Transformation of the warm waters of the North Atlantic from a geostrophic stream function perspective

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ABSTRACT

In order to obtain a description of the hydrographic state of the North Atlantic Current-Subpolar Front (NAC-SPF) system, historical hydrographic data from the subpolar North Atlantic are projected into a baroclinic stream function space, resulting in three dimensional gravest empirical mode (GEM) fields for temperature and specific volume anomaly, parameterized by pressure, dynamic height, and day of the year. From the specific volume anomaly GEM, the corresponding potential vorticity field is calculated. These fields are constructed for 12 subregions, chosen to follow the mean path of the North Atlantic Current-Subpolar Front system. Analysis of the seasonal potential vorticity cycle of the GEM fields shows that the main mechanism for the formation of Subpolar Mode Water is winter convection. The GEM fields are also used to obtain the approximate location of formation sites for the different Subpolar Mode Water classes. The evolution of the mean fields for the waters is studied along baroclinic streamlines of the NAC-SPF system. This shows that cross-frontal mixing, between the cold and fresh subpolar waters, and the salty and warm waters coming north from the subtropics via the Gulf Stream, is the dominant mechanism for the light-to-dense transformation process of the NAC-SPF waters that enter the western subpolar region. On the other hand, a combination of atmospheric cooling, vertical mixing during winter time convection, and en-
trainment of the saltier waters found on the northeastern subtropical gyre, are the main factors transforming the NAC-SPF waters that enter the eastern subpolar gyre. This suggests that an influx along the eastern margin of salty water from the European Basin plays a significant role in the transformation of the NAC-SPF waters that continue their way towards the Nordic Seas.

1. Introduction

The flow of subtropical waters into the subpolar North Atlantic forms an essential link in the meridional overturning circulation. The resulting heat flux plays a major role in moderating the European climate (e.g., Krauss, 1986; Bower et al., 2000). A major source of these warm and salty waters is the Gulf Stream via the North Atlantic Current (NAC). The NAC evolves from a narrow and swift current at the Tail of the Grand Banks, to a broader Subpolar Front (SPF) with imbedded jets once it turns east past the Northwest Corner (e.g., Arhan, 1990; Kearns, 1996; Krauss, 1996). This front diverges after crossing the Mid-Atlantic Ridge (MAR), with its colder waters entering the subpolar gyre via the Irminger Current, while the warmer waters enter the Iceland Basin and continue their way towards the Nordic Seas (e.g., Hansen and Østerhus, 2000; Bower et al., 2002). Figure 1 shows the climatological geostrophic stream function $\Psi$ (dynamic height at 200 dbar, referenced to 1000 dbar), as obtained from historical hydrography. The NAC is the sharp front flowing north aligned
with topography east of the Grand Banks of Canada. The SPF appears as a broad front between $\Psi = 4 \text{ J kg}^{-1}$ and $\Psi = 6.5 \text{ J kg}^{-1}$, diverging once it passes the MAR. Another supply of subtropical waters into the subpolar regions comes along the eastern Atlantic, which brings warm and salty waters along the eastern boundary current (see review in Hanawa and Talley (2001)).

Much of the light-to-dense water conversion that eventually leads to deep convection in the Labrador Sea and Nordic Seas takes place in the subpolar North Atlantic. On their journey towards the sites of deep convection, the subtropical waters start cooling and freshening through winter convection, as well as by mixing with the adjacent subpolar waters (McCartney and Talley, 1982). The degree of mixing is important since it determines the salinity, and hence the maximum density that a fluid parcel eventually can obtain. The winter time heat losses result in high annual variability in the hydrographic conditions of the upper waters. As the waters are advected through the subpolar region, these effects progressively reach deeper. Since the NAC-SPF marks the boundary between the subtropical and subpolar gyres, it is along this front that outcropping of the isopycnals from the subtropical North Atlantic’s main thermocline occurs. The weak stratification above the deepening isopycnals of the main pycnocline make possible the homogenization of thick layers of water (Mode Waters) during winter time on the warm side of the front. During the
subsequent Spring and Summer months, these waters are cut off from exchange
with the atmosphere as the seasonal pycnocline develops (Hanawa and Talley,
2001).

This paper studies the transformation of the warm waters in the northern
North Atlantic, using all the hydrodata available from HydroBase (Curry, 1996).
We are confronted with a process of large spatial and temporal variability: the
NAC position may shift laterally up to 150 km (Kearns and Rossby, 1998), while
the northern edge of the SPF near the Charlie Gibbs Fracture Zone experiences
shifts between 200 km and 300 km (Belkin and Levitus, 1996). To reduce
the variability and smearing associated with the meandering and splitting of
the baroclinic structure of the NAC-SPF system, we use a technique called
Gravest Empirical Mode projection, in which hydrographic data are projected
into geostrophic stream function space. This projection has the advantage of
maintaining the baroclinic structure of the current in question. This would not
be the case if the data were projected in geographical space, the structure of the
baroclinic system would be smoothed and broadened as a consequence of the
local variability in the hydrographic field due to meandering and eddy shedding
by the current studied. The GEM technique has been very successful in reducing
the part of the variance associated with meandering of baroclinic systems such
as the NAC at 42°N (Meinen and Watts, 2000), the Antarctic Circumpolar
Current (Sun and Watts, 2001), and the Kuroshio extension region (Willeford, 2001). The historical hydrographic database for the subpolar North Atlantic is sufficiently large, and the sampling for each month sufficiently well covered, though less so in winter, to be able to construct monthly GEM projections for smaller subregions. This allows for the study of the local seasonal evolution of the hydrographic fields, and of downstream changes along streamlines.

GEM projections of specific volume anomaly, temperature, and potential vorticity are constructed as functions of depth, geostrophic stream function, and time of year, for various subregions in the North Atlantic (Section 2). These fields are then used to study the seasonal evolution of the hydrographic conditions in the area, in particular the formation of Mode Waters, as well as to obtain the mean characteristics of the various classes of Mode Waters found (Section 3). The downstream evolution of these thick layers of water, and of the seasonal thermocline waters, is used to assess the relative importance of heat loss to the atmosphere, net freshwater input from the atmosphere, and mixing with the adjacent waters in the transformation of the warm waters carried by the NAC-Subpolar Front system (Section 4). We finish by comparing our results with previous SPMW studies, and with a discussion of the role that the salt influx from the eastern Atlantic plays in preconditioning the waters for deep convection to occur in the Nordic and Labrador Seas (Section 5).
We use specific volume anomaly ($\delta$) in our analysis, since these surfaces are closer to neutral surfaces than the more commonly used potential density ($\sigma_\theta$) surfaces (McDougall, 1989), especially if a local salinity and temperature mean are used as reference values in calculating $\delta$. In the absence of external forcing, water prefers to flow along neutral surfaces. Also, potential vorticity, calculated with the height between $\delta$ surfaces, is conserved along these surfaces (McDougall, 1989).

2. Gravest Empirical Mode projections

a. Data and methods

We now describe the construction of the GEM projections for temperature, specific volume anomaly, and potential vorticity, which capture the monthly average vertical structure of these variables in stream function space (see also Perez-Brunius, 2002). We use quality controlled CTD and bottle data from HydroBase (Curry, 1996) taken during 1910-1997, and 21 WOCE sections taken after 1996, within the region 40°N-60°N, 50W°-15°W. Only stations that reach deeper than 1000 dbar are used. For the case of bottle data, only those with at least 5 samples in the main thermocline are kept. Specific volume anomaly ($\delta$) is calculated from the temperature and salinity profiles, at each sample depth. We reference the specific volume anomalies to 34.6 psu and 4.9°C, which are the
mean values for the region of the NAC and SPF (Kearns, 1996). To help the reader, a table of $\delta$ values and their corresponding $\sigma_\theta$ values is provided (Table 1). As a reference, $\Delta\delta = 10 \times 10^{-8} \, m^3 \, kg^{-1}$ corresponds to a $\Delta\sigma_\theta \approx 0.1$.

