2.2 North Atlantic circulation, pathways and water masses – Distributions from WOCE observations, altimetry and model results

Upper layer circulation in the subpolar North Atlantic during the WOCE period

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A principal focus of observational upper ocean work in the subpolar North Atlantic is the transformation of inflowing warm, saline subtropical waters into the precursors of intermediate water formed in the Labrador Sea and deep water formed in the Nordic Seas. This constitutes the local upper ocean limb of the meridional overturning circulation whose amplitude is calculated variously at about 15 to 20 Sv. Conventional circulation analyses (e.g. Reid, 1994) show a branching of the Gulf Stream and North Atlantic Current feeding the cyclonic subpolar circulation, which is depicted with broad northward flow in the eastern subpolar region, feeding surface flow into the Norwegian Sea, westward flow along the northern margin and into the Irminger Current which feeds into the Labrador Sea. Some element of the flow following the curve of the Reykjanes Ridge is also indicated, particularly with increasing depth in the water column. Ample evidence for incursion of lower latitude properties has been demonstrated, for instance with the high silica tongue at about 27.5 σ_θ originating from the Gulf Stream and indicating South Atlantic influence moving into the subpolar region (Tsuchiya, 1989). Mass, heat and salt budgets for the transformation of upper ocean waters around the subpolar gyre have been made (e.g. Worthington, 1976; McCartney and Talley, 1984; McCartney 1982; Schmitz and McCartney, 1993). However, the seasonal transformation with careful local flux budgets, and description of the actual transformation process as tied to the fluxes and local circulation has not heretofore been accomplished.

The upper ocean waters of the subpolar gyre are characterised by quite thick layers of low stability, assumed to originate as deep mixed layers in winter. In general these layers are more than 400 m thick, ranging up to more than 600 m, and then to 1500 during intermediate depth convection in the Labrador Sea (McCartney and Talley, 1982). These layers are remarkable on a global scale only in the Antarctic sector of the east Indian and South Pacific Oceans are comparable depths attained (e.g. global mixed layer depth map based on oxygen saturation from Talley, 1999). Because of their thickness and ease of identification, the subpolar mixed layers are termed Subpolar Mode Water (SPMW). The distribution of SPMW based on a relatively sparse 1950s/1960s data set was described by McCartney and Talley (1982). The concept therein was of thick mixed layers moving smoothly eastward and then northward and thence cyclonically around the subpolar gyre into the Labrador Sea, with an initial potential temperature and density of 14°C and 26.9 σ_θ just south of the North Atlantic Current loop, varying smoothly around the gyre to finally arrive at the Labrador Sea Water (LSW) properties of about 3°C/27.84 σ_θ. The North Atlantic Current jet centred at about 52°N was considered the fulcrum of this cyclonic movement. Southward subduction of the 27.1 and 27.2 σ_θ waters of the eastern region into the subtropical gyre is also observed. This set of observations and hypothesis of transformation are items to be tested using the WOCE observations.

Another portion of the upper limb circulation to be tested is the extent to which Mediterranean Water feeds higher salinity into the subpolar gyre. The high salinity of the North Atlantic inflow into the Nordic Seas is a crucial part of the

Table 1. Selected in situ WOCE Observations for the subpolar North Atlantic.

Floats' PI	*Drifters*	*Current Meters (PI)*	*Hydrography (PI)*
Davies (PALACE)	International effort (Niiler)	Canada (Clarke)	Canada (Clarke, Hendry, Lazier)
Owens (PALACE)		Germany (Schott/Fischer)	France (Gaillard, LeCann, Mercier)
Gould (PALACE)		Nordic WOCE (Hansen)	Germany (Bersch, Käse, Koltermann, Meincke, Schott, Sy, Zenk)
LeCann and Speer (ALACE)		United Kingdom (Dickson/Saunders)	Netherlands (van Aken)
Rossby (RAFOS isopycnic)			Nordic WOCE (Blindheim, Østerhus)
Bower and Richardson (RAFOS isopycnic)			Russia (Sokov, Tereshchenkov)
Zenk (RAFOS)			Spain (Parrilla)
			United Kingdom (Bacon, Bryden, Gould, Pollard, Smythe-Wright)
			United States (Curry, Joyce, McCartney, Pickart, Talley)

formation of what becomes North Atlantic Deep Water. The amount of Mediterranean Water influence versus simple incursion of high salinity surface waters is to be quantified. How Mediterranean Water influence spreads northward is to be determined, whether by direct advection in a poleward eastern boundary current or through eddy processes that gradually feed higher salinity northward.

