjacent CTD station pairs or several adjacent pairs, shown by thin lines. These have been used to guide the pathways (bold solid and dashed lines). Also shown as open circles for comparison are the Vivaldi 1991 CTD stations with dotted lines marking the pathways of the NAC [*Pollard et al.*, 1996].

example, along the Knorr 147 line from the Azores to Cape Farewell, transports of 12, 8, 5, 8, 4 and −7 Sv to the northeast are shown. In fact, several pairs of stations showed weak (<3 Sv) southwest flow, and we have adjusted the transports shown to match the observed net northeastward transport of 29 Sv.

[16] Starting at this Knorr section, we find 20 Sv flowing east between 50.4°N and 52.8°N (Figure 4), 12 Sv of which flows in the jet centred on 51°N. A further 24 Sv flows east between 45°N and 48°N (not shown on Figure 4). Are these the northern and southern branches of the NAC? While the latitudes (47°N and 51°N) seem to match earlier definitions, the joint transport of 44 Sv is much larger than the 20–25 Sv estimated for the flow of the NAC into the Iceland Basin in several previous studies [*Bacon*, 1997; *Sy et al.*, 1992; *van Aken and Becker*, 1996]. Furthermore, the salinity on $\sigma_0 = 27.4$ (Figure 3d) is much fresher on the Knorr section west of the Mid Atlantic Ridge than that in our survey area east of the Mid Atlantic Ridge. We conclude that the 24 Sv flowing eastward south of 48°N on the Knorr section must recirculate to the south [*Schmitz and McCartney*, 1993], so does not enter the Iceland Basin and is not relevant to this study. Rather, it appears that, in 1996, the flow crossing 34°W at 51°N splits into two branches further east, as we now show.

[17] Let us call the two NAC branches (the two bold, solid lines shown on Figures 3 and 4) the Northern and Southern Branches. We reuse these names as we do not wish to intoduce new names and the properties of the branches are similar to those of the northern and southern branches found in 1991 [*Pollard et al.*, 1996] even though they are further north and west in 1996 than in 1991. The Southern Branch is easily traceable as far as 60°N in the upper layer salinity map (Figure 3a) by the large (0.2), sharp salinity step centred on 35.2. In Figure 2, for example, it is seen at 58.4°N as a clear horizontal step in salinity and temperature at all depths down to 400 m. The northern Knorr section (not shown) confirms that the front extends to well over 1000 m, with a baroclinic transport between CTDs 55 km apart of 9 Sv at 59°N, 23°W (Figure 4). Note that we have not exactly followed the mapped property contours (in this case salinity = 35.2) because the automated mapping depends on the gridding, which is only well constrained where grid points lie close to observations. For this reason, the CTD station positions and SeaSoar 4 km positions are marked on every figure. The Southern Branch of the NAC crosses two Knorr sections and five SeaSoar lines (Figure 1) on its northward path through the centre of the Iceland Basin, so we have traced a pathway smoothly through the seven points where the Branch crosses those sections.

[18] Another clear property step is found in the 150–350 m maps at 54°N, 28°W (Figures 3a, 3b) but no equivalent step crosses line KJTP (Figure 1) and the evidence indicates that the flow turns back to the west south of that line. We refer to this path as the Northern Branch of the NAC and it is most conveniently traced following the 7°C contour (Figure 3b). It appears to split from the Southern Branch in the vicinity of the Charlie Gibbs Fracture Zone. While we have no data along line TN

(Figure 1), temperatures of 8–9°C along TP are everywhere 2–3°C warmer than at N, which indicates that some of the transport must turn to the northwest, then recross the Reykjanes Ridge to flow north up its western side [*Bacon*, 1997; *Read*, 2001]. The pressure contours on σ_0 = 27.4 (Figure 3e) support this. However, the greater transport, judging from the isobar spacing on Figure 3e, is carried by the Southern Branch into the Iceland Basin. Figure 4 indicates that most of the northward transport across 54°N lies east of the Northern Branch, which may thus be thought of as the northern then western limit of the NAC. The Northern Branch is the boundary between cold, low salinity subarctic waters and warmer, more saline subtropical waters (Figure 3), so is often called the SubArctic Front [*Bersch*, 2002].