Temperature $T$, salinity $S$, and specific volume anomaly $\delta$ are interpolated into 20 dbar bins. Stations with $\delta$ inversions are discarded. Finally, we check the interpolated hydrocasts for thermodynamic consistency following Kearns (1996), rejecting stations for which the difference between the interpolated $\delta$, and the specific volume anomaly calculated from the interpolated temperature and salinity, differed more than $3 \times 10^{-8} \, m^3 \, kg^{-1}$ (which corresponds to $\sim 0.03\sigma_\theta$ units). After the quality control discussed above has been applied to the hydrodata, we are left with 24,244 historical hydrographic profiles of temperature and specific volume anomaly, reaching down to 1000 dbar (Figure 2).

Since the hydrographic conditions change markedly across the area of study, we divided the subpolar North Atlantic into 12 overlapping regions (Figure 2, Table 2).

For each station, dynamic height anomaly ($\Psi$) is calculated from the interpolated temperature and salinity profiles as:

$$\Psi = \int_{1000 \, \text{dbar}}^{200 \, \text{dbar}} \delta_o(p, S, T) dp,$$

(1)
where

$$\delta_o(p, S, T) = \frac{1}{\rho(p, S, T)} - \frac{1}{\rho(p, 35 \text{ psu}, 0 \degree C)},$$

and $\rho(p, S, T)$ is the *in situ* density at pressure $p$, salinity $S$, and temperature $T$.

$\Psi$ is a geostrophic stream function (McDougall, 1989), and is here used as the parameter for the GEM projections of the hydrographic data. This parameter is appropriate for reducing the spatial variability associated with the meandering of the currents studied, considering that oceanic flows are dominated by geostrophy. Since the stream function field moves with the meandering of the baroclinic front, the time variability of the unsteady flow is reduced by this projection (Sun and Watts, 2001). It is useful to have no seasonal signature in the parameter used for the GEM projections, so that we truly have a stream coordinate system in which the GEM fields can be compared both in space (different subregions) and time (different months). Figure 3 shows the vertical extent of the seasonal influences for all subregions. Most of the annual variability takes place in the upper 200 dbar (although regions 1, 2 and 6 have significant variability below 200 dbar). Hence, the shallow limit for $\Psi$ is taken to be 200 dbar in order to reduce the effect of seasonal variability in the integral.

We now examine the annual evolution of the temperature and specific volume anomaly fields, and the spatial changes of those property variables along
the NAC-SPF system: we seek to express temperature ($T$) and specific volume anomaly ($\delta$) as a function of pressure ($p$-vertical coordinate), stream function ($\Psi$-horizontal coordinate), and month ($t$). The construction of these fields follows a procedure similar to that employed by Willeford (2001). For each region, the data are separated into three-month bins, centered on each consecutive month. This ensures enough data coverage for the less sampled winter period. Cubic splines as functions of stream function ($\Psi$) are fitted to the temperature ($T$) and specific volume anomaly ($\delta$) data, at each pressure level and for each time bin. Figures 4 and 5 show examples of the tight relation $\Psi$ has with $\delta$ and $T$ at various pressure levels, for regions 1 and 6, respectively.

b. Labrador Current waters

This projection works well for both $T$ and $\delta$ in most regions analyzed (see Appendix). There is one exception, the temperature projection for the upper 500 dbar in the region of the NAC (regions 1 and 2 in this work). Figure 6 shows that there is a range of $\Psi$ for which the relationship between $T$ and $\Psi$ in the upper 160 dbar is no longer single-valued. The reason for this bimodal structure is that the cold and fresh Labrador Current (LC) meets the warm and salty NAC in this region. The LC is a fresh and cold, largely barotropic current that flows inshore of the NAC. Although there is a strong thermohaline front between these two currents, the specific volume anomaly surfaces are themselves
nearly level between them; the specific volume anomaly of the waters of both currents at each level is the same due to salinity compensation. That is why the geostrophic stream function is insufficient by itself to distinguish between these two currents, and a bimodal structure appears in the projected temperature field. Since this paper focuses on the transformation of the warm waters, we decided to exclude stations sampling the LC. To distinguish these cold waters, the bimodal distribution of temperature along a suitable $\delta$ surface is analyzed, to obtain the cut-off value of temperature that separates the two different modes (Figure 7). Stations for which $T < 3.2^\circ C$ on $\delta = -5 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ are considered LC waters (triangles in Figure 6), and are discarded for the spline fit. Important to note is that the LC certainly helps to cool and freshen the NAC waters through cross-frontal mixing. The LC waters are excluded from the analysis for regions 1 and 2, and their contribution to the warm water transformation is addressed by looking at the changes in the properties of the NAC waters.

c. Annual mean and residual fields

As a result of the projection onto stream function space according to the spline fitting discussed above, we obtain monthly GEM fields as look up tables for temperature: $T_g(p, \Psi, t)$, and specific volume anomaly: $\delta_g(p, \Psi, t)$. By averaging the twelve monthly fields and subtracting this mean from the monthly
fields, the residual GEM fields are obtained:

\[ \gamma'_g(p, \Psi, t) = \gamma_g(p, \Psi, t) - \overline{\gamma_g(p, \Psi)}, (2) \]

where \( \gamma \) is either temperature or specific volume anomaly, \( \overline{\gamma_g} \) is the mean \( \gamma_g \) field, and \( \gamma'_g \) is the residual field. The subscript \( g \) stands for “GEM.” Note that the annual mean so constructed reduces the bias that would otherwise result due to the different sampling frequencies for different months. The reason for this is that the temporal mean is obtained from the monthly GEM fields, and these in turn are fitted splines to data available for the month in question.

d. Potential vorticity

Next we estimate the potential vorticity GEM from the \( \delta_g \) field, using the layer thickness of \( \delta \) surfaces \( 10 \times 10^{-8} \, \text{m}^3 \, \text{kg}^{-1} \) \((\approx 0.1\sigma_g)\) apart. This number is chosen so that it is small enough to capture the PV structure in the vertical:

\[ PV_g(p_o, \Psi, t) = 10^{-4} f \frac{1}{\Delta p(p_o, \Psi, t)}, \]

where \( f \) is the Coriolis parameter for the center latitude of the subregion,

\[ \Delta p(p_o, \Psi, t) = p \left( \delta(p_o, \Psi, t) - \frac{\Delta \delta}{2} \right) - p \left( \delta(p_o, \Psi, t) + \frac{\Delta \delta}{2} \right), \]

where \( \Delta p \) is given in decibars \((1 \, \text{dbar} \approx 1 \, \text{m})\), and \( \Delta \delta = 10 \times 10^{-8} \, \text{m}^3 \, \text{kg}^{-1} \).

To be able to compare our results to previous studies, we had to include the
factor of $10^{-4}$ in Equation 3, since most authors calculate PV as:

$$PV = \frac{\Delta \sigma_\theta}{\rho} f \frac{1}{\Delta p}.$$  \hspace{1cm} (4)

Hence, Equation 3 differs from Equation 4 by a factor $\frac{\Delta \sigma_\theta}{\rho} \approx 0.1$ (since $\Delta \delta = 10 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ corresponds to $\Delta \sigma_\theta \approx 0.1$, see Table 1).

e. Projecting onto $\delta$ surfaces

Given that in the absence of mixing or dissipation water is strongly constrained to flow along neutral surfaces, we can quantify the changes that a water parcel experiences as it flows within the ocean by analyzing water properties along $\delta$ surfaces. Since we are interested in studying the transformation of the waters during their transit through the subpolar North Atlantic, we proceed to map the temperature and potential vorticity GEM fields onto $\delta$ surfaces. The specific volume anomaly GEM field serves as a ‘look up’ table from which the inverse may be found. That is, the pressure field corresponding to a grid of $\delta$ surfaces can be obtained from the monthly specific volume anomaly GEM field:

$$\delta_g(p, \Psi, t) \longrightarrow p_g(\delta, \Psi, t).$$

Having the pressure field as a function of $\delta$ allows us to map $T_g(p, \Psi, t)$ onto $T_g(\delta, \Psi, t)$. PV on $\delta$ surfaces can be calculated quite simply from the $p_g$:

$$PV_g(\delta, \Psi, t) = 10^{-4} f \frac{1}{H_g(\delta, \Psi, t)}.$$  \hspace{1cm} (5)
where $H_g(\delta, \Psi, t) = p_g(\delta - \frac{\Delta \delta}{2}, \Psi, t) - p_g(\delta + \frac{\Delta \delta}{2}, \Psi, t)$ is the layer thickness between $\delta$ surfaces (in decibars) separated by $\Delta \delta = 10 \times 10^8$ m$^3$ kg$^{-1}$ units.

