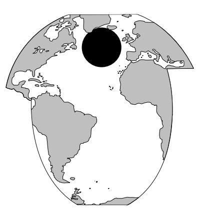
Did the Overflow from the Nordic Seas Intensify in 1996–1997?



Michael McCartney, Woods Hole Oceanographic Institution, Woods Hole, USA; Kathy Donohue, University of Hawaii, Honolulu, USA; Ruth Curry, Woods Hole Oceanographic Institution, USA; C. Mauritzen, Service Hydrographique et Océanographique de la Marine, Brest, France; and Sheldon Bacon, Southampton Oceanography Centre, Southampton, UK. mmccartney@whoi.edu

Warm subtropical waters are transformed to cold deep waters at higher latitudes in the North Atlantic, a meridional overturning circulation releasing considerable heat to the atmosphere. A northward-turning branch of the North Atlantic Current initiates this transformation, which occurs along two distinct pathways, one in the subpolar gyre and one farther north in the Nordic and Polar Seas. Mauritzen (1996a,b) gives a complete discussion of the circulation pathways and mean transformation rates for the latter region; here we present indirect evidence for recent changes there – indirect as the measurements are in the deep flow farther south.

A chilled remnant of the North Atlantic Current enters the Nordic Seas across the Iceland-Scotland Ridge as the initial stage of the high latitude transformation. After additional cooling and freshening along a circuit around the Nordic and Polar Seas, cold, fresh, and very dense waters spill over the Greenland-Iceland-Faroe-Scotland Ridge feeding a Deep Northern Boundary Current (DNBC) system. The dense waters entrain thermocline and intermediate waters as they descend into the DNBC and are joined by a confluence of resident deep waters into the DNBC. The Iceland-Scotland Overflow Water (ISOW) is carried by the DNBC from the Iceland Basin to the Irminger Basin through the Charlie Gibbs Fracture Zone. West of Iceland, Denmark Strait Overflow Water (DSOW) spills over the Greenland-Iceland Ridge to join the ISOW and deep waters from father south in the western basin. The combined outflow of Nordic Seas waters is estimated as about 6 Sverdrups (Sv) near the overflow sills. The entrained thermocline and intermediate waters and the deep-water confluences approximately double the transport: the multi-year direct measurements of dense-water transport of the DNBC off Angmagssalik, Greenland by Dickson and Brown (1994) indicate an amplitude of about 11 Sv below density 27.8.

It is natural to wonder about possible shifts in the intensity of the overflows themselves as well as the water masses carried by the DNBC and its transport. Dickson and Brown (1994) reported transports that were remarkably stationary. In contrast, several investigators have documented that water-mass characteristics of the DNBC/DWBC in the Labrador Basin in the Overflow density range (beneath the local convection of Labrador Sea Water) are significantly variable (Brewer et al., 1983; Swift, 1984; Lazier, 1988). Questions linger as to whether that measured variability is interannual, decadal or partly aliassed by higher frequencies. Dickson et al. (1996) link high/low North Atlantic Oscillation (NAO) index to weak/strong forcing of Nordic Seas water-mass transformation, and strong/weak forcing of subpolar gyre water-mass formation. The NAO index reflects basin-scale changes in wind speed and direction, air temperature, and humidity; fluctuations in the NAO index thus are linked to changes in buoyancy- and wind-driven forcing. This could affect the DNBC in at least four ways. First, changes in buoyancy forcing could alter the amount as well as the salinity and temperature of water transformed into specific density ranges within the Nordic and Polar Seas and exported to lower latitudes by the Overflows. Second, changes in the wind-driven forcing could affect the nature of the large cyclonic circulation system centred on Iceland which includes (and links) the Nordic Seas and the subpolar gyre and their wind-driven exchanges. We are unaware of a study of the relative intensities and patterns of wind-driven circulation that might accompany strongly contrasting wind fields of high and low NAO index states. Third, if the overflow system involves hydraulic control, then the alterations of density structure within the Nordic Seas (“upstream”) could alter that control, including the intensity of overflow. Fourth, the amount and characteristics of warmer subpolar waters entrained into the overflows could change with NAO variations of buoyancy- and wind-forcing of the subpolar gyre and alter DNBC characteristics and transport.

