



Simulated pathways of the overflow waters in the North Atlantic: Subpolar to subtropical export

M. Susan Lozier^{a,*}, Stefan F. Gary^a, Amy S. Bower^b

^a Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, NC 27708, United States

^b Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, United States

ARTICLE INFO

Keywords:

Meridional overturning Lagrangian trajectories Overflow water pathways

ABSTRACT

Motivated by previous observational and modeling studies that demonstrate interior pathways for the export of Labrador Sea Water (LSW) into the subtropical North Atlantic, we analyze whether the deeper, denser overflow water (OW) pathways are similarly distributed in the basin. For this study, we rely on the simulation of OW pathways in the context of an ocean general circulation model. From our analysis, we suggest that OW in the North Atlantic is not restricted to the DWBC in its equatorward transport. Thus, a measure of OW transport variability within the DWBC downstream of the subpolar gyre cannot be safely equated to transport variability of the lower limb of the AMOC. Since this study of OW export pathways relies solely on simulated pathways, the applicability of our results to the North Atlantic rests on the representativeness of the model's deep flow field.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction and background

The deep limb of the ocean's meridional overturning circulation in the Atlantic (AMOC) is considered to be a conduit for heat, freshwater and carbon acquired at the sea surface and carried to depth via water mass formation at high latitudes in the subpolar gyre and within the Nordic Seas. The export of these deep waters from high to low latitudes in the North Atlantic has traditionally been assumed to occur via the Deep Western Boundary Current (DWBC). As such, the transport and property variability of the DWBC in the North Atlantic have been assumed to be the primary indicators of variability in the deep limb of the AMOC. Recent observational and modeling work, however, has cast doubt on that supposition for the shallower DWBC component, namely the Labrador Sea Water (LSW).

In a recent observational program (ExPath) focused on the pathways by which LSW is exported to the subtropics as part of the AMOC lower limb, 76 RAFOS floats were seeded within the southward-flowing DWBC near 50°N from 2003 to 2006. Three floats at 700 m and three others at 1500 m were released approximately every 3 months during this time period: all were acoustically tracked for 2 yrs. As detailed by Bower et al. (2009, 2011), the resultant float pathways revealed that (1) most of the floats recirculated within the subpolar gyre, (2) of those that entered the subtropical gyre, most did so via interior pathways,

and (3) floats preferentially left the DWBC at topographic choke points, most notably the southeastern corner of Flemish Cap and the Tail of the Grand Banks. A follow-on study (Gary et al., 2011) that simulated float pathways using the velocity fields from an eddy-resolving general circulation model attributed the interior pathways to the presence of a large-scale eddy-driven recirculation in the vicinity of the Gulf Stream/North Atlantic Current, an attribution previously based on the homogenization of observed potential vorticity fields (Lozier et al., 1995, 1997).

Based on the pathways of the RAFOS floats and their simulated counterparts, it was suggested (Bower et al., 2009) that the DWBC is not the sole conduit for the equatorward transport of Labrador Sea Water and, more importantly, that the interior subtropical basin has equatorward flow. These results are at odds with Stommel's 1958 study in which he theorized that recently ventilated waters of high latitude origin must be transported equatorward at depth along western-intensified boundary currents (Stommel, 1958) and that interior waters must move poleward. In Stommel's formulation of steady potential vorticity dynamics, the poleward interior flow at depth is needed to balance the stretching of the water column, the latter a consequence of the uniform basin-wide upwelling imposed to balance sources of dense water at high latitudes. These LSW trajectories raise the question as to whether the overflow waters (OW) formed via convective activity in the Nordic Seas and delivered to the North Atlantic across the Greenland–Scotland Ridge, also have interior pathways or if they would instead be transported equatorward via the DWBC. The pathways for these overflow waters, which fill the abyss of the North Atlantic, are the focus of this study.

* Corresponding author. Tel.: +1 919 681 8199.
E-mail address: mslozier@duke.edu (M.S. Lozier).

Knowledge of the abyssal ocean's flow field remains poor, even in the North Atlantic, where observations are the most plentiful of all ocean basins. Direct measures of velocity have largely been limited to boundary currents and these have generally been few and intermittent. Direct measures of the interior flow are largely absent. However, as mentioned above, a prior investigation of historical hydrographic data (Lozier et al., 1995) revealed the signature of eddy-driven gyres below the thermocline: contours of pressure on deep isopycnals trace large-scale anticyclonic recirculations adjacent to the Gulf Stream/North Atlantic Current system. These anticyclonic recirculations create interior pathways in the subtropical region that allow for the equatorward movement of recently ventilated waters outside of the DWBC. Previous modeling work (Holland and Rhines, 1980; Lozier and Riser, 1989, 1990) has demonstrated that instabilities of western boundary currents and their seaward extensions drive these eddy-driven recirculations, and that these recirculations dominate the flow field below the main thermocline. In the absence of potential vorticity sources or sinks, these recirculations act to homogenize potential vorticity (Rhines and Young, 1982). Climatological fields of potential vorticity reveal such homogenization within the confines of the deep recirculation traced by the pressure fields (Lozier, 1997). This recirculation is maximized near 2000 m, diminishes in extent and magnitude at deeper depths, but is still evident at the depths of the overflow waters in the subtropical basin, suggesting an alternative equatorward route to the DWBC for the overflow waters.