Finally, all the monthly fields are linearly interpolated into yearday (from day 1 to day 365), adding the December fields to the beginning of the time record, and the January fields to the end of the record, to ensure continuity between day 365 and day 1. A discussion of the errors associated with the fields is given in the Appendix.

3. Convection and Subpolar Mode Waters formation

Mode Water is the term given to layers with vertically uniform properties. These are usually found on the warm side of a current or front, between the surface and the permanent pycnocline. By definition, they are characterized by their low potential vorticity, and their formation is usually associated with wintertime convection (e.g., Hanawa and Talley, 2001). In the northern North Atlantic, such low potential vorticity waters are called Subpolar Mode Waters (SPMW) after McCartney and Talley (1982). They stand out clearly in Figure 8, which shows the mean potential vorticity GEM fields constructed for the subregions mentioned in Section 2a, where ‘pools’ of $PV$ less than $10 \times 10^{-11}$ m$^{-1}$s$^{-1}$ are found on the warm side of the NAC and SPF (regions 1-5 and 9-12), between the main and seasonal thermoclines. The low $PV$ water ($PV < 4 \times 10^{-4}$m$^{-1}$s$^{-1}$) found on the cold side of the front, below the main pycnocline,
is Labrador Sea Water, which is the densest Mode Water found in the North Atlantic. The northernmost regions (regions 6-8) have very little stratification, most of the density layers of the main pycnocline have outcropped, and we have in general very homogeneous waters throughout the entire domain, with $PV$ less than $8 \times 10^{-11} \text{ m}^{-1}\text{s}^{-1}$. Particularly notable are the very low $PV$ waters (less than $4 \times 10^{-11} \text{ m}^{-1}\text{s}^{-1}$) present in the Rockall Plateau and Trough region (region 6). Such low $PV$ waters are also present in the western European Basin farther south (regions 11 and 12).

The GEM projections constructed in the previous section comprise all hydrographic data available for the region and provide an effective framework in which to analyze the mean characteristics of the SPMW. The method exhibits the seasonal evolution of the hydrographic fields, which in turn helps identify the ventilated layers, and the position within the baroclinic front associated with the NAC-SPF where they outcrop. An example is given in Figure 9 of the seasonal evolution in the NAC region 1 for two streamlines: one on the cold side of the front ($\Psi = 4 \text{ J kg}^{-1}$), and the other on the warm side ($\Psi = 7.5 \text{ J kg}^{-1}$). The evolution of the seasonal thermocline stands out clearly, showing that on the cold side of the front, winter convection does not reach deeper than 100 dbar (Figure 9a, specific volume anomaly panel), resulting in a highly seasonally stratified layer that reaches down to 200 dbar (Figure 9a, potential vorticity
panel). On the other hand, winter convection reaches down to 300 dbar on the warm side of the front (Figure 9b, specific volume anomaly panel), while the seasonal pycnocline is mainly confined to the upper 150 – 200 dbar (Figure 9(b), specific volume anomaly and potential vorticity panels). As a result, the layer that gets ventilated ($\delta \in [50,60] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$) is quite thick ($\approx 100 \text{ dbar}$, which corresponds to $PV \approx 10 \times 10^{-11} \text{ m}^{-1}\text{s}^{-1}$). In other words, Figure 9b shows the process of mode water formation via winter convection, and helps to identify where within the front this occurs (i.e on which streamline), as well as the corresponding density class of the Mode Water in question.

To identify the density classes and corresponding temperatures of the Mode Waters in the various subregions analyzed in this work, the fields are regridded in Figure 10 with specific volume anomaly as the vertical coordinate. Three adjacent regions (regions 4, 5, and 6) are shown for a streamline ($\Psi = 6 \text{ J kg}^{-1}$) along which Mode Waters are formed (i.e., the low $PV$ layer winter outcrops). Note how they become colder and denser: for the SPF section (region 4), the layer of low $PV$ has $\delta \in [20,40] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ and temperatures of 9 – 12$^\circ$C. The Mode Water found in the northern European Basin (region 5) has $\delta \in [10,30] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ and temperatures of 8 – 11$^\circ$C. Finally, in the Rockall Plateau and Trough area (region 6) the layer with lowest $PV$ (less than $6 \times 10^{-11}\text{m}^{-1}\text{s}^{-1}$ is found for $\delta \in [-10,10] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ and temperatures of 8 – 10$^\circ$C. Note that
each of these SPMWs are formed along the same streamline, suggesting that the locally densest mode water is formed from the lighter classes formed upstream, which are advected in and locally modified through in winter time. Specifically, the mode water formed in the SPF (region 4, \( \delta \sim 30 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \)) advects by the NAC-SPF onto regions 5 and 6, where it is locally cooled by the atmosphere in winter time, becoming denser. Hence, during its transit through the Rockall Plateau and Trough area (region 6), its \( \delta \) has been raised by \( \sim 30 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \) (i.e., the water has experienced a buoyancy loss of about 0.3\( \sigma_\theta \) units), resulting in mode water of \( \delta = 0 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \). Note, however, that the discussion above treats the problem in two dimensions: along-stream and in the vertical. We expect that cross-frontal mixing also plays a role in the transformation process, and we will discuss this in Section 4.

We have shown in this section that we can use the GEM fields to identify the ventilated layers, their \( PV \) and temperature, and the location where those layers outcrop in stream function space. We used this to construct an algorithm that identifies the Mode Waters, finds their mean characteristics, and the regions where they are formed. For regions south of 53°N, \( PV \leq 10 \times 10^{-11} \text{ m}^{-1} \text{s}^{-1} \) is used as the identifier of Mode Waters; while \( PV \leq 8 \times 10^{-11} \text{ m}^{-1} \text{s}^{-1} \) is used for regions to the north. These waters are grouped into specific volume anomaly classes, corresponding to layers \( \Delta \delta = 10 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \) thick. The region of
formation of each Mode Water class is defined as the range of streamlines where
the specific volume anomaly bounding the layer on the light side outcropped
in March. Table 3 presents a summary of this analysis. In constructing the
table, the climatological map of $\Psi$ (Figure 1) was used to identify where in the
North Atlantic the SPMW class in question is formed and found. We used the
following criteria: $\Psi \geq 7$ J kg$^{-1}$ represents the recirculation of the NAC in
the Newfoundland Basin; $\Psi \in [4, 6.5]$ J kg$^{-1}$ in regions 4 and 5 are the SPF
branches; Rockall Plateau and Trough correspond to $\Psi > 6$ J kg$^{-1}$ in region 6;
the Iceland Basin corresponds to $\Psi \in [4, 6]$ J kg$^{-1}$ in regions 6 and 7; and the
Irminger Sea is defined as $\Psi < 4$ J kg$^{-1}$ in regions 7 and 8.

In conclusion, SPMWs with $\delta \geq 40 \times 10^{-8}$ m$^3$ kg$^{-1}$ ($\sigma_\theta \leq 27.0$) are formed
on the warm edge of the NAC and south of the SPF, and are part of the
recirculation of the subtropical gyre. We call these Class I. Mode waters with
$\delta = 30 \times 10^{-8}$ m$^3$ kg$^{-1}$ ($\sigma_\theta \leq 27.1$) form between the SPF branches (Class
II). The thickest Mode Waters (Class III) are formed in the northern European
Basin ($\delta = 20 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\sigma_\theta \approx 27.2$), as well as in the Rockall Plateau
and Trough region ($\delta = 10 \times 10^{-8}$ m$^3$ kg, $\sigma_\theta \approx 27.3$). SPMWs with $\delta = 0 \times
10^{-8}$ m$^3$ kg$^{-1}$ ($\sigma_\theta \approx 27.4$) form in the Iceland Basin (class IV). Mode waters
with $\delta \in [-10, -20] \times 10^{-8}$ m$^3$ kg$^{-1}$ ($\sigma_\theta \in [27.5, 27.6]$) are formed in the Irminger
Sea (Class V). The densest Mode Water ($\delta < -20 \times 10^{-8}$ m$^3$ kg$^{-1}$, $\sigma_\theta \geq 27.6$) is
Labrador Sea Water, found in all regions analyzed. The analysis presented here provides the approximate location in stream function space where the different Mode Water classes are formed. This, in turn, indicates where, within the fronts, Mode Water formation takes place. From the GEM analysis alone, it is not possible to accurately determine the distribution in geographical space of the sites where formation of SPMW takes place. Using the results from Table 3, we present a summary in Figure 11 of the approximate locations where different Mode classes may be formed.