Bacon (1997a,b) has examined the variability of the DNBC by estimating transports of the DSOW denser than 27.8 in the DNBC in the southern Irminger basin, south-east of Cape Farewell, Greenland. His estimates are for the most part geostrophic relative to 1000 m reference levels, but a case is made for a link to absolute transport changes. His analysis shows DSOW transports that are relatively weak in 1955–67, relatively strong in 1978–88, and relatively weak again in 1991–97, with a major data gap in 1968–77. Concentrating here on the later two of the three periods of data, the low-transport phase of 1991–97 averages 4.3 Sv, ranging roughly between 3.4 (in 1995) to 5.4 Sv (in 1991), while the high-transport phase of 1978-90 averages about 7.7 Sv with a range 6.7 to 8.7 Sv. The difference in transport in these two multi-year periods is nearly a factor of two (1.8). We report here evidence that the system may be recovering from that low-transport phase.

Bacon used a forward integration of an NAO index to visualise accumulated forcing of Nordic Seas transformation to illustrate that the ocean integrates forcing history. Here we use simple averaging of Hurrell’s NAO index (Hurrell, 1995, and personal communication 1997 for an update through winter 1996–97). The 11-year high-transport phase of the DNBC had an average NAO index of 0.56, while the 6-year low-transport phase had an average NAO index of 1.67. Both periods are thus relatively high NAO index compared to a long 132-year average, with the early 1990's particularly high. As Bacon noted, this is suggestive of a causal link between atmospheric conditions and the intensity of the DSOW transport. It is not definitive due to a lack of a circulation scheme or process interpretation that links the DNBC intensity at a point to all the impacts of variable atmospheric forcing.

We now move to new measurements we have been involved with, in connection with the US-funded ACCE program. These data are supplemented by a UK-funded Cape Farewell section from late August 1997. We have combined the latter with two ACCE sections at nearly the same location from May 1997 and November 1996 to give a set of three Cape Farewell sections spanning about eight months. Farther north the ACCE program repeated sections in November 1996, May 1997 and October 1997 to give a set of three Angmagssalik sections spanning nearly a year, near the location of Dickson and Brown's long-term monitoring array in the 1980's and early 1990's. Fig. 1 shows the locations of the stations crossing the DNBC and interior of the Irminger Basin for all sections.

Fig. 2a,b (page 23) shows the potential-temperature distribution for the three sections at each of the two locations. The DSOW is found as a thin layer along the continental slope of eastern Greenland stretching from the abyss "uphill" to depths shallower than 2000 metres. The westward rise of the DSOW is the signature of its southward geostrophic flow relative to a mid-depth reference level. The sections are striking because the degree of onshore rise of the DSOW varies. The onshore rise seems to progressively increase during the year spanning the measurements at the Angmagssalik location, Fig. 2a, amounting to a net uplift

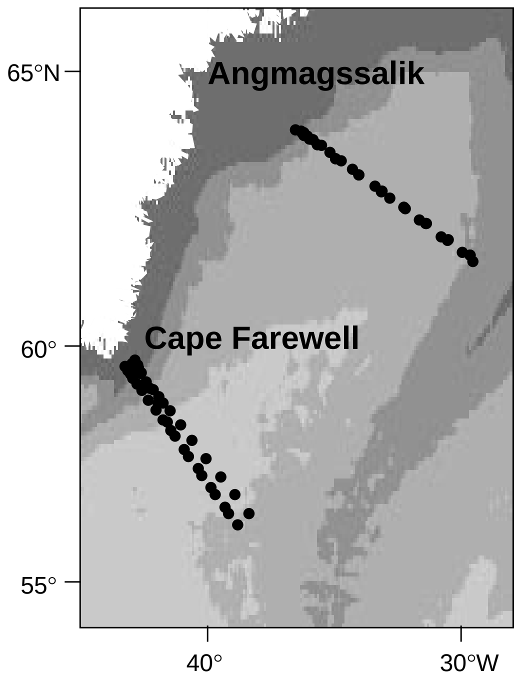


Figure 1. Positions of hydrographic stations used in this study. Bathymetry is shaded in 1000 m depth intervals.