WOCE observations

The WOCE data set for the subpolar North Atlantic is extremely rich, including Lagrangian observations (surface drifters and large numbers of subsurface floats), current meter arrays, and hydrography covering many areas every year since the start of WOCE field observations in 1990. Particularly intensive field observations occurred in 1991 and again in 1997, the latter including many float projects (Table 1). A major observational effort has also been undertaken in the Labrador Sea studying the formation of intermediate water. Challenges for synthesis during the next few years are to gather these data sets from many different investigators and countries and use them to construct the best analyses of the circulation, eddy field, water properties, and transformation/mixing. Because of the major time variations in the subpolar region associated with the North Atlantic Oscillation, care must be taken to examine data sets from uniform time periods. It is hoped that seasonal variation can also be examined for at least the latter years, given the temporal coverage of the data sets.

All results for drifters, floats and current meters described in the next few paragraphs should be referred back to and ascribed to the principal investigator listed for each measurement.

Surface drifter averages for $2° \times 6°$ boxes are possible for all of the region from 1988 to the present, with some regions with coverage sufficient for much higher spatial resolution (P. Niiler, pers. comm.). The drifter averages show the expected elements of the eastward flow of the North Atlantic Current, turning northward into the subpolar region. Average westward flow south of Iceland is remarkably weak. Strong currents resume along the Greenland coast in the Irminger Current, and in the West Greenland and Labrador Currents in the Labrador Sea.

Subsurface floats were deployed in four modes: acoustically tracked (RAFOS) along an isobar, RAFOS along an isopycnal, pop-up without profiling (ALACE), and pop-up with temperature/salinity profiling (PALACE). The first large deployment was of acoustically-tracked floats in the North Atlantic Current at