Given this suggestion and the behavior of the observed and modeled RAFOS floats at the level of the LSW, it is supposed that the overflow pathways are not confined to the DWBC. To test this supposition, we turn to the simulation of float pathways using an ocean general circulation model that was found to successfully reproduce the observed RAFOS pathways at the level of the LSW. While observational floats would obviously be preferable, there have been to date no floats released at the depth of the overflow waters that can reveal the export pathways from subpolar to the subtropical gyre.

In summary, the goal of this paper is to investigate the pathways by which overflow waters of subpolar origin are exported to the subtropics. In the next section, we discuss the methods used for this study. In Section 3 we present the results of the study and follow that with a summary in Section 4.

2. Data and methods

2.1. Description of the OGCM: FLAME

The model used in this analysis is the highest resolution member of the Family of Linked Atlantic Modeling Experiments (FLAME) (Bjastoch et al., 2008; Böning et al., 2006). This model uses a primitive equation, z -coordinate framework (Pacanowski, 1996) that includes isopycnal mixing, biharmonic friction and a bottom boundary layer (Beckmann and Döschner, 1997). In the vertical, the model domain is divided into 45 levels whose spacing increases from 10 m at the surface to a maximum of 250 m in the deepest levels. This regional model spans 18°S to 70°N on a Mercator grid with a resolution of $1/12^\circ \times 1/12^\circ \cos \theta$, where θ is latitude. The initial temperature and salinity fields of the model are specified by the superposition of monthly mean anomalies (Levitus et al., 1994a,b) and annual means (Boyer and Levitus, 1997). During the simulation, sea surface salinity was restored to the monthly climatology with a 15-day time scale. At the open boundaries of the model, temperature and salinity were maintained at climatological values. Flow through the southern boundary was specified by the Sverdrup relation while the northern boundary transport was based on output from a regional Arctic Ocean model (Brauch and Gerdes, 2005). The model was spun up from rest with 10 yrs of ECMWF climatological forcing. The model was then forced with a superposition of the 1990–2004 monthly anomalies of the NCEP/NCAR reanalysis data (Kalnay et al., 1996) and the climatological forcing applied during the spin up. Model temperature, salinity, and velocity fields were stored with snapshots once every 3 days during the 1990–2004 “hindcast” period.

2.2. Comparison of FLAME and historical hydrographic fields at the OW level

The use of FLAME for the study of the North Atlantic has been validated in a number of recent studies (Böning et al., 2006; Bjastoch et al., 2008; Burkholder and Lozier, 2011). The studies most relevant to the work herein are those of Bower et al. (2009, 2011) and Gary et al. (2011), where FLAME property fields at the depth of LSW have been compared with North Atlantic historical hydrographic data from the World Ocean Database 2009 (WOD09) and trajectories simulated from FLAME's velocity fields

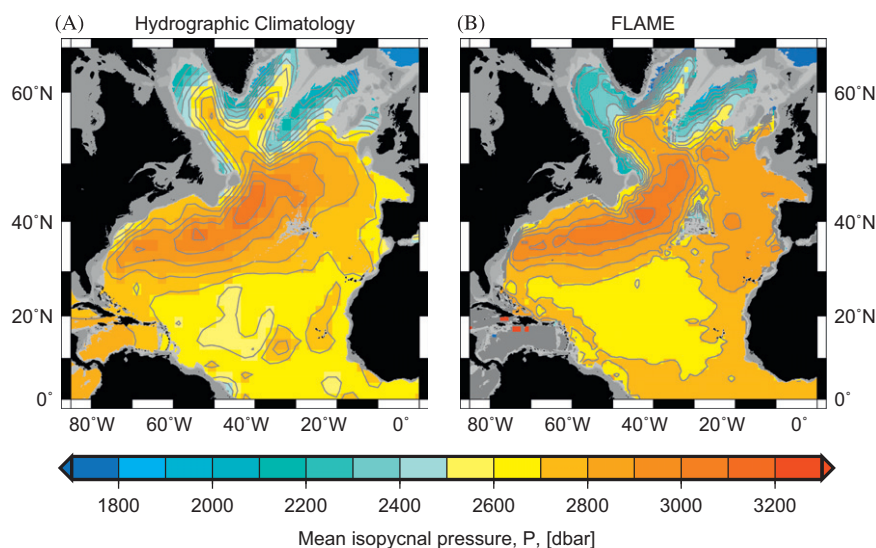


Fig. 1. Climatological pressure (shaded and 100 dbar contour interval, gray lines) on $\sigma_3 = 41.45$, a density surface at the depth of OW, in observations (1960s to present) and FLAME (1990–2004 mean).

(see next section) have been favorably compared to RAFOS trajectories from the ExPath observational program.

To understand the ability of FLAME to simulate the flow fields at the OW depth in the subpolar and subtropical North Atlantic, we compare climatological fields of pressure (from WOD09) on a deep isopycnal with those same fields generated from FLAME model output. Details on the construction of the climatological fields can be found in Gary et al. (2011) and Lozier et al. (1995). As seen in Fig. 1, the signature of a large-scale recirculation, to the south and east of the Gulf Stream/North Atlantic Current system, is evident from the closed isobars in the observed pressure field. With a deep level of no motion, the circulation is anticyclonic, such that the gyre's northern boundary is coincident with the eastward/northeastward flow of the Gulf Stream and North Atlantic Current and its southern branch flows to the south/southwest along approximately 30°N. The signature of deep eddy-driven recirculation gyres is remarkably reproduced in the density structure of the FLAME model. Similar to the climatology constructed from observations, closed isobars on a deep isopycnal in FLAME are present to the south and east of the Gulf Stream/North Atlantic Current. This signature of deep recirculation gyres in the simulation has approximately the same depth and horizontal extent as in the observations.

