Mode waters in the subpolar North Atlantic in historical data and 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. This is the surface layer whose characteristics directly influence the atmosphere, and thus whose transformation is directly relevant to climate.

Conventional circulation analyses show a branching of the Gulf Stream and North Atlantic Current feeding the cyclonic subpolar circulation, which is sometimes depicted with broad northward flow in the eastern subpolar region, splitting into surface flow into the Norwegian Sea and westward flow along the northern margin and into the Irminger Current which feeds into the Labrador Sea. Ample evidence for incursion of lower latitude properties has been demonstrated. Mass, heat and salt budgets for the transformation of upper ocean waters around the subpolar gyre have been computed (e.g. McCartney and Talley, 1984). 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 and is a goal of the WOCE Atlantic Circulation and Climate Experiment (ACCE).

The upper ocean waters of the subpolar gyre are characterised by thick layers of low stability (Subpolar Mode Water – SPMW), 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). The SPMW was depicted therein as 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

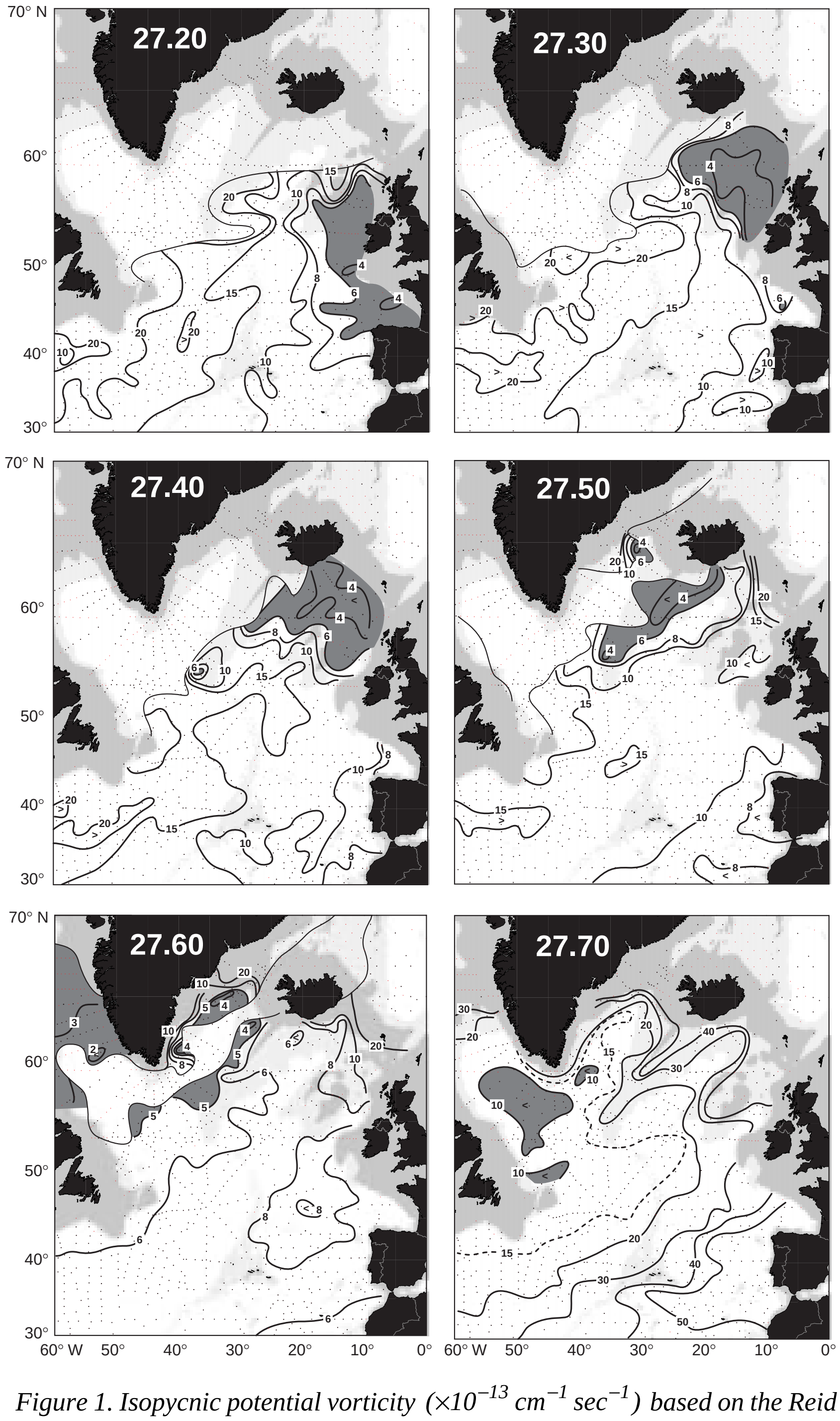

Figure 1. Isopycnic potential vorticity ($\times 10^{-13}$ cm^{-1} sec^{-1}) based on the Reid (1994) data set, most of which was collected in the late 1950s and 1960s, during a period of low North Atlantic Oscillation index. PV less than 4×10^{-13} cm^{-1} sec^{-1} at 27.2 to 27.5 σ_θ is darker shaded; 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.

finally arrive at the Labrador Sea Water (LSW) properties of about 3°C/27.84 σ_θ. The North Atlantic Current jet was 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.

