Subtropical to subpolar pathways in the North Atlantic: Deductions from Lagrangian trajectories

Kristin C. Burkholder[1] and M. Susan Lozier[1]

Received 1 October 2010; revised 6 May 2011; accepted 16 May 2011; published 20 July 2011.

[1] Surface waters of the Gulf Stream and North Atlantic Current are thought to replenish deep water formation sites at high latitudes with warm and salty subtropical waters, thereby closing the large-scale meridional overturning circulation. In recent studies of this subtropical to subpolar throughput, far fewer surface drifters were transported from the subtropical to subpolar gyre than expected on the basis of Eulerian estimates of intergyre exchange. Here, in an attempt to reconcile these Lagrangian observations with the Eulerian-based expectation of significant surface throughput, synthetic drifters launched within an eddy-resolving ocean general circulation model are used to examine Lagrangian pathways from the subtropical to subpolar gyre. The results of this study indicate that drifters in the observational record are limited in their ability to measure intergyre exchange and its temporal variability by their short lifetimes, their variable launch locations, and, importantly, their inability to follow the 3-D flow field. Synthetic floats launched within the ocean model and advected with the 3-D flow field indicate that subtropical to subpolar exchange in the North Atlantic is primarily located subsurface; while less than 5% of floats launched at 15 m reach the eastern subpolar gyre within 4 years, close to 30% of drifters launched at 700 m do so. The transport of subsurface waters to high latitudes is shown to occur primarily along density surfaces as they shoal northward toward subpolar latitudes.

Citation: Burkholder, K. C., and M. S. Lozier (2011), Subtropical to subpolar pathways in the North Atlantic: Deductions from Lagrangian trajectories, *J. Geophys. Res.*, *116*, C07017, doi:10.1029/2010JC006697.

1. Introduction

[2] The traditional "conveyor belt" paradigm depicts the meridional overturning circulation in simplistic terms: warm surface waters transported to high-latitude regions of deep convection cool and sink, then follow subsurface pathways equatorward until they upwell to the surface and return to high latitudes [*Stommel*, 1958; *Gordon*, 1986]. It is generally understood that the surface limb of this overturning circulation transports warm surface waters via the Gulf Stream (GS) and North Atlantic Current (NAC) in a continuous path from the subtropical to the subpolar basin, an image supported by the visual connectivity between the mean surface velocity and sea surface temperature fields of the North Atlantic (as seen in model fields shown in Figures 1a and 1b). Estimates of the magnitude of this subtropical to subpolar throughput range from ~13 to 20 Sv [*Hall and Bryden*, 1982; *Roemmich and Wunsch*, 1985; *Gordon*, 1986; *Schmitz and McCartney*, 1993; *Ganachaud*, 2003; *Cunningham et al.*, 2007; *Willis*, 2010], which is roughly 20–25% of the overall transport by the upper layers of the Gulf Stream [*Brambilla and Talley*, 2006] (hereinafter referred to as BT). However, though the concept of a strong and continuous transport of surface waters from the GS to the NAC appears robust in the mean fields, Lagrangian depictions of the GS/NAC system suggest a much weaker connection between the two currents. In their study of North Atlantic surface drifters that passed through a box surrounding the GS's seaward extension (78–48°W, 35–47°N), BT revealed a lack of connectivity between the subtropical and subpolar basins: though 273 drifters passed through the GS box between 1990 and 2002, only 1 drifter entered the subpolar gyre. A later study of the subtropical to subpolar exchange [*Hakkinen and Rhines*, 2009] (hereinafter referred to as HR) included surface drifter launches through 2007 with similar results: though HR reported an increase in the number of subtropical drifters reaching the subpolar region between 2002 and 2007, the number that reached 53°N (3%) was still far below the number expected to reach the subpolar gyre on the basis of expectations of a strong surface throughput. To explore further the apparent lack of connectivity between the surface waters of the Gulf Stream and those of the eastern subpolar gyre, this study analyzes synthetic drifters launched in an ocean general circulation model (OGCM). Background for this study is presented in section 2, the model used for this study and a description of the methods used for analysis are described in

[1]Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, North Carolina, USA.