In a previous study (Getzlaff et al., 2006), mean velocity cross-sections of the DWBC using FLAME model output were favorably compared to observations of the same at 43°N (Schott et al., 2004) and 53°N (Fischer et al., 2004). In that work, the authors concluded that the FLAME velocity field “captures the salient features of the observed DWBC structure and transports obtained from current-meter sections at 53°N and 43°N”. More details of this comparison can be found in Getzlaff et al. (2006). Additional images of the mean velocity cross-sections of the DWBC using FLAME output can be found in Bower et al. (2009) and Gary et al. (2011).

2.3. Simulation and analysis of trajectories from FLAME

The trajectories of Lagrangian particles are simulated by integrating the FLAME three-dimensional velocity field (Getzlaff et al., 2006; Hüttel-Kabus and Böning, 2008). More information about the trajectory calculation algorithm is documented in Gary et al. (2011). In order to capture the variability of the Lagrangian pathways, particles are launched from an array of launch locations at 30-day intervals. In order to extend the length of particle trajectories beyond the duration of 15 yrs of model output, the 1990–2004 fields are recycled during the simulation with a single discontinuity between December 31, 2004 and January 1, 1990. This temporal discontinuity is bridged with linear interpolation, as are all transitions between the successive 3-day velocity field snapshots. Since vertical velocity information was not stored to

conserve space, the vertical integral of the horizontal velocity divergence is used to determine the vertical velocity at each time step.

The thousands of simulated particle trajectories are efficiently visualized with particle position probability maps. These maps are constructed by counting the number of times (including repetitions) that each particle trajectory is located in each of the 0.25° x 0.25° grid boxes over the North Atlantic domain. The counts are normalized by the total number of particle positions; thus, the map represents the probability that a particle occupies a particular box over the duration of the simulation. The map is similar to the concentration of Lagrangian particles.

2.4. Comparison of FLAME floats with BOUNCE floats

As mentioned earlier, no observational floats have been launched at the depth of the OW in the subpolar North Atlantic, hence the ability of simulated floats to capture subpolar to subtropical pathways cannot be directly evaluated. However, we can compare simulated deep float pathways in the subtropical North Atlantic with RAFOS floats launched as part of the BOUNCE program (Bower and Hunt, 2000a,b). From one deployment in 1994 and another in 1995, 30 total RAFOS floats were released within the DWBC between the Grand Banks and Cape Hatteras and tracked acoustically for 2 yrs. Of these 30 floats, 14 successfully tracked the pathways of the OW in the Gulf Stream region and 12 tracked upper LSW: the remaining four did not return data. Our focus here is on those 14 pathways tracked by isobaric RAFOS floats ballasted to 3000 m. As discussed thoroughly in Bower and Hunt (2000a,b) of the 11 floats that completed full missions (2 yrs in duration), nine had a final destination to the south of the Gulf Stream. Of those nine, nearly half remained close to the continental shelf, while the other half were in the ocean interior.

Simulated trajectories were produced from the FLAME output using the deep BOUNCE launch positions. Additionally, launch positions that differed from the BOUNCE launch location by ± 100 m in depth and by $\pm 1/12^\circ$ in the zonal and meridional directions were used. Since there were 14 deep BOUNCE floats, this launch strategy initialized 98 simulated floats for every 30 days over the 15 yrs of the FLAME model output, resulting in a total of 17,640 trajectories. Floats were simulated for 15 yrs and their positions were recorded daily, as in the observations. Trajectories of observed and simulated floats are shown in Fig. 2(A), where BOUNCE float pathways (black) are superposed on FLAME e-float pathways (red). The visual comparison is favorable: the simulated pathways show evidence of offshore detrainment upstream of Cape Hatteras on a spatial scale comparable to the observed pathways. Also, the along-DWBC pathways simulated by the floats are a fair match to those observed.

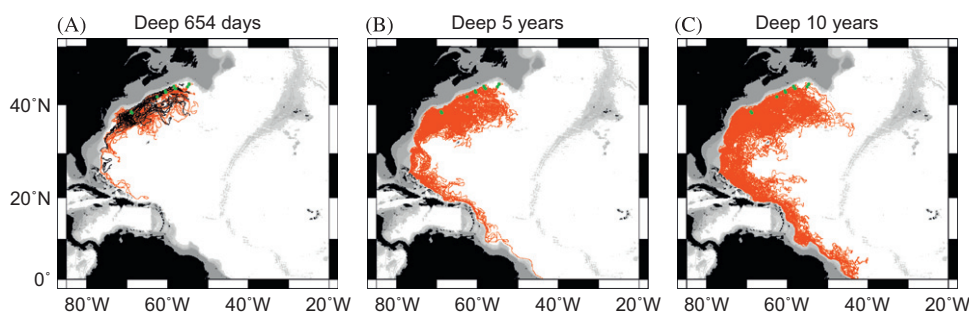


Fig. 2. Trajectories of observed and simulated floats: (A) Trajectories of the 14 deep RAFOS floats in the BOUNCE program (black) and 90 simulated floats, selected at random from an ensemble of 17,640 trajectories, from FLAME (red). The trajectory duration is 654 days, the average lifetime of the deep BOUNCE floats. The average pressure registered by the 14 deep BOUNCE floats is 3114 dbar. The launch locations of the floats are shown with green dots. (B) Trajectories of the 90 simulated floats shown in panel A, extended to 5 yrs. (C) Trajectories of the 90 simulated floats shown in panels B and B, extended to 10 yrs. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