4. Downstream evolution

Another way to investigate the transformation of the waters carried by the NAC-SPF system consists of looking at how properties change along a streamline. Assuming water parcels flow along streamlines, this approach would address the Lagrangian changes in the properties of the water parcel in question. Since the GEM fields are projections onto baroclinic geostrophic stream function space, the analysis is quite straightforward under the assumption that the flow is geostrophic, coherent in the vertical, and that the barotropic and baroclinic components of the flow have the same direction, i.e. the flow is equivalent barotropic.

Using the annual mean GEM fields of temperature and specific volume anomaly (i.e. \( \delta_g(p, \Psi) \), \( \bar{T}_g(p, \Psi) \)), depth averages for various streamlines are
carried out for two different depth ranges: between 0-250 dbar (waters within the seasonal thermocline), and 250-500 dbar (which corresponds to the depth range of the SPMW, in the regions and \( \Psi \) ranges where they are present). The first depth range is chosen to study the effects that both the atmosphere and mixing have in transforming the waters near the surface, and to quantify the relative role that the two processes play in changing the water column’s characteristics. The second depth range is purposefully chosen to focus mainly on mixing: where does it take place, and which water masses are getting mixed.

For this, the following averages are calculated:

\[
\langle \delta(\Psi) \rangle = -\frac{1}{p_{\text{bot}} - p_{\text{top}}} \int_{p_{\text{bot}}}^{p_{\text{top}}} \delta_g(p, \Psi) \, dp,
\]

\[
\langle T(\Psi) \rangle = -\frac{1}{p_{\text{bot}} - p_{\text{top}}} \int_{p_{\text{bot}}}^{p_{\text{top}}} T_g(p, \Psi) \, dp,
\]

for each stream function value, where \((p_{\text{bot}}, p_{\text{top}})\) correspond to the depth intervals mentioned above. Each \((<T>, <\delta>)\) pair was plotted on a T/S diagram, from which the corresponding salinity \(<S>\) was inferred (Figure 12). Each point represents the value of \(<T>\) and \(<S>\) for each region, and contour lines for various values of \(<\delta>\) are shown for reference. Note from Figure 1 that if we follow a water column along the NAC, by going from region 1 to region 8, depending on which streamline \((\Psi)\) this hypothetical water column is, it may either loop back towards the Irminger Sea, skipping regions 5 and
6 (cold waters, $\Psi < 4.5 \text{ J kg}^{-1}$); enter the Iceland Basin and continue northwards, skipping region 8 (SPF waters, $\Psi \in [5, 6] \text{ J kg}^{-1}$); or recirculate within the subtropical gyre, skipping regions 6-8 (warm waters, $\Psi > 6.5 \text{ J kg}^{-1}$).

We now proceed to analyze the changes in the water column shown graphically in Figure 12. Rather different results are obtained for the two depth ranges selected. In the seasonal thermocline layer (Figure 12a), we observe that on the cold side of the stream ($\Psi \leq 4 \text{ J kg}^{-1}$) the waters become $40-50 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ ($\approx 0.4 - 0.5 \sigma_\theta$) denser as they move around the subpolar region. This change is mainly due to an increase in salinity of 0.5 psu, while the temperature stays nearly constant, with a cooling of only $\approx 0.7^\circ\text{C}$. By contrast, waters on the warm side of the stream ($\Psi > 5.5 \text{ J kg}^{-1}$) become denser by cooling ($\Delta T \approx -4^\circ\text{C}$), but in contrast they freshen ($\Delta S \approx -0.3 \text{ psu}$). In the middle of the stream ($\Psi \in (4, 5.5) \text{ J kg}^{-1}$), we have an intermediate situation, where waters get denser both by increasing their salinity and by cooling. Since the depth averaged temperature and specific volume anomaly provide a measure of the heat/buoyancy content of the water column studied, we expect that any downstream changes in the seasonal thermocline layer (0-250 dbar) result both from mixing with adjacent waters, and heat/freshwater exchange with the atmosphere:

$$\frac{D < T >}{Dt} = Mixing + \frac{Q}{\rho C_p h_o},$$  

(7)
where $t$ is time, $Q$ is the ocean heat flux to the atmosphere, $\rho$ is density, $C_p$ the ocean heat capacity, $h_o$ the depth of the water column in question, $\frac{dh}{dt}$ is the rate of precipitation minus evaporation. $Mixing$ is the rate of mixing (which can be both horizontal and vertical, isopycnal and cross-isopycnal). It is important to note that any advection due to cross-frontal flows, such as those observed in the meandering Gulf Stream (e.g., Lindstrom and Watts, 1994; Savidge and Bane, 1999) and in the NAC (Perez-Brunius et al., 2003a), would also contribute to change the water properties along the baroclinic streamline. Those terms cannot be distinguished in this study, but since cross-frontal flows lead to stirring of properties across the current, and hence contribute to cross-frontal mixing, we consider them part of the $Mixing$ term.

We quantify the relative role of mixing versus atmospheric fluxes in the transformation process of the water column (0-250 dbar) by obtaining estimates of the different terms in Equations 7 and 8. For this purpose, we integrate the above Equations over time, assuming that the atmospheric fluxes are constant:

$$\Delta <T> = M_T + \frac{Q}{\rho C_p h_o} \Delta t,$$

$$\Delta <S> = M_S - <S> \frac{1}{h_o} \frac{dh}{dt} \Delta t.$$  

The air-sea fluxes $Q$ and $\frac{dh}{dt}$ are estimated using two full years (1998-1999) of
the gridded NCEP/NCAR reanalysis data (Kalnay et al., 1996). The data include net heat flux, latent heat flux, and precipitation rate on a 1.9° × 1.9° grid. The evaporation rate is derived from the latent heat flux. Figure 13 shows the annual mean heat flux from the atmosphere to the ocean \(Q\) and evaporation-precipitation rates for the region of interest \(-\frac{dh}{dt}\). \(\Delta < T >, \Delta < S >\) in Equations 9 and 10 are the change in temperature and salinity between adjacent regions (see Figure 12a). \(\Delta t\) refers to the Lagrangian time scale (i.e., the time it takes for the water parcel to move between the adjacent regions), which we estimate using the velocity of isopycnal RAFOS floats from two experiments carried out between 1996-2000 (Perez-Brunius et al., 2003b), and the approximate length of the streamline in question, estimated from Figure 1. The mixing terms \(M_T\) and \(M_S\) are then found as the residuals using Equations 9 and 10. This is a rather crude way of getting such estimates, but we are interested in orders of magnitude to compare the mixing term with the atmospheric exchange terms. The results are summarized in Table 4, where the total temperature and salinity changes experienced by the water column through its transit from the Tail of the Grand Banks into the subpolar region are presented for two streamlines \((\Psi = 4 \text{ J kg}^{-1}\text{- cold side, } \Psi = 6 \text{ J kg}^{-1}\text{- warm side})\). That is

\[
\Delta^{tot} < T > = \sum_{\text{regions}} \Delta < T >,
\]  

(11)
\[ \Delta^{\text{tot}} < S > = \sum_{\text{regions}} \Delta < S > , \]  
(12)

\[ \Delta^{\text{atm}} < T > = \sum_{\text{regions}} \frac{Q}{\rho C_p h_o} \Delta t , \]  
(13)

\[ \Delta^{\text{atm}} < S > = - \sum_{\text{regions}} < S > \frac{1}{h_o} \frac{dh}{dt} \Delta t , \]  
(14)

where the sum is carried out from region 1 (southern NAC) to region 8 (Irminger Sea) on the cold side streamline \((\Psi = 4 \text{ J kg}^{-1})\), and from region 1 (southern NAC) to region 6 (Rockall Plateau and Trough) on the warm side streamline \((\Psi = 6 \text{ J kg}^{-1})\). Figure 14 shows the results of Table 4 in vector form.