of the shallow onshore edge of the DSOW of about 600 metres. Associated with this uplift is a strongly enhanced vertical temperature gradient between the onshore edge of the DSOW and the overlying warmer waters of the East Greenland Current in fall, 1997. In Fig. 3a (page 23) we show potential temperature-salinity relations for the Angmagssalik stations which demonstrate a progressive freshening of the DSOW accompanying this alteration of structure. At station 71 of the October 1997 section, where the vertical temperature gradient is most extreme, a linear potential temperature-salinity relation bridges the fresh DSOW to the East Greenland Current water bypassing the normally intervening Labrador Sea Water (LSW), which has been totally "squeezed out". This may indicate enhanced vertical mixing between these waters induced by the DSOW uplift.

Estimates of transport for the three Angmagssalik sections are shown in Fig. 4. Transports for $\sigma_0 = 27.80$, (left column) indicate a progressive increase of baroclinic transport (relative to 1000 m) from 2 Sv through 4 Sv to 6 Sv. The indicated small transport ranges for each curve reflect insensitivity to details of the "bottom triangles" below the deepest common level of station pairs. Simple referencing to ADCP data breaks down the orderliness of this time-progressive transport increase, but still shows the existence of a substantial transport increase. Most of the "noise" induced by the ADCP referencing seems to occur for the lighter parts of the DSOW. Fig. 4 (right column) shows similarly estimated transports for the $\sigma_0 = 27.86$ layer, roughly coinciding with the 2.4°C (shaded on these plots). In the first two realisations there is little difference between the ADCP-referenced transports and the 1000 m referenced transports. In the third realisation they are almost uniformly offset, with ADCP referencing giving an enhancement of about 1.5 Sv. This offset occurs for the contributions involving station 71 – which was noted above as having enhanced vertical temperature gradient and an absence of LSW. The ADCP data combined with the shear indicates a strong barotropic flow associated with station 71.

At Cape Farewell differs somewhat from that at Angmagssalik. The potential temperature sections, Fig. 2b, show that a thickening of the cold DSOW and an uplifting of its onshore edge occurred between the first and second realisations, but little additional change between the second and third realisations. Potential temperature-salinity data (Fig. 3; right panel) shows some freshening of the DSOW between the first two realisations, but little additional freshening in the third realisation. The impression we get is that the initial phase of freshening observed at Angmagssalik had arrived at Cape Farewell in spring 1997, but that the very fresh phase of October 1997 observed at Angmagssalik has not reached Cape Farewell in late August 1997. Fig. 5 shows two columns of transport estimations for Cape Farewell in the same arrangement as Fig. 4. The baroclinic transport at Cape Farewell for $\sigma_0 = 27.80$ relative to 1000 m is about 3.8 Sv in November 1996, which is somewhat lower than Bacon's average of 4.3 Sv for earlier