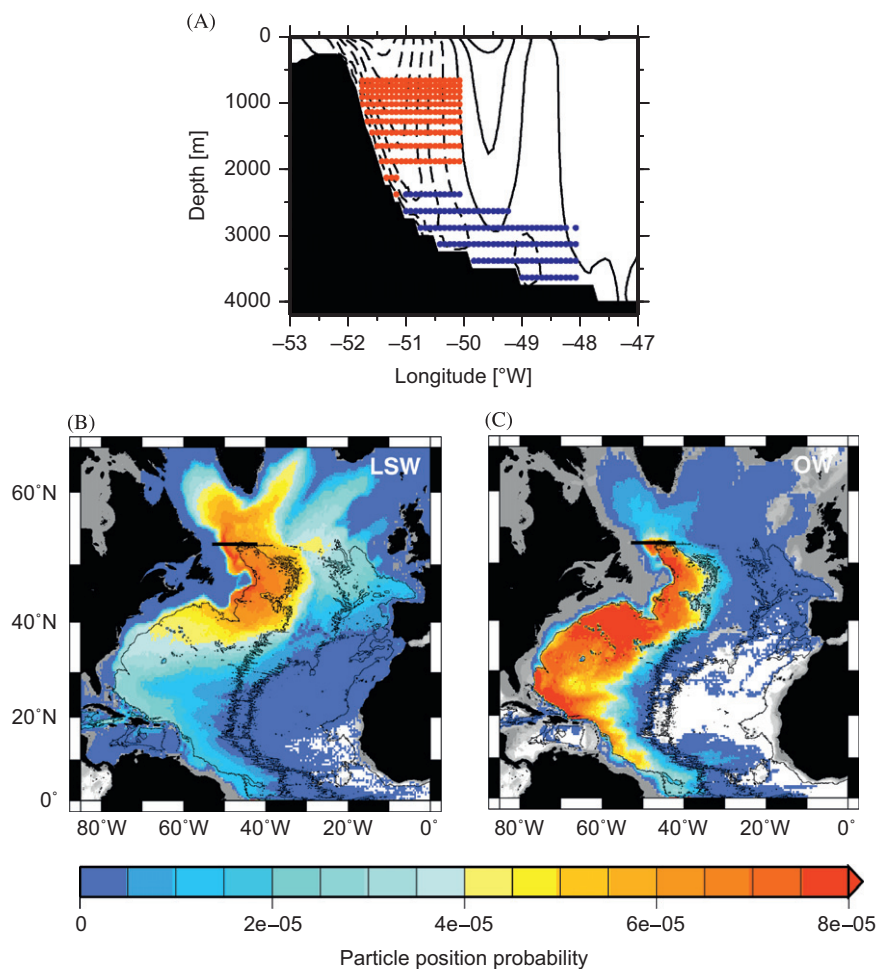


Fig. 3. Probability maps of the OW ($< 2.3^\circ\text{C}$) and LSW (between 3 and 4.5°C) floats launched at 53°N within the DWBC: (A) The mean meridional velocity at 53°N in the FLAME model is contoured with black solid (dashed) lines for positive (negative) values at 5 cm s^{-1} intervals. Launch positions of the 13,894 OW (blue) and 30,563 LSW (red) trajectories are shown with dots. (B) Probability map of all the LSW particles over the course of 50 yrs. (C) Probability map of all the OW particles after 50 yrs. On both maps, the 4000 m isobath is shown with a thin black line to denote the approximate offshore edge of the DWBC. The thick black line in panels B and C is the launch location shown in panel A.

A more quantitative comparison between the observed and simulated trajectories is made by applying the Kolmogorov–Smirnov statistical test specifically designed for Lagrangian data by van Sebille et al. (2009). The time-varying test statistic, D_n , is the instantaneous maximum difference between cumulative probability distributions computed for the scatter of observed and simulated floats at each time step. If the trajectories in both ensembles are identical, $D_n=0$; the maximum value of D_n is 1. The power of the van Sebille et al. (2009) test is quantified by performing Monte Carlo iterations to determine the confidence level, α , around the test statistic. If $\alpha < 0.05$, we reject the null hypothesis that the trajectory ensembles come from the same spatial distribution. Applying this test to the 14 BOUNCE floats and 17,640 particles in FLAME, the time average value of $D_n=0.26 \pm 0.05$ with a confidence level of $\alpha=0.92 \pm 0.08$. Therefore, the spatial distributions of BOUNCE and FLAME trajectories are statistically indistinguishable. This result is consistent with the application of the same statistical test comparing RAFOS floats in the Labrador and Newfoundland basins and the corresponding simulated trajectories from the FLAME model (Gary et al., 2011).

Recognizing that the deep BOUNCE floats were isobaric, we are also interested in whether the e-floats, which follow the full three-dimensional velocity field, exhibit significant depth variability. If so, we cannot be sure that the BOUNCE floats and the e-floats, despite similar spatial distributions, are measuring the same waters.