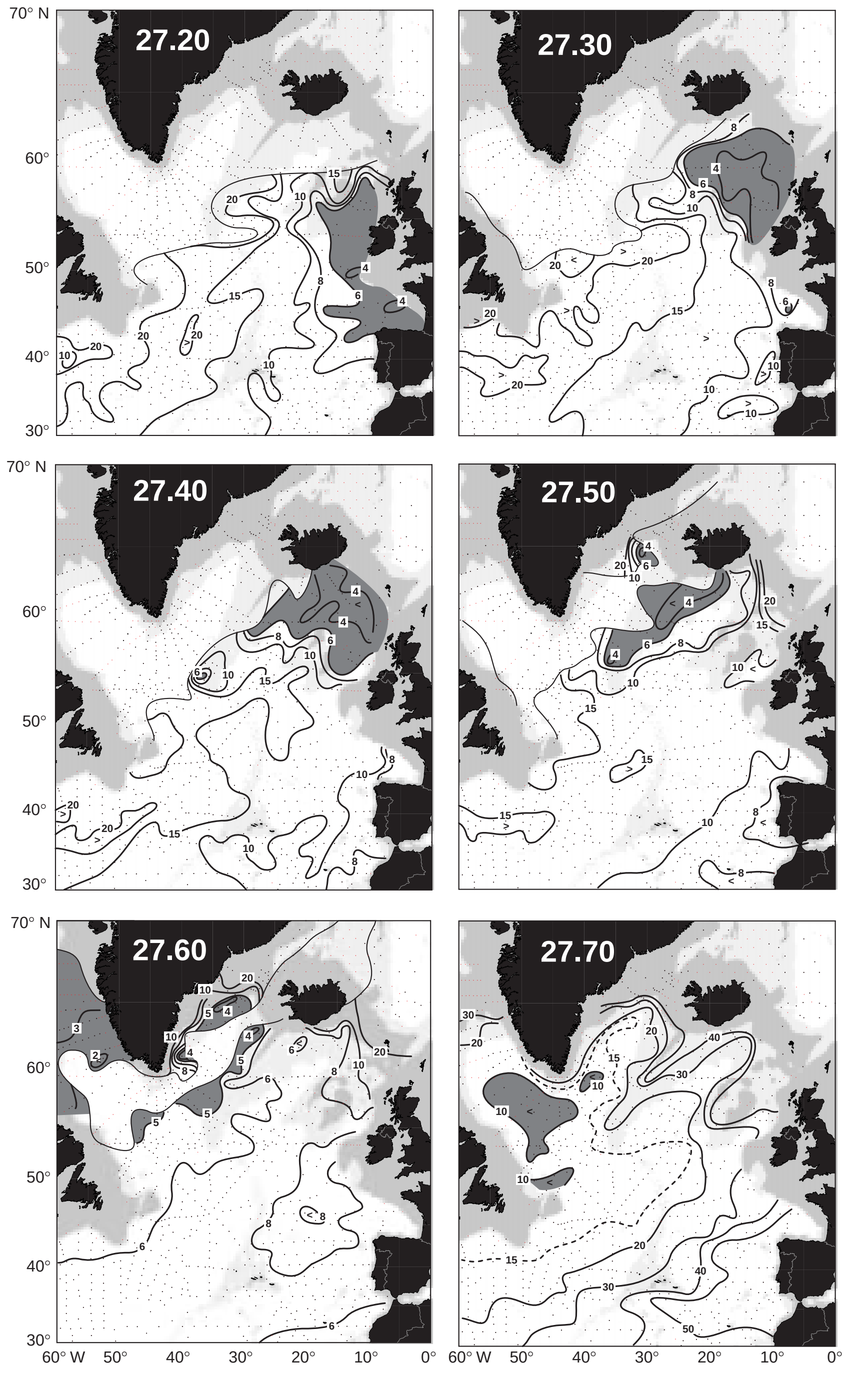

Figure 1. Isopycnic potential vorticity (10^{-13} cm^{-1} sec^{-1}) based on the Reid (1994) data set, most of which was collected in the late 1950s and 1960s, during a period of low North Atlantic Oscillation index. PV less than 4×10^{-13} cm^{-1} sec^{-1} at 27.2 to 27.5 σ_θ is shaded; each of these isopycnals has a similar range of PV. The shaded region at 27.6 σ_θ is less than 5×10^{-13} cm^{-1} sec^{-1}, since PV is somewhat higher on this isopycnal. The shaded region at 27.7 σ_θ is less than 1×10^{-13} cm^{-1} sec^{-1} since PV is generally lower at this density, which lies at the top of the Labrador Sea Water layer.

27.2 and 27.5 σ_θ (Rossby, pers. comm.). (The latter is the density near the base of the thermocline waters feeding into the subpolar region; it outcrops in the eastern Irminger Basin.) The mean velocities from these show a major eddy centred at 42°N, 44°W (Mann Eddy) and describe the loop of the North Atlantic Current into the Labrador Sea. RAFOS floats at 27.5 σ_θ were deployed at and east of the Reykjanes Ridge in 1996–1997, with the first results returning now (Bower and Richardson, pers. comm.), including capture of one float by a meddy near the Goban Spur. RAFOS floats at 1500 dbar east of the Reykjanes Ridge and in the Iceland Basin and Rockall areas show two modes: eddy flow and topography-following flow along Rockall Plateau/Hatton Bank and the Reykjanes Ridge (Zenk, pers. comm.).

PALACE floats have been deployed at 450, 1000 and 1750 dbar east of the Reykjanes Ridge as part of the project ARCANE (LeCann and Speer, pers. comm.). At 450 dbar, the floats describe westward circulation out of the Bay of Biscay and southward flow west of Portugal. At 1000 dbar, the mean vectors describe a poleward current along the eastern boundary along Portugal, the north side of the Bay of Biscay and along the Celtic shelf. They also show an anticyclonic flow (eddy) west of the Celtic shelf and cyclonic flow in the northern part of the Bay of Biscay. PALACE floats have been deployed in the western Labrador Sea at 1500 m (Schott and Fischer, pers. comm.). Most of those that escaped the Labrador Sea did so in the North Atlantic Current or southward around Flemish Cap, but none continued southward into the deep western boundary current. A transport-resolving array in the Labrador Current at 53°N accompanied the float program and showed a southward transport top-to-bottom of 40 to 50 Sv (Schott and Fischer).