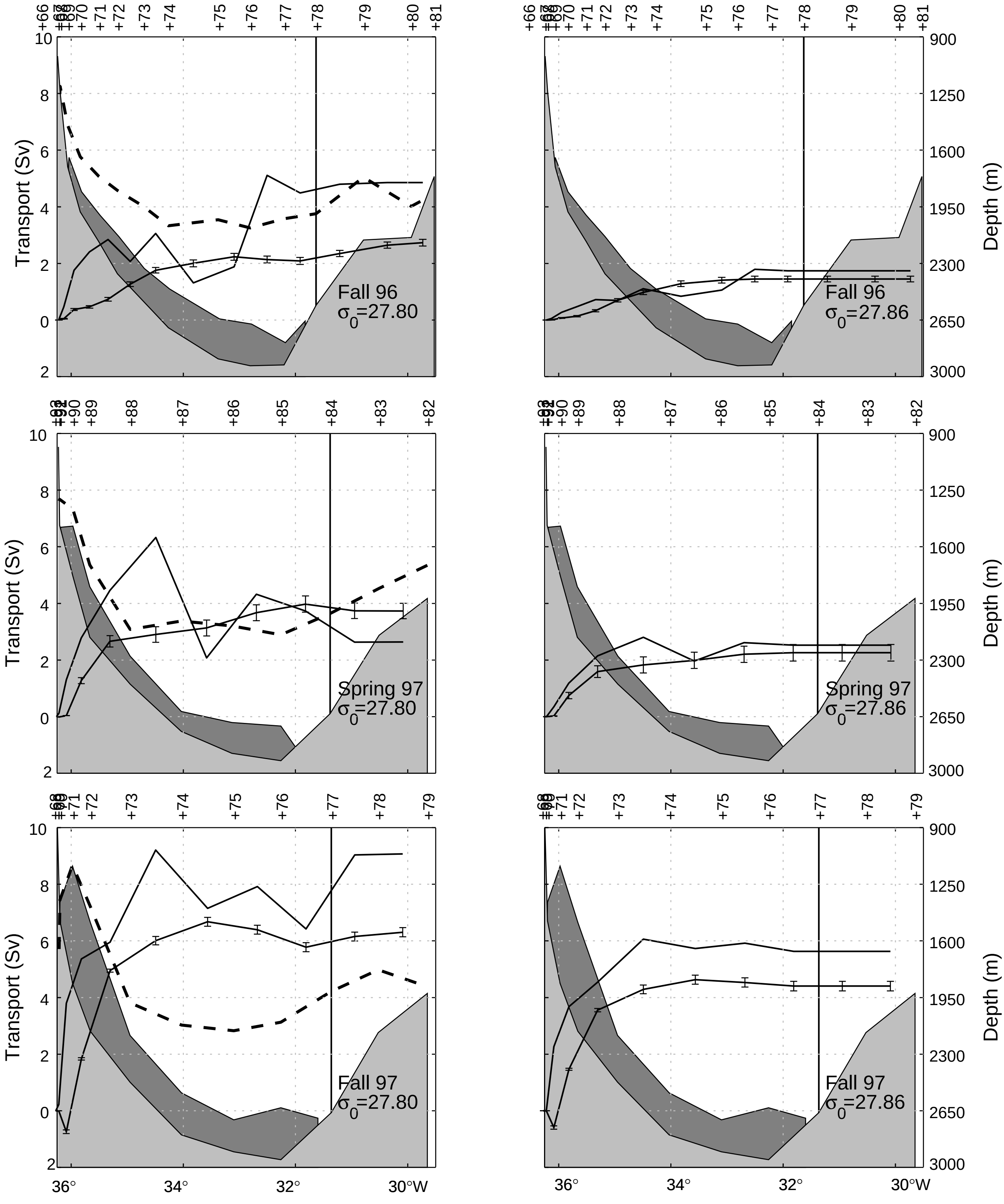


Figure 4. Transports for the Angmagssalik sections accumulated from Greenland (positive is southwestward). Transport below the deepest common level (DCL) is estimated with two methods, using a fixed speed (the DCL speed) or extrapolation of the deep shear from above the DCL. Geostrophic transports plotted are the average of the two methods, and the short vertical bars give the range of the two forms of estimates. ADCP-referenced transports use the average of the underway ADCP velocity normal to the section as a reference speed, and for this curve the range reflecting the two DCL methods is not included in the plot. Bathymetry is shaded light grey. Dark grey shading represents potential temperatures <2.4°C. The dashed line is the σ_0 = 27.80 contour. Right (left) panels are transports σ_0 = 27.80 (27.86). The vertical line corresponds to the first offshore stations without potential temperatures less than 2.5°C, and this is used as an estimate of the offshore edge of the DNBC.