Using the 17,640 deep e-floats, the average vertical displacement from the initial launch depth is calculated to be $19 \pm 136\text{ m}$ over the first 654 days. The largest displacements occur at the end of the 654 days, where the displacements are $\sim \pm 200\text{ m}$. Given the relatively large vertical scales at the depth of the BOUNCE floats (3000 m), we conclude that the e-floats are sampling approximately the same waters as the BOUNCE floats did (overlooking the fact that the e-floats are in modeled water).

An obvious advantage of the simulated floats is that they are not restricted in number or in lifetime. Thus, to evaluate whether the simulated pathways follow the expected route of the overflow waters, the trajectory simulation was extended to 5 yrs (Fig. 2B) and then to 10 yrs (Fig. 2C). The float pathways show general movement equatorward, though any expectation of this movement occurring principally along the narrow DWBC corridor is not supported. The simulated floats, all launched within the DWBC, progress equatorward in a relatively broad swath along the western boundary. The degree to which the floats do or do not follow the DWBC in their equatorward transit is addressed in the following section.

3. Results

In this section, we examine the distribution of simulated floats from their launch in the DWBC at 53°N in the western subpolar

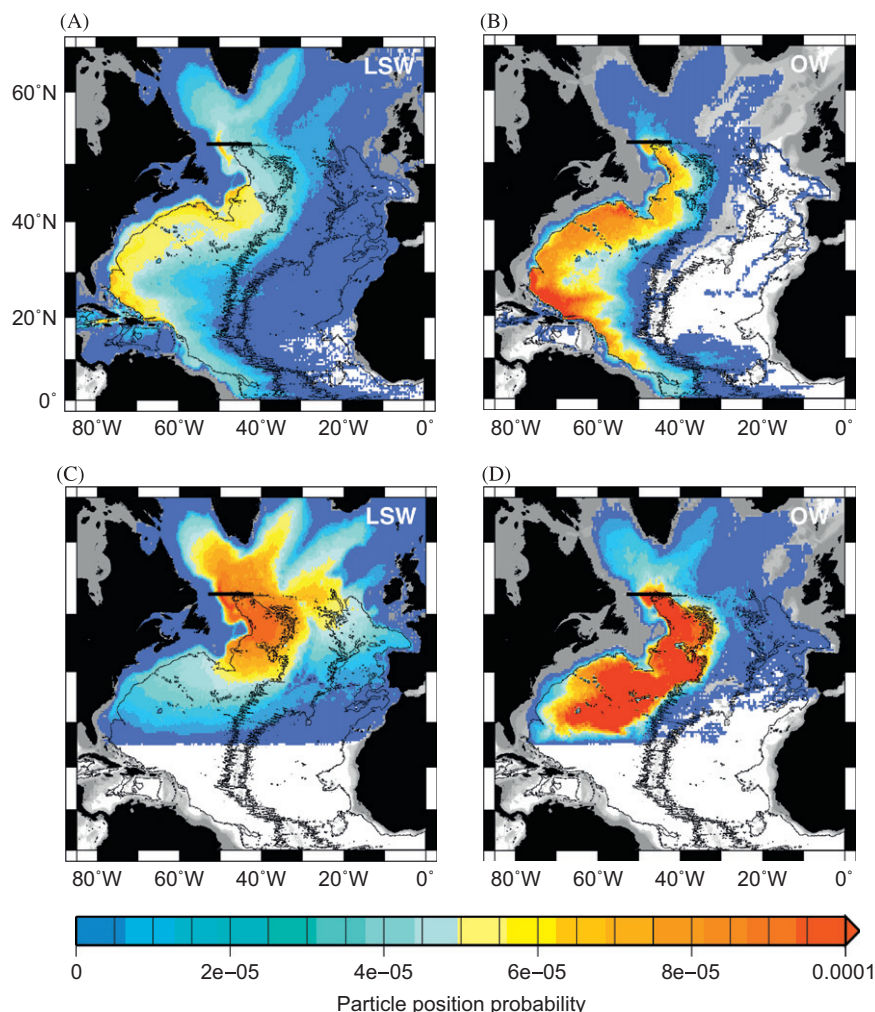


Fig. 4. Probability maps for trajectories sorted by arrival at 25°N. Trajectories that reach 25°N after 50 yrs are shown in (A) for 13,645 LSW particles and (B) for 10,957 OW particles. Trajectories that did not reach 25°N after 50 yrs are shown in (C) for 16,918 LSW particles and (D) for 2937 OW particles. On all maps, the 4000 m isobath is shown with a thin black line to denote the approximate offshore edge of the DWBC and the thick black line indicates the launch location of the trajectories.

North Atlantic. This launch site was selected because the floats in the ExPath observational program were deployed in the vicinity of this location. Furthermore, detailed measurements of the velocity in the DWBC have been made at 53°N (Fischer et al., 2010), thus facilitating a comparison between the model and observations. Finally, previous model simulations of LSW pathways used this launch site. Since our study of the OW pathways is in large part a comparative study with the LSW pathways, we opt to use the same launch site for the exploration of subpolar to subtropical pathways. Furthermore, to facilitate the comparison, all pathway simulations and subsequent analyses are conducted for both OW and LSW.