PALACE floats deployed in great numbers at 700 and 1500 m in the Labrador Sea (Davis) and with somewhat sparser coverage in the remainder of the subpolar region (Owens) have been used to create a dynamic height map at 700 m, with the use of vertical shear from Levitus climatology to map the deeper float velocities upward. Coverage began in 1994, with a steep ramp-up to a large number of profiles in 1997 and 1998. The Labrador Sea floats describe the outer rim current and a “short circuit” into the Irminger Sea. Of the few floats that rounded Flemish Cap to the south, none continued southward in the deep western boundary current. Floats in the south-eastern region (40 to 50°N and east of 30°W) show weak flow dominated by eddies. One float in the Rockall region managed to pass north of the Iceland-Scotland ridge after grounding and continued vigorously northward along the Norwegian coast. The 700 m dynamic topography reveals a very interesting feature of an anticyclonic flow or countercurrent inshore of the rim current around the Labrador Sea. The low dynamic topography between the rim current and countercurrent may be the site of deeper mixed layers and convection. The two main exit paths from the Labrador Sea are thus due to the countercurrent into the Irminger Basin, south of Greenland, and also along the North Atlantic Current. Elsewhere, flow closely follows the Reykjanes Ridge and is cyclonic in the Iceland Basin and possibly anticyclonic in Rockall Trough. A separate large-scale cyclonic flow is found east of the Reykjanes Ridge and south of the Iceland Basin. The field in the south-eastern region appears dominated by eddies.

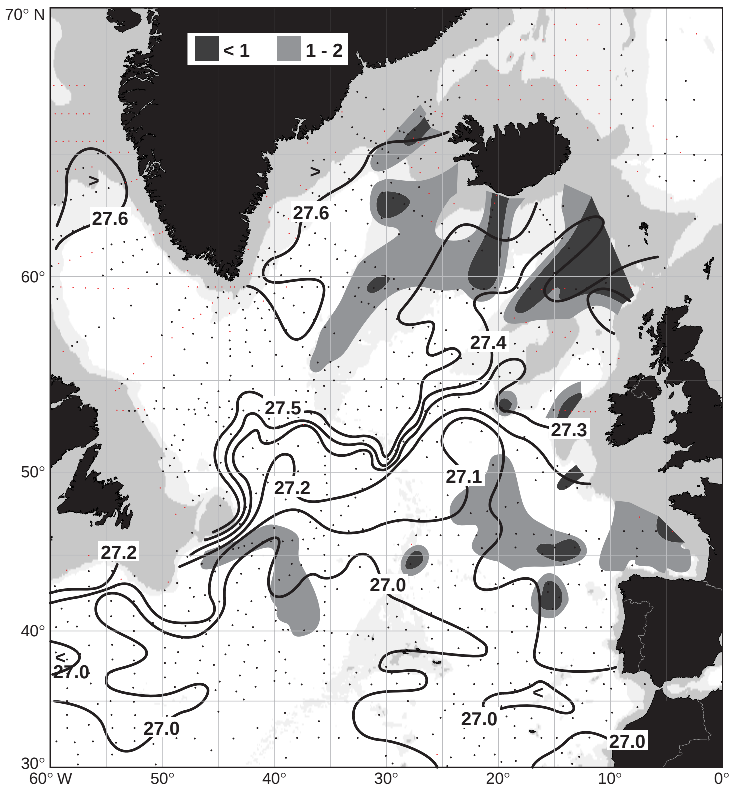

Figure 2. Potential density σ_θ at the absolute potential vorticity minimum (for densities less than 27.65 σ_θ), using the Reid (1994) data set. Regions of potential vorticity of less than 2×10^{-13} cm^{-1} sec^{-1} are shaded (dark and light, respectively).

Observations in the Irminger Basin

Many PALACE floats produce profiles of temperature and salinity. At some point it is presumed that these can be used to augment the hydrographic data set. The total hydrographic data set and many results are much too extensive to be described here. An immediate challenge is to assemble this ongoing data set, which consists of a number of sections that are repeated every year. Because of the large interannual changes in the subpolar regions’ water properties, the following analysis of hydrographic data is confined to May–August 1997 when there was reasonably good coverage of the whole region.

Subpolar Mode Water

The data set consisting primarily of stations collected in the 1950s and early 1960s, assembled by Reid (1994) was first used to map the Subpolar Mode Water (SPMW) for that period. During that time, the NAO was in a protracted low phase, and so it is expected

Table 2. WOCE CTD data sources for Figure 3.

A24	Talley	Knorr	June 1997
AR19	Koltermann	Gauss	May 1998
AR7W	Schott	Meteor	July/Aug 1997
A25	Bacon	Discovery	Aug/Sept 1997
	Zenk	Meteor	May 1997

that the data set, while covering many years, is reasonably uniform. It was relatively easy to create maps from the data set, suggesting that indeed the data set was internally consistent. This data set has much better spatial resolution than the more limited data set used in McCartney and Talley (1982) where the SPMW was first described, although both data sets are from about the same time.