The preliminary analysis of SPMW presented here, using both historical and recent WOCE data, contradicts this smooth picture of SPMW property distribution and advection. Further analysis combining additional hydrography, float observations, satellite and surface flux fields is being pursued to clarify the transformation and circulation of SPMW. This preliminary work is presented because the new maps of SPMW distribution provide a rather different view of SPMW than earlier work. Because of significant temporal variations in surface and water mass properties, linked to the North Atlantic Oscillation, data must be sorted in time. The analysis below uses historical data collected during the 1950s and 1960s for comprehensive mapping of the SPMW. WOCE data collected during the summer of 1997 are then used to show greater detail within highly-resolved vertical sections; SPMW properties are contrasted with those of the low NAO 1950s/1960s period.

Subpolar Mode Water using historical hydrographic data

Subpolar Mode Water (SPMW) for the 1950s and 1960s is mapped here using data assembled by Reid (1994). During that time, the NAO was in a protracted low phase, and so it is expected that the data set, while covering many years, is reasonably uniform. It was relatively easy to create maps from the data set, suggesting that the data set is internally consistent. This data set has much better spatial resolution than the more limited data set used in McCartney and Talley (1982) who first described the SPMW; the more limited data set is included in the Reid data set.

Isopycnic potential vorticity ($f\partial\rho / \rho\partial z$) 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, sluggish circulation in these regions, 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 importance 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, as described in McCartney (1982). 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 north-east, and a large area of density 27.5 σ_θ is located 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.