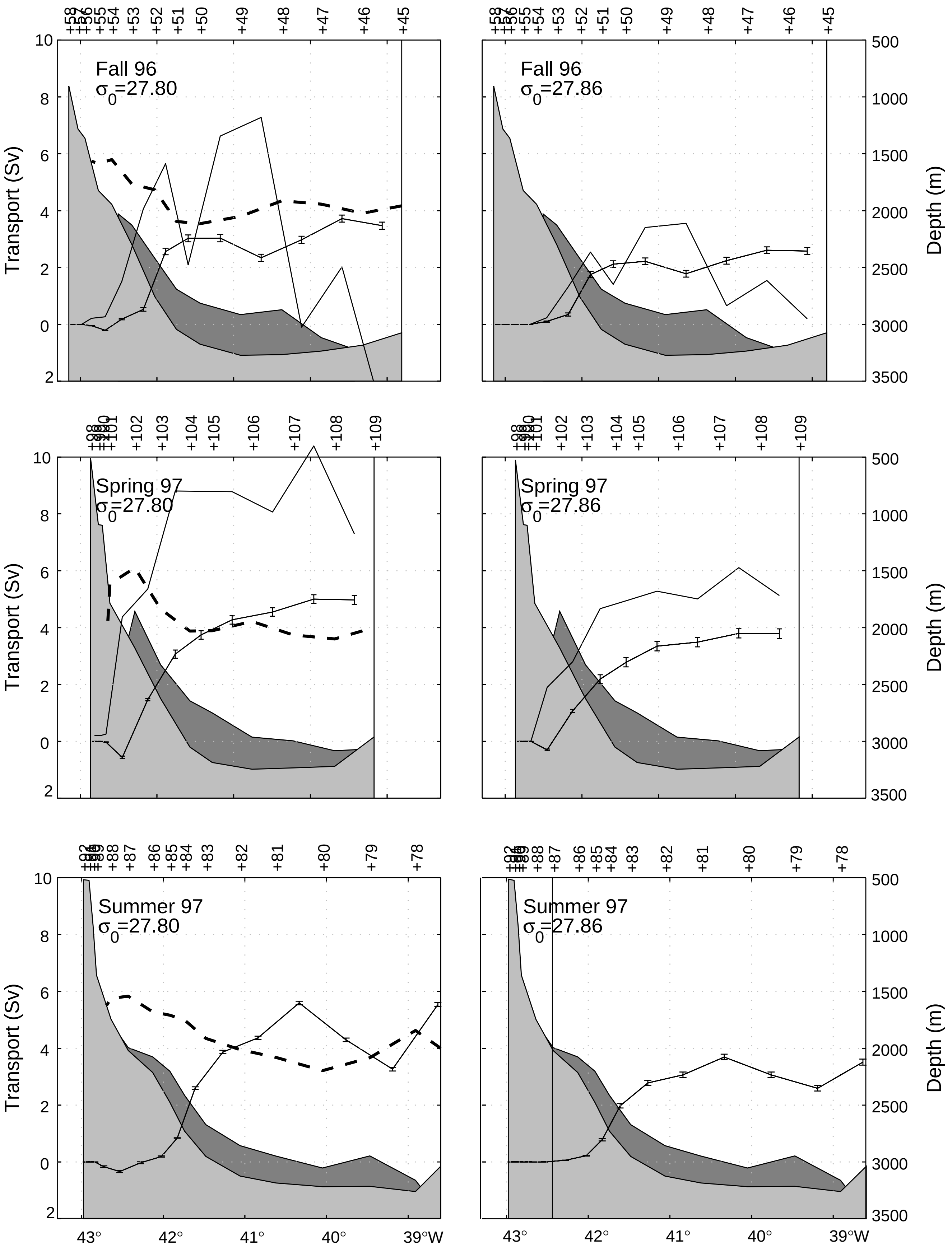


Figure 5. Same as Fig. 4 but for the Cape Farewell sections.