3.1. All LSW and OW pathways

To establish probable pathways for water parcels within the subpolar DWBC, sequential launches of floats are released at 53°N and tracked for 50 yrs. Float launch sites are superposed on the model's mean velocity field in Fig. 3(A). Waters between 3 and 4.5 °C at the time of launch were tagged as LSW parcels (marked in red in Fig. 3A), while waters < 2.3 °C were tagged as OW parcels (marked as blue in Fig. 3A). All releases were dynamic: a release was made only if the grid box containing the float was within the correct temperature range and if there was southward flow. From the collection of floats, probability maps

(described in Section 2) were produced for each water mass. The LSW probability map, similar to that presented in Bower et al. (2009), shows the relatively broad reach of the pathways: there is some recirculation back into the Labrador Sea, but that is mostly overshadowed by the equatorward progression of the parcels. Though the DWBC is indicated as a highly probable equatorward pathway just downstream of the launch site, it loses its preferential status before the Tail of the Grand Banks. Instead, the equatorward progression fills the basin from the western boundary to the Mid-Atlantic Ridge. The region mapped out by these parcels coincides with the large eddy-driven recirculation, as discussed above, and also bears a remarkable similarity to the map of CFC-11 inventory for Classical Labrador Sea Water produced from WOCE data collected from 1996 to 1998 (LeBel et al., 2008).

The probability map for the OW has some notable contrasts with the LSW map: there is no appreciable recirculation of these parcels back into the Labrador Sea; the concentration of the parcels to the west of the Mid-Atlantic Ridge is nearly complete; and the equatorward progress is much greater. The similarity between the two maps is also of note: as with LSW, the southward progression of OW is not bound to the DWBC, but is instead distributed throughout the western basin of the North Atlantic. The preference for the DWBC as a conduit for this deep water mass is quickly lost downstream. As noted above for LSW, the OW

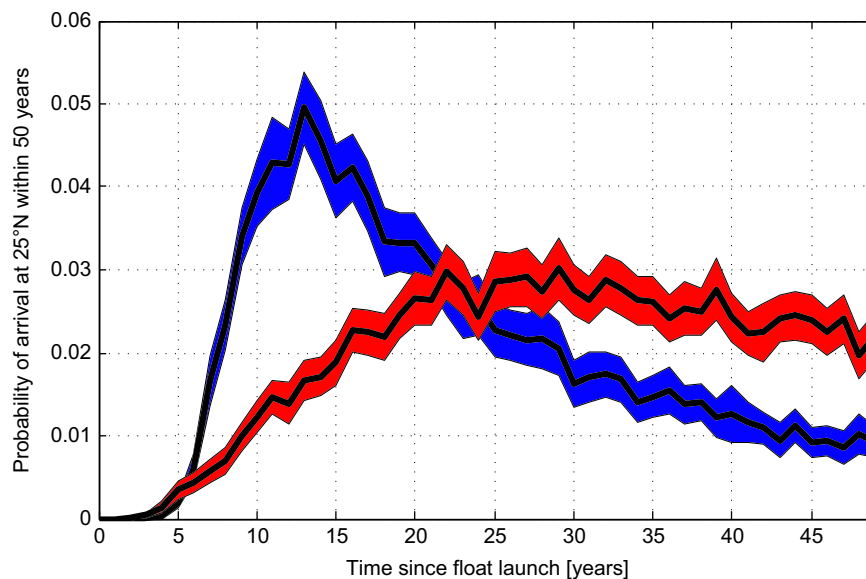


Fig. 5. Transit time distributions (TTDs) of the OW and LSW floats' arrival at 25 °N shown in the probability maps of Fig. 4(A) and (B) (black lines). Only the 13,645 LSW particles and 10,957 OW particles that made it to 25 °N within 50 yrs were used to construct these TTDs. Shading (blue for OW and red for LSW) indicates the one standard deviation envelope for each TTD computed with a Monte Carlo simulation. This envelope was estimated by drawing 1000 randomly-sized subsets from each trajectory ensemble, computing the TTD for each subset, and then computing the standard deviation of the number of floats that arrive at 25 °N in each temporal interval. The size of the envelopes for 1000 iterations (shown) is the same as for 100 iterations, an indication of convergence for the Monte Carlo simulation (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

probability map produced from the FLAME trajectories compares favorably with the CFC-11 inventory maps for Iceland Scotland Overflow Waters and for Denmark Straits Overflow Water (LeBel et al., 2008).

3.2. LSW and OW pathways that reach 25°N

Since the focus of our paper is on the export of water masses out of the subpolar gyre as part of the large-scale overturning, we restrict our attention in this section to a subset of those parcels that are launched in the DWBC at 53 °N: plotted in Fig. 4(A), (B) is the probability distributions for those LSW and OW parcels shown in Fig. 3(B), (C) that reach 25 °N in 50 yrs. Approximately 79% and 45% of the OW and LSW trajectories, respectively, reach 25 °N within 50 yrs. With this restriction, the distributions become more similar as fewer pathways lead to the Labrador Sea for the LSW parcels. Again, the OW parcels are more restricted to the western basin and they show a larger concentration at points further south along the western boundary compared to the LSW parcels. In both maps, however, the probability of finding an LSW or OW parcel in the interior of the subtropical basin is as large as finding it in the DWBC, despite the fact that all floats were released upstream in the DWBC.

Maps of the distribution of all of those parcels in Fig. 3(B), (C) that have been excluded in Fig. 4(A),(B) (in other words, all those parcels that did not make it to 25 °N in 50 yrs) are shown in Fig. 4(C), (D). For LSW, parcels that do not reach 25 °N after 50 yrs are found predominantly in the subpolar basin and, to a lesser extent, in the eastern subtropical basin. In contrast, the OW floats that do not reach 25 °N are located in the recirculation gyre of the subtropical basin. Apparently, these parcels are southward-bound, but the time scale for their transit exceeds 50 yrs. Thus, from these simulations, it appears that a significant fraction of LSW in the subpolar DWBC recirculates in the subpolar basin, whereas most, if not all, of the OW in the subpolar DWBC is exported equatorward.