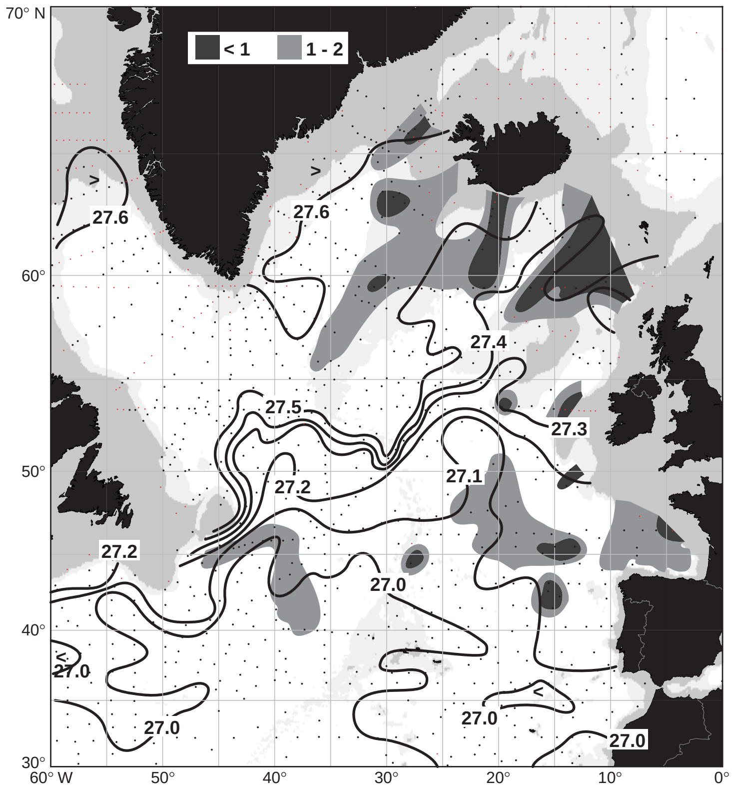

Figure 2. Potential density σ_θ at the absolute potential vorticity minimum (for densities less than 27.65 σ_θ), using the Reid (1994) data set. Regions of potential vorticity of less than 1 and 2×10^{-13} cm^{-1} sec^{-1} are shaded (dark and light, respectively).

Subpolar Mode Water in summer 1997

SPMW in May–August 1997 was mapped using WOCE hydrographic section data (Fig. 3). (Data from: WOCE A24 [Talley/Knorr], AR19 [Koltermann, Meteor], AR7W [Schott, Meteor], A25 [Bacon, Discovery], Zenk [Meteor].) This year followed a protracted period of high NAO, although the NAO during 1997 was low. Compared with the historical data examined above, freshening of waters by about 0.01 psu at 27.5 to 27.7 σ_θ in the Labrador and Irminger basins is apparent. Salinity at 27.3 to 27.5 was higher in the eastern boundary region in 1997, 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 Figs. 3a and b. 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/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. 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 shows that in general there are large regions of coherently low PV with very slowly varying density, terminating abruptly and switching to another density. An example of this blocky structure is shown in Fig. 4 (page 11) which is the WOCE A24 section from Greenland to the United Kingdom (summer 1997). A break in mode water potential vorticity and density is evident at the subarctic front located at 22–23°W. It is difficult to depict this type of structure on a contoured horizontal map. Fig. 3c shows the regions as indicated by these sections, with the average densities of the SPMWs in each region listed. There clearly were not enough data to completely map the features, but the continuity of mode water properties from one section to another within a region supports the suggestion that the properties change nearly discontinuously and that they are nearly uniform over mappable areas.

Prominent in this SPMW distribution based on WOCE data 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 (Fig. 4). South and east of the front, SPMWs fall into 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 periods, 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. (This impression of eddy domination in this region in comparison with the rest of the subpolar gyre corresponds well to results from recent subsurface float data from the subpolar and northern subtropical gyre – Davis, Owens and Lavender, pers. comm.) Data along the Iceland–Scotland Ridge from this period were not available to me and so mapping of the northern SPMW is not included.

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.