Note that the atmosphere cools and freshens the water column on both sides of the current (Figure 14, Table 4). In the cold side of the stream \((\Psi = 4 \text{ J kg}^{-1})\), the atmospheric fluxes are complemented by mixing with the salty and warm subtropical waters flowing north with the NAC. This suggests that cross-frontal mixing plays an important role in the transformation of the cold waters of the NAC-SPF system, on their journey towards the deep convection region in the Labrador Sea. This argument is strengthened by looking at the transformation of the waters on the warm side of the stream \((\Psi = 6 \text{ J kg}^{-1})\), which become denser not only by atmospheric cooling and freshening, but also by mixing with the waters of subpolar origin found across the current. Note that the salinity increase due to mixing in the cold side is larger than the salinity decrease in the warm side of the front. If these changes result from cross-frontal mixing, we
would expect them to be of the same magnitude (although opposite direction) for both sides. The fact that the warm waters are not getting as fresh as expected by our cross-frontal mixing hypothesis suggests an additional source of salt, affecting the warm side of the current.

In the depth range below the seasonal thermocline (Figure 12b), the downstream changes are much more modest; in general, the water column gets saltier past the Northwest Corner (region 3) for all streamlines. Note that regions where SPMW is present in the water column are marked with a circle in Figure 12b. On the cold side of the stream ($\Psi \leq 5 \ J \ kg^{-1}$), the specific volume anomaly does not change significantly, indicating that most of the mixing takes place along isopycnals. Waters get saltier as they mix across the front with the saltier waters that came along the Gulf Stream via the NAC. By contrast, as waters on the warm side of the SPF ($\Psi \geq 5.5 \ J \ kg^{-1}$) enter the Iceland Basin/Rockall Plateau and Trough area (region 6), they become denser by as much as $\Delta \delta = 10 \times 10^{-8} \ m^3 \ kg^{-1}$. Note that largest changes are observed between regions 5 and 6, hence suggesting that much of the transformation of the water column occurs in the western European Basin and the Rockall Plateau/Trough area. Also noticeable is that the winter mixed layer reaches down to 500 dbar in region 6 (Rockall Plateau and Trough area), leading to the formation of the thickest SPMWs.
It is interesting to observe the difference in how the buoyancy change is achieved at the 250-500 dbar depth range (Figure 12b) compared to the seasonal thermocline layer (Figure 12a), between the Northwest Corner (region 3) and the Rockall Trough and Plateau area (region 6). In the upper depth range, cooling drives most of the buoyancy loss of the warm waters. At depth, however, the buoyancy loss results from an increase in salinity, while any temperature changes remain comparatively small. Recalling that this layer remains mostly isolated from the atmosphere, we attribute the increase in salinity to an influx of salty waters entering the subpolar region from the northeastern subtropics, which are the saltiest subtropical waters found on this density range ($\approx 27.2 - 27.4 \sigma_\theta$, Lozier et al., 1995). Vertical mixing during winter time convection could also lead to an increase in salinity in the 250-500 dbar layer, and a corresponding freshening in the upper layer. The combined effect of an influx at depth of salty Eastern North Atlantic waters, and vertical mixing with the upper layer during winter time, could explain why the warm waters in the upper layer freshen less than the increase in salinity on the opposite side of the front, as we pointed out previously.

In conclusion, cross-frontal mixing helps explain why the upper layer gets saltier on the cold side of the current, and fresher on its warm side, while atmospheric cooling results in a net cooling of the water column for both cases.
Freshwater fluxes play a small role in the transformation process. Cross-frontal mixing alone would require that the freshening of the warm waters be as large as the salting of the cold waters. We observe that the warm waters are not getting as fresh as expected. On the other hand, the warm waters below the seasonal thermocline get denser by increasing their salinity as they enter the eastern subpolar gyre. This supports the idea of an additional source of salty water to the system. Vertical mixing with the saltier upper layer during winter time convection could contribute to the salinity increase of the warm waters on the lower layer, but would result in additional freshening of the upper layer by the combined effect of vertical and cross-frontal mixing. However, we have argued that the upper layer gains more salt than expected, hence there is a need for a salt source for both the upper and lower warm waters. As a result, we suggest that there is an additional source of salt besides the supply coming from the Gulf Stream via the NAC. We conclude that the warm SPF waters that enter the Iceland Basin (region 6), and presumably continue towards the Nordic Seas, become denser by a combined effect of vertical mixing with the upper layer, and entrainment of the very salty waters found in the European Basin, on the northeastern boundary of the subtropical gyre (regions 11 and 12 in this study). Whether this entrainment of salty water occurs through a diffusive process driven by the eddy field or by a mean flow across the baroclinic
streamlines analyzed in this study remains to be determined.

5. Discussion and summary

The projection of historical hydrographic data into stream function space allowed us to examine the process of transformation of the waters carried by the North Atlantic Current-Supolar Front (NAC-SPF) system into the subpolar region. The analysis of the seasonal evolution of the potential vorticity and temperature GEM fields, as functions of specific volume anomaly, permits us to identify with greater clarity where and when those thick layers of uniform water properties are formed by winter convection, and subsequently cut off from the influence of the atmosphere during Spring and Summer as the seasonal thermocline develops.

The view of how and where the different SPMW classes are formed has changed since they were first described by McCartney and Talley (1982). There it was suggested that these Mode Waters are formed in the NAC region and then advected along the current as they become cooler and denser. From there some recirculate back in the subtropical gyre, and the rest enter the eastern subpolar region as part of the warm inflow into the subpolar gyre. In that argument, the SPMWs would be transformed gradually into denser classes as they are advected along the NAC-SPF system. In a later study, Talley (1999) suggests that there may not be such a smooth connection between the different density
classes of SPMW. She suggests that the warmest modes are associated with the recirculation of the subtropical gyre, and hence do not enter the subpolar region. Also, she finds no connection between the Mode Waters found on either side of the Reykjanes Ridge (see review in Hanawa and Talley, 2001). Our results corroborate this point of view: the lighter Mode Water classes form and remain on streamlines associated with the recirculation of the subtropical gyre. Also, the Mode Waters formed on either side of the Reykjanes Ridge are formed on different geostrophic streamlines. Hence, the denser classes found in the eastern Irminger Sea are formed locally, and do not result from the combined advection and buoyancy loss of lighter Mode Waters formed in the Iceland Basin-Rockall Plateau and Trough region. On the other hand, Mode Waters formed within the SPF branches ($\delta = 30 \times 10^{-8}$ m$^3$ kg$^{-1}$) suffer a buoyancy loss of around $\Delta\delta = 20 \times 10^{-8}$ m$^3$ kg$^{-1}$ units as they enter the Iceland Basin-Rockall Plateau and Trough region. This points out that the largest transformation of the subtropical waters as they flow towards the Nordic Seas, occurs on the warm side of the Subpolar Front after it enters the Rockall Plateau and Trough area.

We obtained the mean characteristics for the different Mode Water classes, as well as the regions and streamlines where they are formed. The location of the different SPMW classes generally agrees with Talley (1999), although a more detailed comparison cannot be carried out since our method does not provide a
sufficiently fine description of the geographical distribution of these thick layers of uniform water (these GEM fields give a fine description on geostrophic stream function parameter space, but coarse boxes in geographical coordinates).

We suggest the following pattern of circulation for the different SPMW classes. Those with $\delta > 30 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ recirculate in the subtropical gyre. Mode Waters formed within the branches of the SPF ($\delta = 30 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$) enter the eastern subpolar North Atlantic, where they transform into denser classes ($\delta \in [10, 20] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$). In the Iceland Basin/Rockall Plateau region, Mode Waters with $\delta = 0 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ are formed. The rest ($\delta \leq -10 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$) are formed within the recirculation of the subpolar gyre, and $\delta = -30 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ characterizes Labrador Sea Water, which is the densest Mode Water found in the area.