1990–1996 data. In the second realisation there is a transport increase to about 5 Sv, and in the third realisation maximum transport approach 6 Sv. Overall these baroclinic estimates are suggestive of a trend of increasing transport at this site in parallel with that at Angmagssalik, but offshore reversals of flow in the third realisation at Cape Farewell cloud the issue (there is an eddy of some sort at station 79, see also Fig. 2b). ADCP data is not yet available for this third realisation. The two ADCP-referenced estimates available now suggest that the DSOW transport was greatly enhanced in the second realisation compared to the first at Cape Farewell, but we will await the ADCP data for the third realisation to reassure us on the reality of simultaneous transport growth at both locations.

Returning to the question of forcing, the last two winters are notable for the abrupt shift of the NAO index from its very high values in the earlier 1990's. In winter 1995–96, the NAO index (Hurrell, personal communication) dropped from the second highest recorded value +3.94 (in 132 years, the highest was 1989, +5.07), to the second lowest, -3.88. The index recovered in winter 1996–97 only to a slightly positive value of +0.41. Thus our observations of an apparently intensifying and freshening flow of DSOW at Angmagssalik, and related signals at Cape Farewell, occurred one-to-two years after a precipitous drop of the NAO index. The very low-index winter of 1995–96 certainly would have strongly enhanced buoyancy forcing of water-mass transformation compared to the preceding several years of very high NAO index. This again suggests but does not prove a causal link between the atmospheric conditions and the intensity of DSOW transport. We await with curiosity additional measurements to be made by the international community along the coast of Greenland in 1998 as well as wondering what the current winter will yield for a NAO index.

The Overflow system east of Iceland may also have changes in this period. Our three Angmagssalik sections (Fig. 2a) are the western ends of sections reaching to the eastern boundary (Rockall Trough). In mid-basin we obtained three crossings of the ISOW near 60°N where the DNBC carries the ISOW south-west along the eastern flank of the Reykjanes Ridge towards the Charlie Gibbs Fracture Zone. In the third of these crossings, Fall 1997, the coldest ISOW exhibited a cold bottom layer near 2.06°C, about 0.2°C colder than in the earlier two realisations and colder than regional average historical data. In the Iceland Basin the main thermocline is deeper than in the Irminger Basin, so we use a 1500 db reference level to make preliminary baroclinic transport estimates of 4.1, 3.4, and 5.0 Sv for the water 27.80 in fall 1996, spring 1997, and fall 1997, respectively, indicating here too an enhanced dense water transport by late 1997. Thus it is possible that the entire DNBC system accelerated in 1997, and that this may be a reflection of NAO-induced change in the forcing of both DSOW and ISOW.

Acknowledgements

The authors thank Lynne Talley and Eric Firing for the use of the spring 1997 ACCE data.

References

Bacon, S., 1997a: Decadal variability of the North Atlantic Overflows. Int. WOCE News., 26, 29–30.

Bacon, S., 1997b: Decadal variability in the Outflow from the Nordic Seas to the Deep North Atlantic. Nature, subjudice.

Brewer, P. G., W. S. Broecker, W. J. Jenkins, P. B. Rhines, C. G. Rooth, J. H. Swift, T. Takahashi, and R. T. Williams, 1983: A climatic freshening of the deep Atlantic north of 50°N over the past 20 years. Science, 222, 1237–1239.

Dickson, R. R., and J. Brown, 1994: The production of North Atlantic Deep Water: Sources, rates and pathways. J. Geophys. Res., 99, 12319–12341.

Dickson, R. R., J. R. N. Lazier, J. Meincke, P. Rhines, and J. Swift, 1996: Long-term coordinated changes in the convective activity of the North Atlantic. Prog. Oceanogr., 38, 241–295.