[19] The bold dashed line round the Irminger Basin (Figure 3) follows 8 Sv of baroclinic transport (Figure 4) that does not cross the Reyjanes Ridge at all, but heads directly into the Irminger Basin as part of the Irminger Current. Finally, the baroclinic transports suggest a pathway (the eastern bold dashed line) transporting 7–9 Sv that reaches the entrance to the Rockall Trough at 53°N, 17°W before turning sharply back to the northwest and north to continue up the western flank of Hatton Bank. This pathway [*Ellett*, 1993] is consistent with the contours on the isopycnic maps (Figures 3d–3f) and is confirmed by the tongue of warm (>10.5°C) water (Figure 3b, purple) penetrating along SeaSoar line SR around the southwest flank of the Rockall and Hatton Banks, as shown by the open arrow. For ease of reference we shall call this the Rockall Hatton Branch of the NAC. The consequence of this branch is that the Hatton and Rockall Banks are entirely covered by warm, saline ENAW [*Pollard et al.*, 1996].

[20] In summary, we have introduced four main pathways seen in our data in late 1996. From west to east in Figure 3, they will be referred to in this paper as the direct branch of the Irminger Current, the Northern and Southern Branches of the NAC, and the Rockall Hatton Branch of the NAC.

3.2. North Iceland Basin

[21] Consider now the north Iceland Basin and the eastern flank of the Reykjanes Ridge. What can we infer about the pathways of the NAC north of 60°N? From the rapidly sloping isobars on σ_0 = 27.4 (Figure 3e) one's first impression is that much of the flow turns northeastward to exit the Iceland Basin between Iceland and Lousy Bank. However, this is misleading, for several reasons. First, the northward transports shown on Figure 4 of 12 Sv east of 60°N, 20°W and 15 Sv crossing the line between Iceland and Lousy Bank are too large compared to longterm observations [*Hansen and Østerhus*, 2000], which suggest that only 7 Sv exits into the Norwegian Seas in the upper layers. Second, the contouring around 60°N, 20°W on Figure 3e is controlled by the single CTD cast (station 84) at that point. Thus the 6–12 Sv cyclonic baroclinic transport around station 84 (Figure 4) could simply reflect an eddy. Third, while isobars from Iceland to Lousy Bank slope strongly at 63°N indicating eastward baroclinic transport of 11 Sv relative to a deep level of no motion, in fact ISOW flows westward at depth [*Bower et al.*, 2002; *Saunders*, 1996]. Thus northward baroclinic transport only indicates that the southward flow weakens toward the surface. The absolute northeastward transport will be <11 Sv, indeed could be negative. Further east, however, 4 Sv of baroclinic transport heading northeast just west of Lousy Bank (Figure 4) supported by property contours (Figure 3) may well indicate the path for a few Sv of transport into the Norwegian Sea.

[22] Upper ocean properties, on the other hand, are well resolved along the SeaSoar lines (Figure 3), and these show clearly a tongue of warm, saline water penetrating westward, which we have marked by open arrows on Figures 3a and 3b and copied onto other maps. The tongue originates from the north Rockall Trough, exiting the Trough westward at 59°N, 13°W between Rockall and Lousy Banks (Figure 3). On each of three SeaSoar sections, from B south to CTD84, HE and FE (Figure 1), the saline tongue can be seen, freshening as it proceeds westward. Figure 2 shows the cross-section FE through the tongue, and Figures 3c and 3f prove that it is relatively weakly stratified. It is noteworthy that there are three observations of southwestward baroclinic transport (Figure 4) on the eastern flank of the Reykjanes Ridge, in each case a little under 3 Sv. These observations lie (1) between CTD86 and E (Figure 1); (2) just east of there a few weeks later on Knorr; and (3) between J and T. These are likely to be underestimates, as the deep ISOW beneath is flowing southwest [*Bower et al.*, 2002]. Drifting floats also show southwestward flow up to 10 cm s^{-1} [*Orvik and Niiler*, 2002; *Valdimarsson and Malmberg*, 1999] on the east flank of the Reykjanes Ridge. West of the Ridge the flow is northward in the Irminger Current, so there is anticyclonic circulation elongated along or just to the east of the Reykjanes Ridge. We suspect that this circulation leads to the formation of a local variety of mode water through winter mixing, resulting in the weak stratification that is apparent in the saline tongue (Figure 3c).