3.3. LSW and OW age distributions

To quantify the differences in the export of LSW and OW within the context of FLAME, the ages of the simulated floats once they cross 25 °N was computed. Age was computed as time since launch. The distribution of these ages (Fig. 5) reveals that the OW are, in general, younger than LSW at this latitude, with the average age of 22 ± 11 yrs for the former and 30 ± 11 yrs for the latter. The younger ages for OW are attributable to faster pathways since the two water masses were tagged at the same release location. The later arrival of LSW, compared to OW, is attributable to (1) more recirculation within the Labrador Sea that delays the time until export and (2) larger-scale recirculation gyres adjacent to the Gulf Stream/North Atlantic Current that create longer (and hence slower) pathways. This result is consistent with water mass ages inferred from tritium/He³ measurements in the DWBC of the North Atlantic (Doney and Jenkins, 1994): ages at intermediate depths in the North Atlantic are greater than those in the deepest waters of the boundary current. Lozier (1999) showed that the oldest waters reside at the depth where the recirculation gyres are their largest in extent. Hence, the age difference is dominated by circulation differences rather than by upstream source water changes. We note here that topographic constraints also play a role in the age difference between LSW and OW: pathways at the OW level are restricted to the western basin by the presence of the Mid-Atlantic Ridge, a restriction that does not apply to LSW pathways.

4. Summary

This analysis of the export pathways of deep water from the subpolar gyre to the subtropics in the North Atlantic has focused on OW pathways. Motivated by previous observational and modeling studies that demonstrated interior pathways for LSW, here, in the absence of relevant Lagrangian observations, we rely on the simulation of OW pathways in the context of an ocean general circulation model.

From this analysis of simulated OW pathways, and their comparison with observed and simulated LSW pathways, we suggest that OW in the North Atlantic, like LSW, is not restricted to the DWBC in its equatorward transport. Recirculations allow for interior pathways that substantially contribute to the export. Thus, a measure of DWBC transport variability cannot be safely equated to transport variability of the lower limb of the AMOC.

From this analysis, we also suggest that the spread of OW pathways contrasts with the spread of LSW pathways in the North Atlantic: OW export from the subpolar gyre is primarily equatorward, its pathways are restricted to the western basin and its mean time of arrival at 25N is ~22 yrs. LSW pathways reveal a strong recirculation within the Labrador Sea as well as equatorward progression, they spread throughout the entire North Atlantic and their arrival at 25-N takes on average ~30 yrs.

Finally, we note that our summary is purposely couched as suggestions rather than conclusions since this study of OW export pathways relies solely on simulated pathways. Observational pathways may differ from the simulated pathways presented herein if the model's mean and time-varying flow are sufficiently different than that observed. Though the model–observation comparisons that have been made are favorable, because of the sparse observational database for the deep North Atlantic, those comparisons are restricted to just a few locales. In addition to the rather general caution about a mismatch between the modeled and actual deep North Atlantic circulation, a more specific caution is added: the OW pathways traced here were based on fluid particles released in the southward-flowing subpolar DWBC within waters with temperatures that matched observed OW temperatures. However, upstream conditions for the modeled OW that differ significantly from observed OW conditions may considerably impact their downstream pathways. Thus, until there is an opportunity to test this set of simulated floats with observations, the characteristics of OW pathways revealed in this study should be placed in the context of these cautions.

Acknowledgments

The authors gratefully acknowledge the U.S. National Science Foundation for the support of this work. Thanks are also extended to Claus Böning and Arne Biastoch (GEOMAR, Kiel) for access to the FLAME model output. All authors trace their interest in and affinity for the Lagrangian view of the ocean to Dr. H. Thomas Rossby. It is hard to overstate the influence that acoustically tracked subsurface floats have had on our current understanding of ocean circulation. Forged from Tom's creative, intellectual and technical efforts, these floats have revealed a much more complex and thus much more interesting ocean than previously thought. For that alone we are grateful to Tom, but our gratitude also extends to his mentoring, his collegiality and above all his limitless enthusiasm for uncovering the workings of the ocean.

References

Beckmann, A., Döschner, R., 1997. A method for improved representation of dense water spreading over topography in geopotential-coordinate models. *J. Phys. Oceanogr.* 27, 581–591.

Biastoch, A., Böning, C.W., Getzlaff, J., Molines, J.M., Madec, G., 2008. Causes of interannual–decadal variability in the meridional overturning circulation of the midlatitude North Atlantic Ocean. *J. Climate* 21, 6599–6615.

Böning, C.W., Scheinert, M., Dengg, J., Biastoch, A., Funk, A., 2006. Decadal variability of subpolar gyre transport and its reverberation in the North Atlantic overturning. *Geophys. Res. Lett.* 33, L21S01 <http://dx.doi.org/10.1029/2006GL026906>.

Bower, A., Hunt, H.D., 2000a. Lagrangian observations of the deep western boundary current in the North Atlantic Ocean. Part I: large-scale pathways and spreading rates. *J. Phys. Oceanogr.* 30, 764–783.

Bower, A., Hunt, H.D., 2000b. Lagrangian observations of the deep western boundary current in the North Atlantic Ocean. Part II: the Gulf Stream–deep western boundary current crossover. *J. Phys. Oceanogr.* 30, 784–804.