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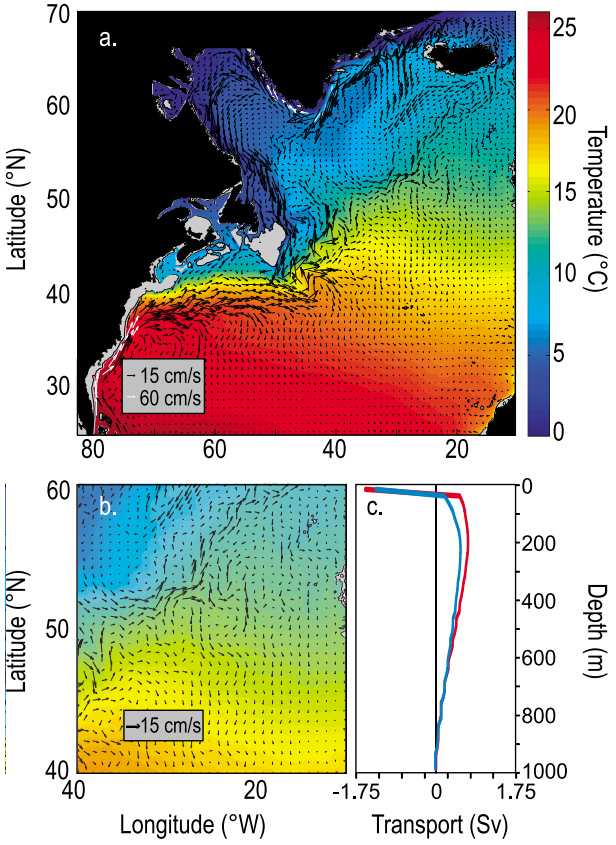


Figure 1. (a) Mean velocity field superposed on the mean temperature field at 15 m in FLAME. Temperature is shown at the full 1/12° resolution while velocity is averaged in 1° × 1° bins. Velocities greater than 50 cm/s are shown by white arrows; all other velocities are shown by black arrows. Bathymetry less than 100 m is shaded gray. (b) As in Figure 1a but zoomed in to highlight velocities and temperatures in the northeastern North Atlantic. (c) Mean zonally averaged meridional transport between (red) 40°N – 50°N and (blue) 52°N –54°N in FLAME. Transports are calculated in 25 m intervals. Total transport over the upper 1000 m between 40°N and 50°N and at 53°N are 13.0 and 9.8 Sv, respectively.

section 3, results follow in section 4, and a summary and concluding remarks are presented in section 5.

2. Background

[3] In their exploration of the limited intergyre exchange exhibited by surface drifters, BT offered four hypotheses as to why so few drifters were transported to high latitudes by the GS/NAC system: (1) limited drifter coverage and short drifter lifetimes could have biased the observed amount of exchange, (2) the net southward Ekman transport induced by the strong westerly winds in the region could have restricted the northward transport of the drifters as they neared the subpolar gyre, (3) the drifters, restricted to 15 m and thus prevented from following the true 3-D pathways which occur near the frontal zone at the intergyre boundary [*Qiu and Huang*, 1995], may not have accurately measured the true intergyre exchange, and (4) drifters could have been biased by a preferential inclusion in cyclonic eddies. As described below, the first two hypotheses were tested by BT. In section 4, we will address the third hypothesis. Though the fourth hypothesis will not be explicitly examined in this paper, it should be noted that the OGCM used in this study is fully eddy-resolving and hence contains both cyclonic and anticyclonic eddies in the region of the Gulf Stream. As described in section 3, care is taken in all model tests to ensure that bias based on launch location is removed.