[23] On the basis of these findings, we have continued the Southern Branch of the NAC by turning it back on itself around 60°N, 20°W, following the outline of the saline tongue (the 35.05 salinity contour in Figure 3d, the 40 dbar thickness contour in Figure 3f). Exactly what happens to the transport through the north Iceland Basin remains unresolved. All our sections indicate up to 20 Sv of baroclinic transport entering the Iceland Basin from the south (Figure 4). Where does this flow exit? Or how do we adjust reference velocities to reduce it? Transport of 7 Sv must continue northeastward past the Faroes [*Hansen and Østerhus*, 2000]. The remainder must recirculate cyclonically round the Iceland Basin, flowing down the eastern flank of the Reykjanes Ridge, and possibly becoming denser even in summer by entrainment with the ISOW. However, one is left with the impression of two flows crossing each other around 60°N, 15°W, the northward flow turning east toward the Faroes and the warm, saline tongue from Rockall heading westward. Perhaps eddies or seasonal variations allow these pathways to alternate temporally.

3.3. Subarctic Intermediate Water

[24] Subarctic Intermediate Water (SAIW) is stratified, cold, fresh water that issues from the western boundary of the subpolar gyre, i.e., the Labrador Current [*Arhan*, 1990]. SAIW is most clearly identified as the highly stratified tongue in Figure 3c entering the survey area from the west between the Northern and Southern Branches of the NAC.

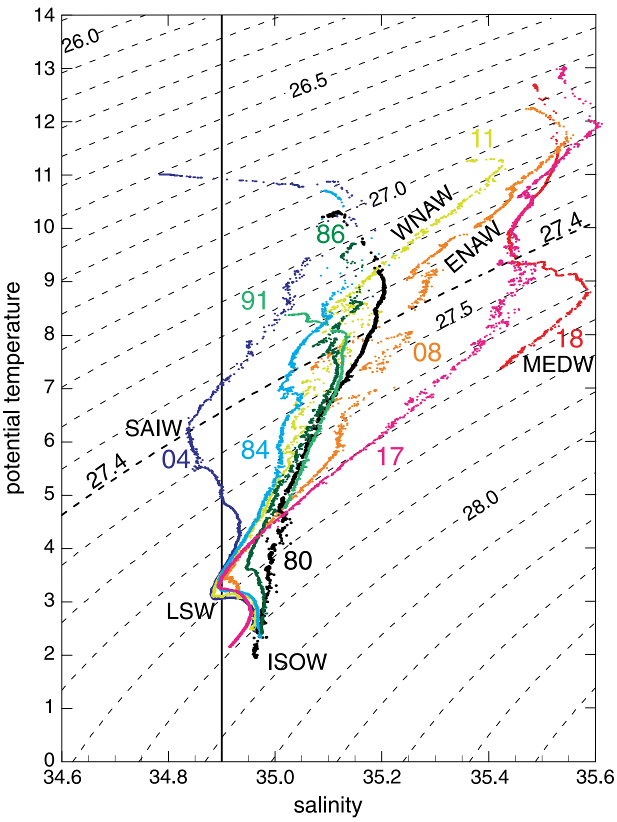

Figure 5. The θ/S (potential temperature/salinity) curves are shown for selected stations as marked on Figure 1.

The properties of SAIW have been defined to lie in a diamond shaped area in T/S space [*Harvey and Arhan*, 1988], but for this study pure SAIW is easily identified on the $\sigma_0 = 27.4$ surface by salinities <34.9 (Figures 3d and 5). The T/S curves for a few representative CTDs are plotted in Figure 5, and that for CTD04 (Figure 1) at 54°N, 29°W shows the SAIW minimum clearly. SAIW is found in the surface layer to the north of the NAC and subducts beneath it [*Arhan*, 1990], so is carried by the NAC into the Iceland Basin north and west of the Southern Branch of the NAC (Figure 3d).

[25] The freshening influence of SAIW is a useful tracer of circulation into the Iceland Basin, as there is no other source of fresh water except Labrador Seawater (LSW) on a much deeper density surface (Figure 5). Figure 3d shows the freshest SAIW (S < 34.9, shades of blue) swinging north in the Northern Branch and penetrating northward to 57°N in the centre of the Iceland Basin. However, SAIW influence (i.e., S < 35.1, shades of green) is present in most of the Iceland Basin west of Hatton Bank, though concentrated primarily west of the Southern Branch of the NAC. This study confirms that SAIW influence is found as far east as 18°W south of Hatton Bank along 54°N [*Read and Ellett*, 1998; *Wade et al.*, 1997] where the Rockall Hatton Branch of the NAC turns sharply back on itself [*Ellett*, 1993]. In 1996, the northern limit of SAIW influence was 60°N, 20°W at CTD84 (Figures 3d and 5). At the northern end of the Iceland Basin, CTD80 (Figure 1) shows no influence of SAIW or indeed of LSW, its T/S curve (Figure 5) descending smoothly from surface waters to ISOW. Nor is there SAIW influence on the eastern side of the Reykjanes Ridge (CTDs 86 and 91, Figure 5 and Figure 3d), where the saline tongue penetrates southward as discussed above.