Bower, A.S., Lozier, M.S., Gary, S.F., 2011. The export of Labrador Sea Water from the subpolar North Atlantic: a Lagrangian perspective. *Deep-Sea Res.* 58, 1798–1818.

Bower, A.S., Lozier, M.S., Gary, S.F., Böning, C., 2009. Interior pathways of the Atlantic meridional overturning circulation. *Nature* 39, 1800–1817.

Boyer, T.P., & Levitus, S. (1997). Objective Analyses of temperature and salinity for the world ocean on a 1/4 grid. NOAA/NESDIS Atlas 11. Washington D.C.: U.S. Gov. Printing Office.

Brauch, J.P., Gerdes, R., 2005. Response of the northern North Atlantic and Arctic oceans to a sudden change of the North Atlantic oscillation. *J. Geophys. Res.* 110, C11018 <http://dx.doi.org/10.1029/2004JC002436>.

Burkholder, K.C., Lozier, M.S., 2011. Subtropical to subpolar pathways in the North Atlantic. *J. Geophys. Res.—Oceans* 116, C07017 <http://dx.doi.org/10.1029/2010JC006697>.

Doney, S.C., Jenkins, W.J., 1994. Ventilation of the deep western boundary current and abyssal western North Atlantic: estimates from tritium and the distributions. *J. Phys. Oceanogr.* 24, 638–659.

Fischer, J., Schott, F.A., Dengler, M., 2004. Boundary circulation at the exit of the Labrador Sea. *J. Phys. Oceanogr.* 34, 1548–1570.

Fischer, J., Visbeck, M., Zantopp, M., Nunes, N., 2010. Interannual to decadal variability of outflow from the Labrador Sea. *Geophys. Res. Lett.* 37, L24610 <http://dx.doi.org/10.1029/2010GL045321>.

Gary, S.F., Lozier, M.S., Böning, C., Biastoch, A., 2011. Deciphering the pathways for the deep limb of the meridional overturning circulation. *Deep-Sea Res.* 58, 1781–1797.

Getzlaff, K.C., Böning, C.W., Dengg, J., 2006. Lagrangian perspectives of deep water export from the subpolar North Atlantic. *Geophys. Res. Lett.* 33, L21S08 <http://dx.doi.org/10.1029/2006GL026470>.

Holland, W.R., Rhines, P.B., 1980. An example of eddy induced ocean circulation. *J. Phys. Oceanogr.* 10, 1010–1031.

Hüttl-Kabus, S., Böning, C.W., 2008. Pathways and variability of the off-equatorial undercurrents in the Atlantic Ocean. *J. Geophys. Res.* 113, C10018 <http://dx.doi.org/10.1029/2007JC004700>.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al., 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteorol. Soc.* 77 (3), 437–471.

LeBel, D.A., Smethie, W.M., Rhein, M., Kieke, D., Fine, R.A., Bullister, J.L., Min, D.-H., Roether, W., Weiss, R.F., Chantal, A., Smythe-Wright, D., Jones, E.P., 2008. The distribution of CFC-11 in the North Atlantic during WOCE: inventories and calculated water mass formation rates. *Deep-Sea Res.* 55, 891–910.

Levitus, S., Antonov, J., Boyer, T.P., 1994a. Interannual variability of temperature at 125 m depth in the North Atlantic Ocean. *Science* 266, 96–99.

Levitus, S., Boyer, T.P., & Antonov, J., 1994b. World Ocean Atlas, vol. 4, Temperature NOAA Atlas NESDIS 4. Washington D.C.: U.S. Government Printing Office, p. 117.

Lozier, M.S., 1997. Evidence for large-scale eddy-driven gyres in the North Atlantic. *Science* 277, 361–364.

Lozier, M.S., 1999. The impact of mid-depth recirculations on the distribution of tracers in the North Atlantic. *Geophys. Res. Lett.* 26, 219–222.

Lozier, M.S., Owens, W.B., Curry, R.G., 1995. The climatology of the North Atlantic. *Prog. Oceanogr.* 36, 1–44.

Lozier, M.S., Riser, S.C., 1989. Potential vorticity dynamics of boundary currents in a quasigeostrophic ocean. *J. Phys. Oceanogr.* 19, 1373–1396.

Lozier, M.S., Riser, S.C., 1990. Potential vorticity sources and sinks in a quasigeostrophic ocean: beyond western boundary currents. *J. Phys. Oceanogr.* 20, 1608–1627.

Pacanowski, R.C., 1996. MOM 2 Documentation User's Guide and Reference Manual. NJ: GFDL/NOAA, Princeton.

Rhines, P.B., Young, W.R., 1982. Homogenization of potential vorticity in planetary gyres. *J. Fluid Mech.* 122, 347–367.

Schott, F.A., Zantopp, R., Stramma, L., Dengler, M., Fischer, J., Wibaux, M., 2004. Circulation and deep-water export at the western exit of the subpolar North Atlantic. *J. Phys. Oceanogr.* 34, 817–843.

Stommel, H., 1958. The abyssal circulation. *Deep-Sea Res.* 5, 80.

van Sebille, E., Leeuwen, P.J. v., Biastoch, A., Barron, C.N., De Ruijter, W.P.M., 2009. Lagrangian validation of numerical drifter trajectories using drifting buoys: application to the Agulhas region. *Ocean Modelling* 29, 269–276.