[4] BT calculated the mean lifetime of drifters in the observational record to be 271 ± 260 days, far short of their estimate (400–500 days) of the time required for a drifter launched in the Gulf Stream region to reach the Iceland basin. BT studied the effect of such a short drifter lifetime using examinations of both observational and synthetic trajectories. In one test, BT linked observed trajectories end-to-end until their combined lifetimes totaled more than 600 days. With 600 day lifetimes, 4%–5% of linked drifters reached the subpolar gyre. In a second examination, BT launched synthetic drifters in the area bounded by 78°W–48°W and 35°N–47°N and then advected the drifters forward in time using both mean and turbulent velocity fields. Their mean surface velocity field was constructed using surface drifter trajectories averaged in 1/2° bins over the period 1990–2002. A time-varying field was created from this mean field by adding a turbulent velocity component for each bin that was calculated from the standard deviation of the velocity for that bin. Advection of the drifters through the mean (turbulent) field resulted in 1% (6%) of drifters reaching the subpolar gyre after 3 years, a slight increase relative to the 1/273 drifters reaching 53°N with realistic lifetimes in the observational record.

[5] Advection through the mean and turbulent velocity fields was also used by BT to examine the effect of Ekman drift on the number of drifters reaching the subpolar gyre. By removing the Ekman component of the mean (turbulent) velocity field, BT noted an increase in the amount of intergyre exchange by 5% (6%). Interestingly, the ~5% decrease in intergyre exchange related to Ekman drift was found to be roughly proportional to the increase in intergyre exchange resulting from adding a turbulent component to the velocity field (~5%).

[6] In their study of surface drifter trajectories between 1990 and 2007, HR offered another explanation for the small number of surface drifters observed to reach high latitudes in the BT study. Following on the work of *Rhines and Schopp* [1991], HR proposed that the zero of the wind stress curl, a dynamical boundary between the subtropical and subpolar gyres, dictated the extent to which subtropical drifters were able to penetrate into high-latitude waters: when the line of zero wind stress curl was essentially zonal, it created a boundary that impeded the northward progress of surface drifters. Conversely, when the line increased its meridional tilt, it allowed for an expansion of the subtropical gyre into the northeastern Atlantic and essentially connected the Gulf Stream area and the entry to the Nordic seas. HR concluded that this connection represented a new pathway for subtropical waters to reach high latitudes and suggested that the opening of this pathway was responsible for the observed increase in the number of drifters transported from