[26] This discussion confirms that water with SAIW influence was in 1996 carried into the Iceland Basin by the Southern Branch of the NAC, reaching as far north as 60°N at 20°W. It is not found north of 60°N nor on the eastern flank of the Reykjanes Ridge, consistent with our conclusion that saline ENAW penetrates westward across the north Iceland Basin then southwestward along the Ridge. Comparing Figures 3d and 3e, we note that SAIW influence can be seen in water subducting to depths of 500 m beneath the Southern Branch to the south and west of Hatton Bank.

3.4. Comparison With Drifters and Floats

[27] While this paper presents a two-month snapshot of the circulation, drifter or deep float data sets present a long-term mean picture, weighted by the spatial and temporal distribution of the sampling points. Deep floats spanning the years 1993–2001 [*Bower et al.*, 2002] show two main circulation pathways on the $\sigma_0 = 27.5$ surface. One of these enters the southern Iceland Basin near 52°N, turns north between 25° and 30°W, then exits the Iceland Basin back into the Irminger Basin crossing the Reykjanes Ridge south of 57°N. From our Figure 4, this pattern equates to the transport we found between the Northern and Southern Branches, confirming that a significant fraction of the NAC transport shortcircuits the north Iceland Basin. Their second pathway follows a track similar to our Rockall Hatton Branch, turning sharply back to the west at the southern entrance to the Rockall Trough, then circulating cyclonically round the margin of the north Iceland Basin.

[28] Drifter data, in contrast, are interpreted [*Fratantoni*, 2001; *Orvik and Niiler*, 2002] to show two NAC branches passing through the Rockall Trough and the Iceland Basin, both passing into the Norwegian Sea [*Orvik and Niiler*, 2002]. Some interpretations show southwestward recirculation down the eastern flank of the Reykjanes Ridge [*Orvik and Niiler*, 2002; *Valdimarsson and Malmberg*, 1999], others do not [*Fratantoni*, 2001]. These apparent differences can be reconciled.

[29] Long-term hydrography across the Rockall Trough [*Holliday et al.*, 2000] begun by Ellett in 1975 [*Ellett et al.*, 1986] shows that there is ~4 ± 2 Sv of transport through the Rockall Trough (cf Figure 4), most of which (3 Sv) is in the shelf-edge current. Surface drifters entering the Rockall Trough reflect this transport, though some [*Pingree*, 1993] turn sharply to circulate anticyclonically round Rockall Bank. Other drifters following the Rockall Hatton Branch would approach close to the shelf west of Ireland at 53–54°N before turning sharply west (Figure 4, and *Bower et al.* [2002]) back to the western side of the Rockall and Hatton Banks. However, it is incorrect to interpret the drifter data [*Fratantoni*, 2001; *Orvik et al.*, 2001] as a continuous branch of the NAC entering the Rockall Trough. The shelf edge current is distinct from the Rockall Hatton Branch of the NAC, carrying saline ENAW from the south into the Rockall Trough [*Pollard et al.*, 1996].

[30] There can be little doubt that there is weak surface southwestward flow down the eastern flank of the Reykjanes Ridge [*Bower et al.*, 2002; *Orvik et al.*, 2001;

Valdimarsson and Malmberg, 1999] and hence stronger southwestward flow at depth [*Bower et al.*, 2002]. While this pathway is not shown by *Fratantoni* [2001], his schematic shows only "the most significant surface circulation features" and close examination of his Plate 10 reveals that all his (six) significant current vectors on the eastern flank of the Reykjanes Ridge show weak southwestward flow.

3.5. Temporal Change

[31] On Figure 4 are marked the pathways of the Northern and Southern Branches of the NAC in 1991 and 1996. In 1991 these are taken south and north of 54°N respectively from the Vivaldi 1991 [*Pollard et al.*, 1996] and Convex [*Read*, 2001] surveys. There is close agreement on the 1991 pathways where the two surveys overlap south of 54°N. *Bersch et al.* [1999], from a repeated section across the region between Greenland and Ireland, concluded that the SubArctic Front (called here the Northern Branch) retreated westward between 1995 and 1996. Our work complements theirs. Where *Bersch et al.* [1999] could resolve interannual changes but could make "no estimates on the horizontal displacement" of the front, our spatial surveys in 1991 and 1996 allow us to map and compare the pathways of the NAC, but we cannot say when changes occurred.