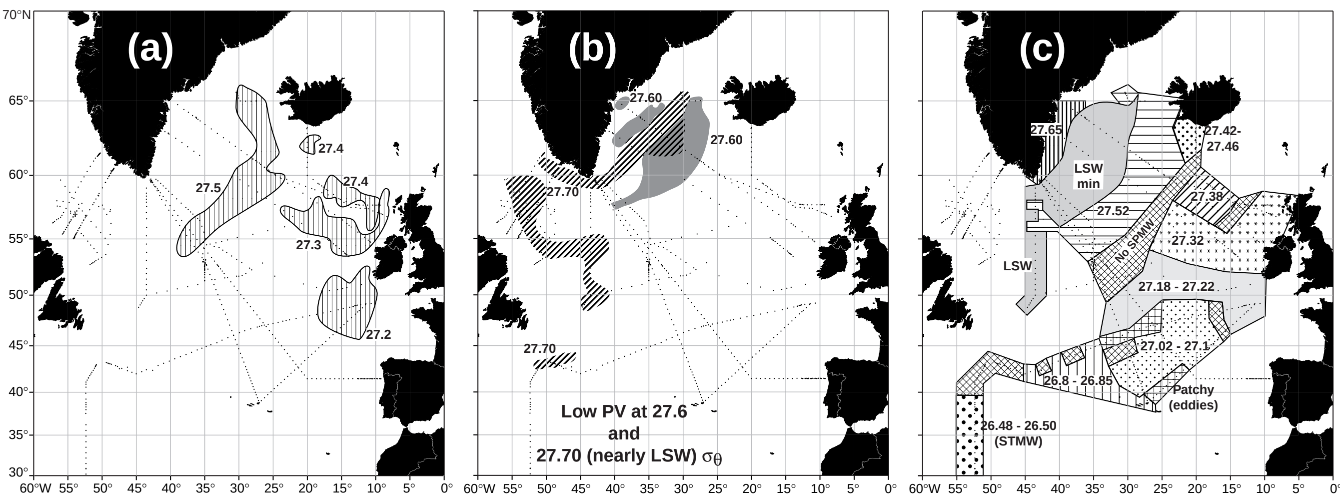

Figure 3. (a) Areas of potential vorticity less than $4 \times 10^{-13}\ cm^{-1}\ sec^{-1}$ for isopycnals 27.2 to 27.5 σ_θ, based on WOCE hydrographic sections collected in May–August 1997. Data were smoothed CTD profiles, and so the potential vorticity numbers are not precisely comparable with those calculated from bottle data, as were used in Figs. 1 and 2. (b) Potential vorticity less than $6 \times 10^{-13}\ cm^{-1}\ sec^{-1}$ at 27.6 and less than $3 \times 10^{-13}\ cm^{-1}\ sec^{-1}$ at 27.7, for the same data set. (c) 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.

Modes at a density of 27.65 σ_θ are found at the few stations in Denmark Strait and 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.

Acknowledgements

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WOCE Global Data on CD-ROMs (Version 2) to be issued mid-2000

The WOCE Data Assembly Centres (DACs) are already in the process of finalising data sets and associated metadata that will be included on the second version of the WOCE Global Data CDs. The new issue will be a significant upgrade from Version 1.0 which included data that were submitted by early 1998, before the field programme was completed and well before the basic 2 year PI proprietary period had passed for many data sets. It appears at present that none of the CDs will contain all WOCE data of a specific type (current meter, hydrography etc.) for the entire WOCE observational period (1990–98) but a few will be close and could be complete with help from PIs. The Data Information Unit, NASA/JPL and IFREMER are also preparing updates of their CDs for inclusion with the new issue. The final version of the WOCE Global Data (Version 3.0) will be issued in 2003 at the time of the final WOCE Conference.

The schedule for production and delivery of Version 2.0 is as follows:

April 2000	Data delivered to DACs and CD contents finalised
June 2000	Master copies of the CDs go to US-NODC for reproduction
Aug./Sept. 2000	CD-ROM sets distributed to the community

Around 80% of WOCE data have been submitted to the DACs, which means of course, that another 20% still reside with PIs. Some data already submitted are not yet public and can only be released with the permission of the PI concerned. The DACs and DIU are working with PIs to arrange delivery and to obtain authority to release their data in time to meet the above schedule. Anyone uncertain about how to submit data can contact the DIU (woce.diu@diu.cms.udel.edu, http://diu.cms.udel.edu/woce/, Tel (+1) 302-645-4278, Fax (+1) 302-645-4007) or any of the DACs. Anyone holding data should expect to be contacted very soon if they haven't been already.