This study shows that the light-to-dense conversion of the waters advected by the NAC-SPF is not only due to fluxes of heat and freshwater between the ocean and the atmosphere: there is strong evidence for the importance of crossfrontal mixing in the transformation process. This has also been observed in a related study (Perez-Brunius et al., 2003a), where strong barotropic recirculations associated with the steep meanders of the northward flowing NAC are found, causing flow across baroclinic streamlines. These recirculations favour exchange of waters across the current, resulting in a net cooling of the NAC
by cross-frontal mixing. The present study also finds that, at depths below the influence of the atmosphere, the SPF waters become saltier as they enter the subpolar North Atlantic, indicating that the warm and salty influx comes not only from the Gulf Stream via the NAC; this suggests the European Basin must contribute a significant amount of salt along the eastern margin. Evidence for this has been shown by Reid (1994), who discusses the role of salty Mediterranean Overflow in preconditioning the waters for deep convection, suggesting a flow along the eastern margin that advects Mediterranean waters into the Nordic Seas. McCartney and Mauritzen (2001) offer a different hypothesis, arguing that Mediterranean Overflow Water influences the salinity inflow into the deep convection sites in a dilute and indirect manner (by changing the properties of the NAC and SPMW waters in the subpolar region), rather than by direct advection into the Nordic Seas as proposed by Reid (1994). McCartney and Mauritzen (2001) also suggest a poleward flow along the continental slope of SPMW originating from the Bay of Biscay. Other studies suggest that the saline Eastern North Atlantic Water found in the eastern European Basin, and transported north along the continental margin, is also a contributor to the salt influx into the subpolar region (see review in Hanawa and Talley (2001)).

Our study points out the important role that cross-frontal mixing plays in the transformation of the NAC-SPF waters found on the cold side of the front,
which subsequently enter the recirculation of the subpolar gyre. Both at 250-500 m depth as well as in the 0-250 m layer influenced by the atmosphere, waters become denser by an increase in their salinity. We attribute this to mixing with the saltier waters found across the stream, a process that may be important in preconditioning the NAC-SPF waters for deep convection in the Labrador Sea. The situation for the NAC-SPF waters on the warm side of the front is rather different, especially as they enter the Iceland Basin-Rockall Plateau region, presumably continuing towards the regions of deep convection in the Nordic Seas. For the top 250 dbar, the waters become denser by cooling, while their salinity tends to decrease. Hence, both atmospheric cooling and cross-frontal mixing play a role in transforming the upper waters. At depths below the influence of the atmosphere (> 250 dbar), however, the buoyancy loss is mostly due to an increase in salinity. We propose vertical mixing with the saltier upper layer and an influx of salty waters from the European Basin as the likely causes for the observed salinity increase of these waters. Consequently, the salty waters from the eastern margin play an important role in the light-to-dense transformation of the NAC-SPF waters that continue to the Nordic Seas. This is in contrast to McCartney and Mauritzen (2001), who argued that the light-to-dense transformation of the warm waters is mostly due to cooling of the waters through atmospheric heat loss, and entrainment into a deepening
mixed layer by horizontal flow across the mixed layer base, as the layer continues its transit through the subpolar region. In the same paper, they observe the NAC-SPF waters becoming colder and fresher as they enter the eastern subpolar gyre. Our results suggest that the transformed waters between 250 and 500 dbar become denser by becoming saltier, while their temperature remains relatively unchanged.

In conclusion, this study finds that the transformation process for the top 500 dbar of the water column is different for the two pathways that the NAC-SPF waters follow in the subpolar region. Cross-frontal mixing apparently dominates in preconditioning the NAC-SPF waters for deep convection to occur in the Labrador Sea. The process is more complex for the waters along the southern margin of the SPF, which become denser as they enter the Iceland Basin/Rockall Plateau and Trough area by a combination of three processes: entrainment of salty water from the European Basin; vertical mixing due to a deep winter mixed layer; and atmospheric cooling.

**APPENDIX**

**GEM errors**

The errors associated to the GEM technique have been thoroughly analyzed by Meinen and Watts (2000), Book et al. (2002), and Sun and Watts (2001).
The rms error ($\sigma_r$) is used to see how well the GEM fields reproduce the profiles of the hydrocasts used in their construction: $\sigma_r^2 = \langle (\delta g - \delta_{\text{hydrocasts}})^2 \rangle$. Below 100 dbar, the rms values correspond to less than 10% of the vertical range in specific volume anomaly (or temperature), with the largest deviations present in the main and seasonal thermoclines. The exception is region 6, where the corresponding percentage for the main thermocline is about 15% (Figure 15).

The GEM fields explain above 90% of the variance of the hydrocasts in regions with strong baroclinicity (large range in $\Psi$) and stratification, such as the NAC (region 2) and SPF (region 4). As the stratification and baroclinicity is reduced, so does the variance in the hydrocasts, and the GEM fields work less well at reproducing the variability (Figure 16). This is because in those regions, the variability in the hydrographic conditions is less associated with the meandering fronts, and more to changes in the properties of the water masses present. This becomes clearer in Figure 17, where we see enhanced variability at depth in the vertical profiles of specific volume anomaly of region 6, where the variance explained by the GEM is poor. For the other regions, however, the GEMs reproduce well the hydrographic profiles.

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graduate fellowship provided by the Consejo Nacional de Ciencia y Tecnología, México, and a Fulbright-García Robles grant.
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Table captions

Table 1. List of specific volume anomaly surfaces and their potential density analogues. Specific volume anomaly values in the first column are referenced to an intermediate temperature (4.9°C) and salinity (34.6 psu). The second column has specific volume anomaly calculated using the standard 0°C and 35 psu values.

Table 2. Subregions of the North Atlantic used for the construction of the GEM fields in the Subpolar North Atlantic.

Table 3. Subpolar Mode Water classes: mean characteristics, and regions and approximate streamlines where they are formed.

Table 4. Estimates of temperature and salinity changes of the water column (0-250dbar) on its transit from the Tail of the Grand Banks (region 1) into the subpolar region (region> 5), on two different streamlines Ψ (see text for details). The results from this Table are shown graphically in Figure 14.
Figure captions

Figure 1. Climatological map of dynamic height at 200dbar (referenced to 1000dbar) for the northern North Atlantic (constructed with data from HydroBase (Curry, 1996)). It represents the approximate mean geostrophic flow for the region.

Figure 2. Subregions selected for the construction of the GEM fields. Dots represent the hydrographic stations used, obtained from HydroBase (Curry, 1996).

Figure 3. Monthly differences from the annual mean of specific volume anomaly for the regions of Figure 3. Dashed line is the depth for which the difference is less than $5 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. Note that the seasonal influence is usually greatest within the upper 200 dbar.

Figure 4. Specific volume anomaly versus $\Psi$ for various pressure levels for March, in region 1 (southern NAC). The line is the spline fitted to the hydrodata (dots), which results in the corresponding GEM field.

Figure 5. Temperature versus $\Psi$ for various pressure levels for September, in region 6 (Iceland Basin). The line is the spline fitted to the hydrodata (dots), which results in the corresponding GEM field.

Figure 6. Temperature versus $\Psi$ at various pressure levels, for the region of the southern NAC (region 1). Note the bimodal structure of the field for
\( \Psi \leq 4.7 \text{ J kg}^{-1} \). The triangles represent hydrocasts in the Labrador Current, while the dots are stations taken within the NAC.

**Figure 7.** Histogram of temperature on \( \delta = -5 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \). The bimodal structure is due to the presence of cold Labrador Current waters flowing side by side with the warm NAC waters. The arrow represents the cut off temperature \( (T \approx 3.1^\circ \text{C}) \) used to distinguish the two currents.

**Figure 8.** Annual mean potential vorticity GEM fields for the 12 regions of Figure 2, in \( 10^{-11} \text{ m}^{-1} \text{s}^{-1} \).

**Figure 9.** Seasonal evolution of the GEM fields for two different streamlines in the NAC region (region 1): (a) cold side of the current \( (\Psi = 4 \text{ J kg}^{-1}) \), (b) warm side of the current \( (\Psi = 7.5 \text{ J kg}^{-1}) \).