[32] Figure 4 confirms that the Subpolar Gyre contracted westward between 1991 and 1996. In 1991, the Northern Branch of the NAC penetrated as far east as 25°W, allowing fresh Subarctic Water [*Dickson et al.*, 1988] into the southern Iceland Basin between 51°N and 54°N. By 1996 eastward penetration of the Northern Branch had reduced significantly, turning sharply northward along 28.3°W (on 54°N) compared to 23.5°W [*Pollard et al.*, 1996]. This is a westward shift of 300 km. However, in both years the Northern Branch appears to turn back westward between 54°N and 55°N, to recross the Reykjanes Ridge then turn north in the Irminger Current.

[33] The Southern Branch contracted northward as well as westward between 1991 and 1996 (Figure 4). In 1991, it crossed 32°W at 48°N, but shifted northward to cross 30°W at 50°N (Figure 4). In 1996, it appears to have crossed the Knorr section at 33°W, 50.5°N, in close proximity to the Northern Branch. Thus the eastward flow appears to have been 100 km to 200 km further north in 1996.

[34] After turning northward, the Southern Branch ran close to due north in both years. In 1991, it ran north from 51°N to 57°N along ~21°W, leading *Bacon* [1997] to conclude that the major upper ocean transport of 16 Sv was "squeezed onto the west side of the Rockall-Hatton Plateau". In 1996, on the other hand, the Southern Branch ran slightly west of north from 53°N to 57°N, crossing 54°N at 23.7°W and 57°N at 25.2°W. Thus the westward shift ranges from 125 km at 54°N (accurately resolved by SeaSoar sections) to ~290 km at 57°N. In 1996 therefore the Southern Branch ran north up the middle of the Iceland Basin, and its associated transport was certainly not close to the Hatton Plateau. Indeed, the northern Knorr section shows 9 Sv of baroclinic transport crossing 59°N at 23°W (Figure 4), well away from any bathymetric feature. However, the sparse Vivaldi CTDs a few weeks earlier showed baroclinic transport of 14 Sv across 57°N spread over 600 km from 20°W and 30°W.

[35] In summary, both branches of the NAC shifted significantly between 1991 and 1996. The Northern Branch shifted several degrees westward, from 25°W to 28°W, reducing the amount of SAIW entering the southern Iceland Basin. The Southern Branch also moved several degrees west, from 21°W to 24°–25°W, thus flowing northward up the middle of the Iceland Basin in 1996, after being close to Hatton Bank in 1991. Other authors [*Bersch*, 2002] have discussed the relationship between the different pathways and the NAO. The north and westward shift we find in late 1996 is consistent with the change to negative NAO index in that year.

4. Conclusions

[36] The Vivaldi 1996 survey was unusual in providing wide area spatial coverage with high along-track resolution in the space of two months, compared with single section repeat surveys giving temporal resolution [*Bersch*, 2002; *Bersch et al.*, 1999] or spatial coverage from float data collected over several years [*Bower et al.*, 2002; *Orvik and Niiler*, 2002]. With this spatial resolution, it has been possible to trace several pathways of the NAC round the Iceland and Irminger Basins. The major path for the NAC into the Iceland Basin is traced as the Southern Branch of the NAC. In late 1996 it ran northward up the middle of the Iceland Basin, several degrees further west than in 1991, confirming that the SubPolar gyre had contracted in that period [*Bersch et al.*, 1999].

[37] SAIW is a useful tracer of the extent of penetration of the NAC into the Iceland Basin. It is identified by low salinities (Figure 3d) and strong upper layer stratification (Figure 3c). In pure form (salinities <34.9 on σ_0 = 27.4) SAIW is primarily found in and west of the Northern Branch (SubArctic Front) of the NAC, though it does penetrate as far as 25°W and 57°N (Figure 3d). In diluted form (salinities <35.1) it is found as far into the Basin as 60°N, 20°W. North of there upper layer structure strongly indicates westward recirculation of saline water (ENAW) from the Rockall Trough. This water can exit the Rockall Trough between Rockall Bank and Lousy Bank, resulting in a saline tongue that can be seen extending southwest on the eastern flank of the Reykjanes Ridge. Weak stratification (Figure 3f) and high salinity (Figure 3d) on σ_0 = 27.4 identify this tongue as a different water mass from that entering the Iceland Basin in the NAC.

[38] **Acknowledgments.** October is not the most pleasant time of year to be in the northern North Atlantic, but thanks to the Master, Mike Harding, crew, and scientific complement of RRS *Discovery*, we obtained an excellent data set.

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