Isopycnic potential vorticity ($f\,d\rho\,/\,\rho\,dz$) was calculated from the historical bottle data as outlined first in Talley and McCartney (1982). PV was mapped on isopycnals at every 0.1 σ_θ from 26.8 to 27.7 σ_θ. Maps for 27.2 to 27.7 σ_θ are shown in Fig. 1. Low PV indicates a relatively thick layer. On all isopycnals, low potential vorticity occurs near the isopycnal surface outcrop, and hence is bounded by a high lateral gradient of PV on the outcrop margin. The thickest layers proceed from the Bay of Biscay at 27.2 σ_θ, to Rockall Trough/Plateau at 27.3 σ_θ, to the south side of the Iceland–Scotland Ridge at 27.4 σ_θ, to along the Reykjanes Ridge at 27.5 σ_θ, around the perimeter of the outcrop in the Irminger Basin at 27.6 σ_θ, to the central Labrador Sea at 27.7 σ_θ. The last distribution is very similar to that of the denser LSW (Talley and McCartney, 1982). In contrast to the smooth, wide SPMW distribution shown in McCartney and Talley (1982), these maps show that the deep mixed layers are strongly confined to the boundary regions. The most extreme low PV is mostly associated with topography – the shelf around the UK, Rockall Plateau/Hatton Bank, the Iceland-Scotland Ridge, the Reykjanes Ridge and the Greenland Shelf. This could be due variously to strong eddies forming near the margins or enhanced mixing over topography, possibly due to large tidal dissipation. Measurements do not extend up on to the shelves in general in this data set and so the relative efficacy of mixing on the shelves was not evaluated.

The density of the SPMW potential vorticity minimum (Fig. 2) shows the tight North Atlantic Current, turning northward after crossing the Reykjanes Ridge, and a fanning of isopycnals from this tight feature. In contrast to the picture of McCartney and Talley (1982), this more detailed view suggests that the warmer mode waters south of 50°N (27.0 to 27.15 σ_θ or so) are mainly associated with the subtropical circulation and move southward. The SPMW that proceeds into NADW formation more likely originates directly from the North Atlantic Current waters. Little SPMW is found between 27.2 and 27.3 σ_θ; this is likely the primary bifurcation density between the subtropical and subpolar circulations. A large area of SPMW around 27.4 σ_θ is found in the northeast, and a large area of density 27.5 σ_θ over the western flank of the Reykjanes Ridge and most of the Irminger Basin. The very lowest potential vorticity at the minimum is shaded in the figure, and shows the importance of the ridge complexes.

The WOCE data from May–August 1997 followed a protracted time of high NAO, although the NAO during that particular year was low. Differences in properties of the subpolar region between the 1960s and the mid-1990s have been described elsewhere. From the isopycnals examined here, freshening of the Labrador and Irminger basins is clear, due to increased import of fresh waters from the north. Salinity along the eastern boundary SPMWs, at 27.3 to 27.5 was higher in the eastern boundary region, suggesting increased flow of saline waters from the south. The lowest potential vorticity, indicating a nearby outcrop, for each of the isopycnals is shown in Fig. 3a. As with the earlier data, the importance of the boundary regions and ridges is clear, especially in the extension of the 27.5 σ_θ SPMW southward along the Reykjanes Ridge. In comparison with the 1950s/