Hurrell, J. W., 1995: Decadal Trends in the North Atlantic Oscillation Regional Temperatures and Precipitation. Science, 269. 676–679.

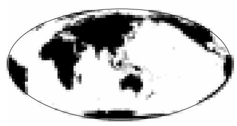
Lazier, J. R. N., 1988: Temperature and salinity changes in the deep Labrador Sea, 1962–1986. Deep-Sea Res., 35, 1247–1253.

Mauritzen, C., 1996a: Production of Dense Overflow Waters Feeding the North Atlantic Across the Greenland-Scotland Ridge. Part 1: Evidence for a revised Circulation Scheme. Deep-Sea Res., 43, 769–806.

Mauritzen, C., 1996b: Production of Dense Overflow Waters Feeding the North Atlantic Across the Greenland-Scotland Ridge. Part 2: An Inverse Model. Deep-Sea Res., 43, 807–835.

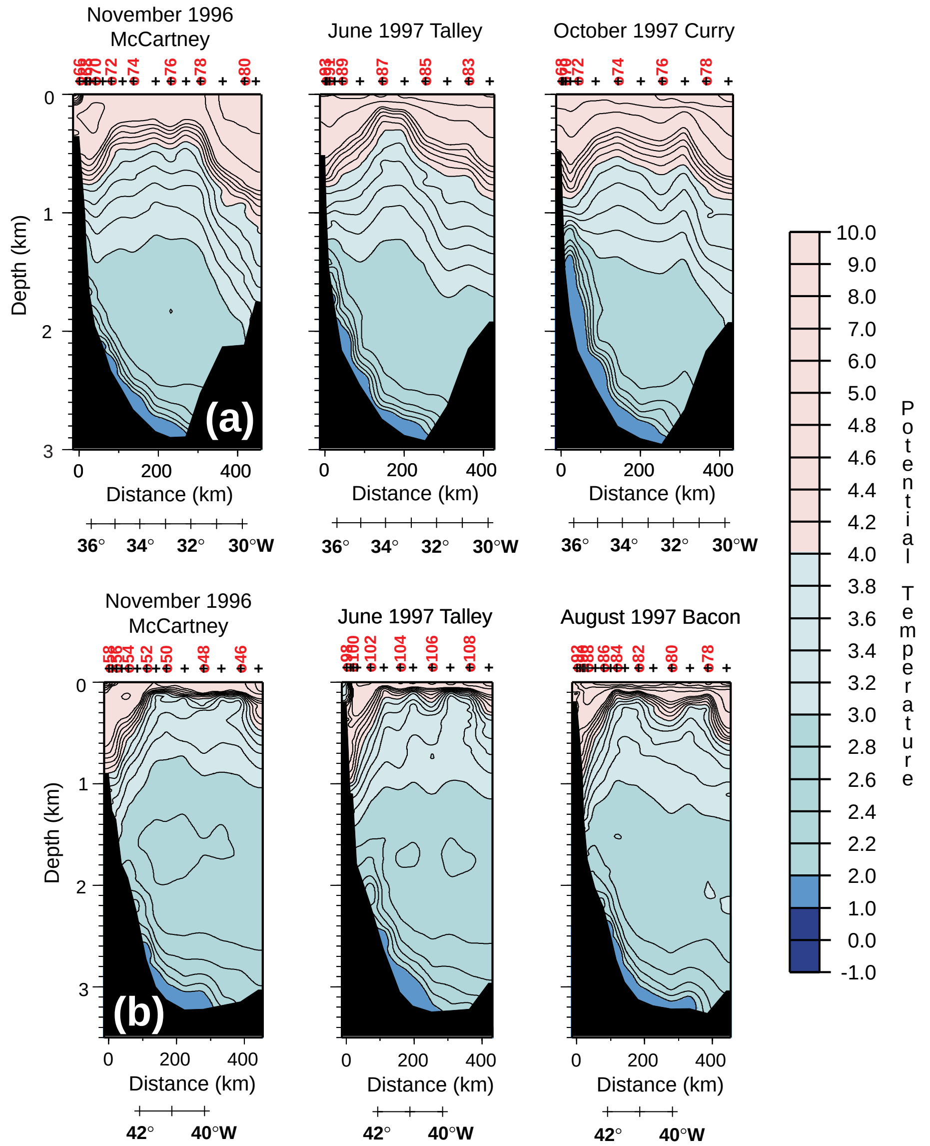
Swift, J. H., 1984: A recent T-S shift in the deep water of the northern North Atlantic. In: Climate processes and climate sensitivity, J. E. Hansen and T. Takahashi, editors. Geophysical Monographs, 29, Maurice Ewing Volume 5, American Geophysical Union, Washington DC, 39–47.