**Figure 10.** Seasonal evolution of the GEM fields, using specific volume anomaly as the vertical coordinate, for three different regions, on \( \Psi = 6 \text{ J kg}^{-1} \). (a) SPF (region 4), (b) northern European Basin (region 5), (c) Iceland Basin (region 6).

**Figure 11.** Summary of Table, showing the approximate location where different classes of SPMWs are formed. Class I: \( \delta \geq 30 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \), Class II: \( \delta = [30] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \), Class III: \( \delta \in [10, 20] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \), Class IV: \( \delta = [0] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \), Class V: \( \delta \in [-20, -10] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \). On top are shown contours of dynamic height at 200 dbar (ref. to 1000 dbar) with intervals.
every 0.5 J kg\(^{-1}\).

**Figure 12.** (a) T/S diagram for the seasonal thermocline layer waters, constructed from the annual mean temperature and specific volume anomaly fields, averaged over the top 250 dbar. It shows the downstream evolution of the properties of a water column flowing along the NAC-SPF system (from region 1 to region 8). Each group of circles joined by a line represent a streamline, and each circle on a given streamline is the mean value of temperature, salinity and \(\delta\) for each region (labeled by the symbol). Filled circles indicate the presence of SPMW in the water column. (b) Same as (a) except that the diagram is for the mean properties of the waters between 250 and 500 dbar.

**Figure 13.** Same as Figure 12, except that the T/S diagram corresponds to mean properties of waters between 250-500 dbar.

**Figure 14.** Annual mean air-sea fluxes obtained from 2 years of NCEP data. (a) Net air-sea heat flux in W m\(^{-2}\) (a negative value indicates that heat is lost to the atmosphere). (b) Net air-sea freshwater flux in 10\(^{-2}\) cm day\(^{-1}\) (a negative value indicates freshwater gained by the ocean).

**Figure 15.** T/S diagram summarizing the downstream evolution of the properties of a water column on its transit from the Tail of the Grand Banks into the subpolar region, for two streamlines (\(\Psi=4\) J kg\(^{-1}\)-cold side, \(\Psi=6\) J kg\(^{-1}\)-warm side). This Figure is a graphic representation of the results from Ta-
Table 4. Total = $(\Delta^{\text{tot}} < T >, \Delta^{\text{tot}} < S >)$ is the total change in temperature and salinity of the water column flowing along the NAC-SPF system (from region 1 to region 8). The subscript $\Psi = 4$ refers to changes along the cold side streamline, and $\Psi = 6$ corresponds to the warm side streamline;

$\text{Atm} = (\Delta^{\text{atm}} < T >, \Delta^{\text{atm}} < S >)$ refers to changes due to atmospheric fluxes;

$\text{Diff} = \text{Total} - \text{Atm} = (M_T, M_S)$.

**Figure 16.** Mean-square error for the specific volume anomaly GEM field, contoured as the percentage of the vertical range of $\delta$, for three different regions:

(a) region 1 (Southern NAC), (b) region 4 (SPF), and (c) region 6 (Rockall Plateau and Trough).

**Figure 17.** Percentage of the variance explained by the temperature GEM fields, for four different regions. Region 2- Northern NAC, region 4- SPF, region 8- Irminger and Labrador Seas, and region 10- eastern Newfoundland Basin.

**Figure 18.** Groups of hydrodata specific volume anomaly profiles (thin lines) compared to the corresponding GEM specific volume anomaly profiles (thick lines) for various values of $\Psi$, in four regions. The profiles are shifted $100 \times 10^{-8}$ m$^3$ kg$^{-1}$ units: (a) region 1 (hydrodata profiles with $\Psi$ within 2 J kg$^{-1}$ - southern NAC), (b) region 6 (hydrodata profiles with $\Psi$ within 0.6 J kg$^{-1}$ - Rockall Plateau and Trough), (c) region 8 (hydrodata profiles with $\Psi$ within 0.4 J kg$^{-1}$ - Irminger and Labrador Seas), and (d) region 11 (hydrodata profiles
with $\Psi$ within 0.2 J kg$^{-1}$ - southern European Basin).
Table 1: List of specific volume anomaly surfaces and their potential density analogues. Specific volume anomaly values in the first column are referenced to an intermediate temperature (4.9°C) and salinity (34.6 psu). The second column has specific volume anomaly calculated using the standard 0°C and 35 psu values.

<table>
<thead>
<tr>
<th>Specific Volume Anomaly (34.6 psu, 4.9°C) $\left(10^{-8} \text{ m}^3 \text{ kg}^{-1}\right)$</th>
<th>Specific Volume Anomaly (35 psu, 0°C) $\left(10^{-8} \text{ m}^3 \text{ kg}^{-1}\right)$</th>
<th>Potential Density $(\sigma_\theta \pm 0.02)$</th>
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<tr>
<td>70</td>
<td>$\approx 142$</td>
<td>$26.68 \approx 26.7$</td>
</tr>
<tr>
<td>60</td>
<td>$\approx 134$</td>
<td>$26.78 \approx 26.8$</td>
</tr>
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<td>50</td>
<td>$\approx 127$</td>
<td>$26.89 \approx 26.9$</td>
</tr>
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<td>40</td>
<td>$\approx 119$</td>
<td>$26.98 \approx 27.0$</td>
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<td>30</td>
<td>$\approx 109$</td>
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</tr>
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<td>20</td>
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<td>10</td>
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<tr>
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<td>$27.69 \approx 27.7$</td>
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Table 2: Subregions of the North Atlantic used for the construction of the GEM fields in the Subpolar North Atlantic.

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<th>Region #</th>
<th>Region name</th>
<th># of hydrocasts</th>
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<tr>
<td>1</td>
<td>southern NAC (Mann eddy)</td>
<td>5267</td>
</tr>
<tr>
<td>2</td>
<td>northern NAC (Flemish Cap)</td>
<td>6450</td>
</tr>
<tr>
<td>3</td>
<td>Northwest Corner</td>
<td>844</td>
</tr>
<tr>
<td>4</td>
<td>Subpolar Front (Charlie Gibbs Fracture Zone)</td>
<td>10781</td>
</tr>
<tr>
<td>5</td>
<td>western European Basin</td>
<td>1181</td>
</tr>
<tr>
<td>6</td>
<td>Rockall Plateau and Trough</td>
<td>2590</td>
</tr>
<tr>
<td>7</td>
<td>Iceland Basin and Reykjanes Ridge</td>
<td>10699</td>
</tr>
<tr>
<td>8</td>
<td>Irminger Sea</td>
<td>1264</td>
</tr>
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<td>9</td>
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<tr>
<td>10</td>
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<tr>
<td>11</td>
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<td>1035</td>
</tr>
<tr>
<td>12</td>
<td>northern European Basin</td>
<td>1266</td>
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</table>
Table 3: Subpolar Mode Water classes: mean characteristics, and regions and approximate streamlines where they are formed.

<table>
<thead>
<tr>
<th>δ layer (±5 × 10⁻⁸ m³ kg⁻¹)</th>
<th>Temperature range (°C)</th>
<th>Layer thickness (dbar)</th>
<th>Regions where formed</th>
<th>Approx. streamlines where formed (J kg⁻¹)</th>
</tr>
</thead>
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<tr>
<td>60</td>
<td>13.7-15.3</td>
<td>≤ 200</td>
<td>NAC</td>
<td>Ψ &gt; 6.5,7.0</td>
</tr>
<tr>
<td>50</td>
<td>12.3-14.4</td>
<td>≤ 250</td>
<td>NAC</td>
<td>Ψ ∈ [5.0,7.5]</td>
</tr>
<tr>
<td>40</td>
<td>11.4-13.4</td>
<td>≤ 300</td>
<td>south of SPF and Newfoundland Basin</td>
<td>Ψ ∈ [7.3, 8.0]</td>
</tr>
<tr>
<td>30</td>
<td>10.1-12.5</td>
<td>∈ [140,250]</td>
<td>between SPF branches (4 &amp; 5)</td>
<td>Ψ ∈ [5.7,7.3]</td>
</tr>
<tr>
<td>20</td>
<td>8.9-11.3</td>
<td>∈ [200,500]</td>
<td>northern European Basin (12)</td>
<td>Ψ ∈ [5.3,7.7]</td>
</tr>
<tr>
<td>10</td>
<td>8.6-10.2</td>
<td>∈ [200,500]</td>
<td>Rockall Plateau and Trough (6)</td>
<td>Ψ ≥ 6.5</td>
</tr>
<tr>
<td>0</td>
<td>6.6-9.0</td>
<td>∈ [140,300]</td>
<td>Iceland Basin (6 &amp; 7)</td>
<td>Ψ ∈ [4.5,6.2]</td>
</tr>
<tr>
<td>-10</td>
<td>5.6-7.5</td>
<td>∈ [170,200]</td>
<td>eastern Irminger Sea (7, &amp; 8)</td>
<td>Ψ ∈ [3.8, 3.9]</td>
</tr>
<tr>
<td>-20</td>
<td>4.6-6.5</td>
<td>∈ [170,200]</td>
<td>Irminger Sea (8)</td>
<td>Ψ ≥ 3.5</td>
</tr>
<tr>
<td>-30</td>
<td>3.8-5.2</td>
<td>∈ [200,500]</td>
<td>LSW- formed in Labrador Sea</td>
<td></td>
</tr>
</tbody>
</table>