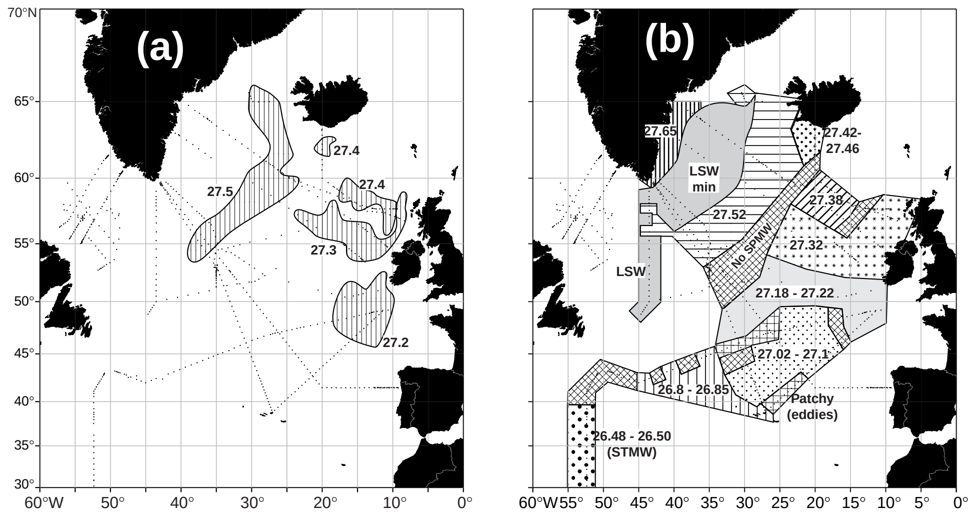

Figure 3. (a) Areas of potential vorticity less than 4×10^{-13} cm^{-1} sec^{-1} for isopycnals 27.2 to 27.7 σ_θ, based on WOCE hydrographic sections collected in May–August 1997. Data sources are listed in Table 2. Data were smoothed CTD profiles, and so the potential vorticity numbers are not precisely comparable with those calculated from bottle data, as in Figs. 1 and 2. (b) Density of the potential vorticity minimum in the SPMW in May–August 1997. Shaded regions indicate where a clear SPMW potential vorticity minimum is not present. Potential density values listed in the various regions are the average SPMW density for that region, about which there is only small variation.

1960s, the SPMW in the eastern subpolar region is somewhat denser, with the 27.3 and 27.4 isopycnals outcropping several degrees of latitude farther south in 1997. The Irminger and Labrador Sea SPMW centres are similar in the two time periods, although the 27.7 σ_θ mode extends more clearly into the Irminger Sea in 1997. This is presumably associated with the average circulation defined by the Labrador Sea PALACE floats, as described above.

Examination of PV along the individual, highly-resolved WOCE sections shows that in general there are large regions of coherently low PV centred at one density or with very slowly varying density, terminating abruptly and switching to another density. It is difficult to depict this building block structure on a contoured horizontal map. Fig. 3 shows the regions as indicated by these sections, with the average densities of the SPMWs in each region listed. Prominent in this SPMW distribution is the North Atlantic Current and its northward extension in the subarctic front, as defined on each section by at least two stations. Within this feature there is no SPMW. South and east of the front, SPMWs fall into five separate density classes, which appear nearly discontinuous. It is not claimed herein that these exact density classes would be found in each year, but the general increase in density towards the north is a robust feature of all data sets, while the probability of quantisation within this general increase is very likely for other years, and should be pursued with data sets from other years. In the southern region, south of about 47°N, the mode waters are broken up by an eddy field. Thus the impression of domination by eddies in this region based on PALACE float data, as described above, extends to hydrography as well. Data from this period were not available along the Iceland–Scotland Ridge and so the final mapping of the northern modes was not possible.

West of the subarctic front, in the eastern Irminger Basin and along the Reykjanes Ridge, the SPMW density is remarkably uniform, centred at 27.52 σ_θ, with none of the progression of densities observed east of the front. Modes at a density of 27.65 σ_θ are found only along the Greenland shelf, and appear to be associated with thick mixed layers formed locally there. The central Irminger Basin is dominated by Labrador Sea Water, and so identification of an SPMW there is not sensible in this data set.

In summary, this initial view of the SPMW distribution based on more detailed analysis of the 1950s/1960s data and WOCE data from summer 1997 suggests major refinements to previous ideas: boundary intensification of the low potential vorticity areas, association of the major SPMW modes with topographic features, a clear demarcation between SPMWs east and west of the subarctic front, quantisation of SPMW densities, with SPMW west of the subarctic front being of nearly uniform density. Much further analysis is required to pursue these SPMW features, to attempt to identify specific formation sites or regions for each SPMW "type" and the connections between them, and hopefully to identify the processes producing such remarkably thick mixed layers. Important adjunct data sets are the floats for the circulation and eddy field, surface fluxes, and high resolution SST and altimetry to better define the horizontal structures and relation to the eddy field and fronts.

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Some features of the North Atlantic circulation in high resolution models

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Following the early WOCE Community Model Experiments initiated at NCAR by Holland and Bryan (1989), a large number of models of the North Atlantic circulation have been run during the WOCE years. Those models range from "eddy-permitting" (typically, 1/3° grid size) to what we call today "eddy-resolving" (1/10°).

Much in the same way as weather forecast models, high-resolution ocean models are meant to reach a high degree of realism. With such models it becomes possible to make local, quantitative comparisons with data. When the model fails to represent the details of the observed flows one asks why – something which is not usually done with low-resolution models.