Toward an Estimate of the Global Circulation from WOCE Data and a General Circulation Model

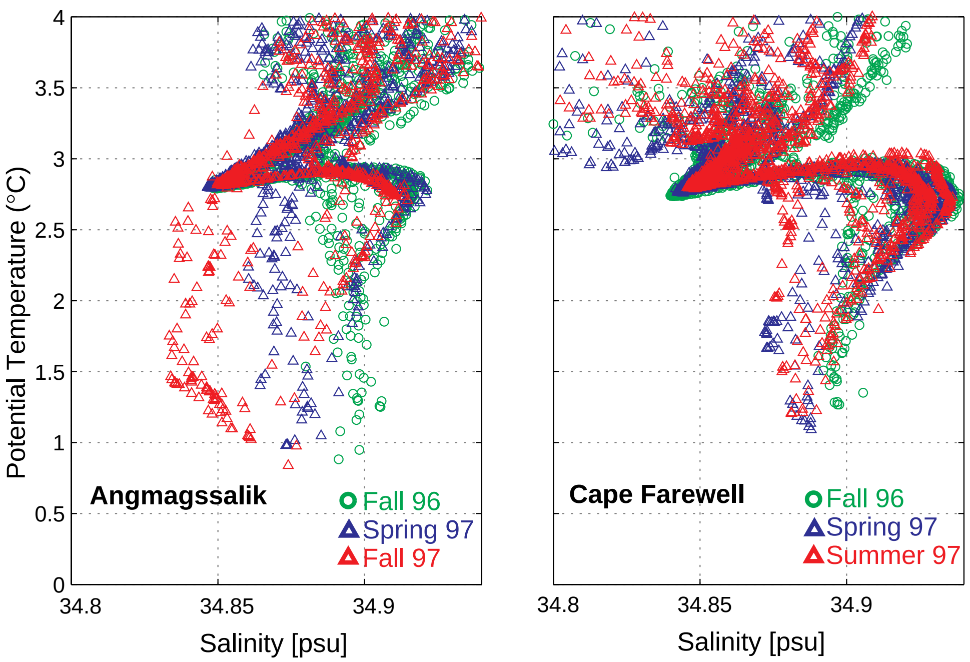


Detlef Stammer, Massachusetts Institute of Technology, USA. detlef@lagoon.mit.edu

A primary objective of WOCE is to obtain an understanding of the absolute time-varying large-scale circulation of the world ocean, and its impact on climate. To meet this goal, all available data need to be evaluated jointly and in a way consistent with data uncertainties and with our best knowledge about dynamics as it is embodied in modern Ocean General Circulation Models (OGCMs). All important aspects of the circulation and its transport properties can be studied subsequently from the estimated ocean state and its uncertainty. Here we illustrate preliminary results of such a global estimation system for the time-evolving, absolute circulation of the ocean and describe work in progress.



McCartney et al., page 3, *Figure 2. (a) Potential temperature along the three Angmagssalik sections. In these sections Greenland is on the left and you are looking northwards through the sections. (b) Potential temperature along the three Cape Farewell sections.*



McCartney et al., page 3, *Figure 3. Potential temperature-salinity diagram for the Angmagssalik (left panel) and the Cape Farewell (right panel) sections.*