Table 4: Estimates of temperature and salinity changes of the water column (0-250dbar) on its transit from the Tail of the Grand Banks (region 1) into the subpolar region (region > 5), on two different streamlines $\Psi$ (see text for details). The results from this Table are shown graphically in Figure 14.

<table>
<thead>
<tr>
<th>$\Psi$ (J kg$^{-1}$)</th>
<th>$\Delta^{tot} &lt; T &gt;$ (±0.2°C)</th>
<th>$\Delta^{atm} &lt; T &gt;$ (°C)</th>
<th>$M_T$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>-0.7</td>
<td>-3.7</td>
<td>3.0</td>
</tr>
<tr>
<td>6</td>
<td>-4.2</td>
<td>-4.1</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Psi$ (J kg$^{-1}$)</th>
<th>$\Delta^{tot} &lt; S &gt;$ (±0.06 psu)</th>
<th>$\Delta^{atm} &lt; S &gt;$ (psu)</th>
<th>$M_S$ (psu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.51</td>
<td>-0.15</td>
<td>0.66</td>
</tr>
<tr>
<td>6</td>
<td>-0.28</td>
<td>-0.05</td>
<td>-0.23</td>
</tr>
</tbody>
</table>
Figure 1: Climatological map of dynamic height at 200 dbar (referenced to 1000 dbar) for the northern North Atlantic (constructed with data from HydroBase (Curry, 1996)). It represents the approximate mean geostrophic flow for the region.
Figure 2: Subregions selected for the construction of the GEM fields. Dots represent the hydrographic stations used, obtained from HydroBase (Curry, 1996).
Figure 3: Monthly differences from the annual mean of specific volume anomaly for the regions of Figure 3. Dashed line is the depth for which the difference is less than $5 \times 10^{-8}$ m$^3$ kg$^{-1}$. Note that the seasonal influence is usually greatest within the upper 200 dbar.
Figure 4: Specific volume anomaly versus $\Psi$ for various pressure levels for March, in region 1 (southern NAC). The line is the spline fitted to the hydrodata (dots), which results in the corresponding GEM field.
Figure 5: Temperature versus $\Psi$ for various pressure levels for September, in region 6 (Iceland Basin). The line is the spline fitted to the hydro data (dots), which results in the corresponding GEM field.
Figure 6: Temperature versus $\Psi$ at various pressure levels, for the region of the southern NAC (region 1). Note the bimodal structure of the field for $\Psi \leq 4.7$ J kg$^{-1}$. The triangles represent hydrocasts in the Labrador Current, while the dots are stations taken within the NAC.
Figure 7: Histogram of temperature on $\delta = -5 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. The bimodal structure is due to the presence of cold Labrador Current waters flowing side by side with the warm NAC waters. The arrow represents the cut off temperature ($T \approx 3.1^\circ \text{C}$) used to distinguish the two currents.
Figure 8: Annual mean potential vorticity GEM fields for the 12 regions of Figure 2, in $10^{-11} \, \text{m}^{-1} \text{s}^{-1}$. 
Figure 9: Seasonal evolution of the GEM fields for two different streamlines in the NAC region (region 1): (a) cold side of the current ($\Psi = 4 \text{ J kg}^{-1}$), (b) warm side of the current ($\Psi = 7.5 \text{ J kg}^{-1}$).
Figure 10: Seasonal evolution of the GEM fields, using specific volume anomaly as the vertical coordinate, for three different regions, on $\Psi = 6 \text{ J kg}^{-1}$. (a) SPF (region 4), (b) northern European Basin (region 5), (c) Iceland Basin (region 6).
Figure 11: Summary of Table, showing the approximate location where different classes of SPMWs are formed. Class I: $\delta \geq 30 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, Class II: $\delta = [30] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, Class III: $\delta \in [10, 20] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, Class IV: $\delta = [0] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, Class V: $\delta \in [-20, -10] \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. On top are shown contours of dynamic height at 200 dbar (ref. to 1000 dbar) with intervals every 0.5 J kg$^{-1}$. 
Figure 12: (a) T/S diagram for the seasonal thermocline layer waters, constructed from the annual mean temperature and specific volume anomaly fields, averaged over the top 250 dbar. It shows the downstream evolution of the properties of a water column flowing along the NAC-SPF system (from region 1 to region 8). Each group of circles joined by a line represent a streamline, and each circle on a given streamline is the mean value of temperature, salinity and $\delta$ for each region (labeled by the symbol). Filled circles indicate the presence of SPMW in the water column. (b) Same as (a) except that the diagram is for the mean properties of the waters between 250 and 500 dbar.
Figure 13: Annual mean air-sea fluxes obtained from 2 years of NCEP data. (a) Net air-sea heat flux in W m$^{-2}$ (a negative value indicates that heat is lost to the atmosphere). (b) Net air-sea freshwater flux in 10$^{-2}$ cm day$^{-1}$ (a negative value indicates freshwater gained by the ocean).
Figure 14: T/S diagram summarizing the downstream evolution of the properties of a water column on its transit from the Tail of the Grand Banks into the subpolar region, for two streamlines (Ψ=4 J kg$^{-1}$-cold side, Ψ=6 J kg$^{-1}$-warm side). This Figure is a graphic representation of the results from Table 4. Total=(Δ$_{tot}^T$, Δ$_{tot}^S$) is the total change in temperature and salinity of the water column flowing along the NAC-SPF system (from region 1 to region 8). The subscript Ψ = 4 refers to changes along the cold side streamline, and Ψ = 6 corresponds to the warm side streamline; Atm=(Δ$_{atm}^T$, Δ$_{atm}^S$) refers to changes due to atmospheric fluxes; Diff=Total-Atm= ($M_T$, $M_S$).
Figure 15: Mean-square error for the specific volume anomaly GEM field, contoured as the percentage of the vertical range of $\delta$, for three different regions: (a) region 1 (Southern NAC), (b) region 4 (SPF), and (c) region 6 (Rockall Plateau and Trough).
Figure 16: Percentage of the variance explained by the temperature GEM fields, for four different regions. Region 2—Northern NAC, region 4—SPF, region 8—Irminger and Labrador Seas, and region 10—eastern Newfoundland Basin.
Figure 17: Groups of hydrodata specific volume anomaly profiles (thin lines) compared to the corresponding GEM specific volume anomaly profiles (thick lines) for various values of $\Psi$, in four regions. The profiles are shifted $100 \times 10^{-8}$ m$^3$ kg$^{-1}$ units: (a) region 1 (hydrodata profiles with $\Psi$ within 2 J kg$^{-1}$ - southern NAC), (b) region 6 (hydrodata profiles with $\Psi$ within 0.6 J kg$^{-1}$ - Rockall Plateau and Trough), (c) region 8 (hydrodata profiles with $\Psi$ within 0.4 J kg$^{-1}$ - Irminger and Labrador Seas), and (d) region 11 (hydrodata profiles with $\Psi$ within 0.2 J kg$^{-1}$ - southern European Basin).