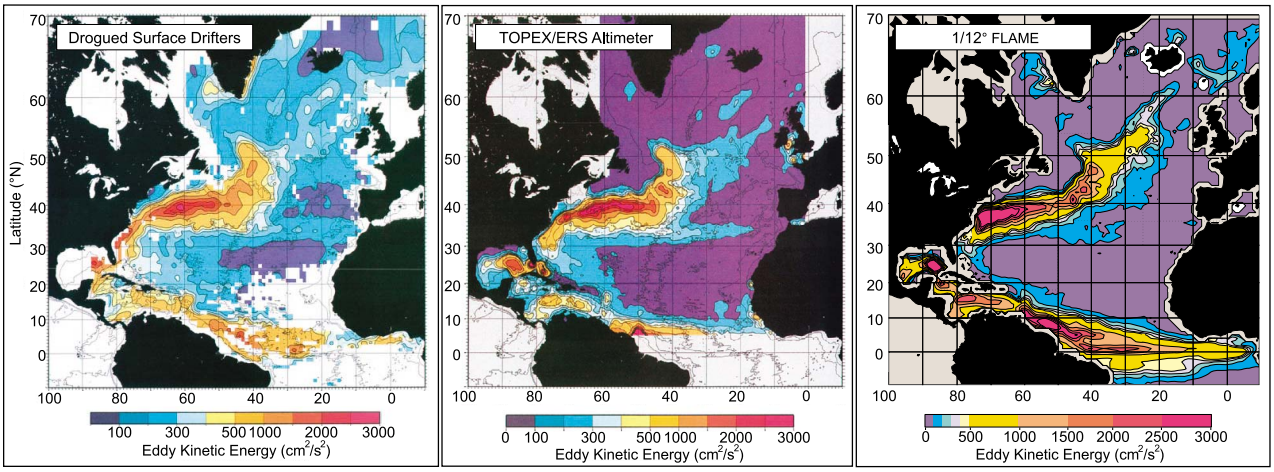


Figure 2. Comparison of EKE fields from surface drifters and satellite measurements with the EKE field from FLAME. All EKE fields were calculated using 1° × 1° bins. Altimeter data analyzed by *Fratantoni* [2001] were averaged over 1992–1998 and calculated from the geostrophic velocity field. Drifter and FLAME EKE fields were averaged over 1990–1999 and calculated from the full velocity fields. The Ekman contribution to the drifter derived EKE fields was estimated to be less than 20 cm^2/s^2 over the entire North Atlantic [*Ducet et al.*, 1999]. Drifter and satellite fields are reproduced from *Fratantoni* [2001] by permission of the American Geophysical Union.

the "Gulf Stream box" to 53°N between 1991 and 2007, albeit from only 1/101 (1%) to 8/270 (3%). Although the number of surface drifters reaching high latitudes was small even when the pathway was open, these results raise the possibility that the small amount of exchange measured by drifters in the 1990s and early 2000s was not representative of the "true" intergyre exchange at the surface but was rather a snapshot of a temporally variable system.

[7] In summary, the small amount of subtropical to subpolar exchange indicated by North Atlantic surface drifters has previously been linked to an underestimate caused by short drifter lifetime and/or a dynamical constraint imposed by Ekman drift. Additionally, it has been suggested that the amount of subtropical waters reaching high latitudes is temporally variable because of shifts in the wind field. Left unexplored from the observational studies of BT and HR are the possible bias in intergyre exchange introduced by drifter launch locations and the possible bias introduced by the drifters' inability to move in 3-D. To examine these possibilities, we analyze synthetic trajectories produced from an eddy-resolving general circulation model. Although the model is not a substitute for the actual drifter-observed exchange, it can be used to place these rather sparse measurements in context. Furthermore, the model affords the opportunity to examine subsurface pathways of exchange.

[8] Two fundamental questions will be addressed with this study: (1) Can surface drifters from the observational record provide an accurate assessment of surface intergyre exchange and its temporal variability? and (2) Is the amount of intergyre exchange at the surface representative of the overall subtropical to subpolar exchange? With this second question, we stress that our intent is not to suggest or establish the absolute Lagrangian exchange that would be congruent with Eulerian measures but rather to investigate the depth dependence of intergyre exchange in a Lagrangian framework.

3. Methods

[9] This study utilizes 15 years of output from a realization of the 1/12° resolution Family of Linked Atlantic Model Experiments (FLAME) ocean general circulation model [*Böning et al.*, 2006; *Biastoch et al.*, 2008]. FLAME has 45 z coordinate vertical levels spaced 10 m apart near the surface that spread to a maximum spacing of 250 m at depth. The horizontal bounds of the model are 100°W–16°E and 18°S–70°N. Following a 10 year spin-up, the particular model realization analyzed in this study was forced at the surface with monthly averaged National Centers for Environmental Prediction and National Center for Atmospheric Research anomalies superposed on European Center for Medium-Range Weather Forecasts monthly climatologies. The available model output spans the years 1990–2004 with a 3 day temporal resolution.

[10] A comparison of the mean surface velocity field from FLAME with that calculated from North Atlantic surface drifters [*Fratantoni*, 2001; *Brambilla and Talley*, 2006; *Flatau et al.*, 2003] demonstrates that FLAME gives a reasonable representation of the surface circulation of the North Atlantic. Mean velocities at 15 m in the model (Figures 1a and 1b) recreate the major surface circulation features measured by drifters, including a strong Gulf Stream with peak velocities in excess of 2 m/s and a retroflection in the northwest corner of the NAC (~40°W, 50°N). Furthermore, mean zonally averaged meridional transports between 40°N and 50°N and between 52°N and 54°N (Figure 1c) total 13.0 and 9.8 Sv, respectively, in the upper 1000 m, which, as described previously, falls within the range (13–20 Sv) of observational estimates. Mean eddy

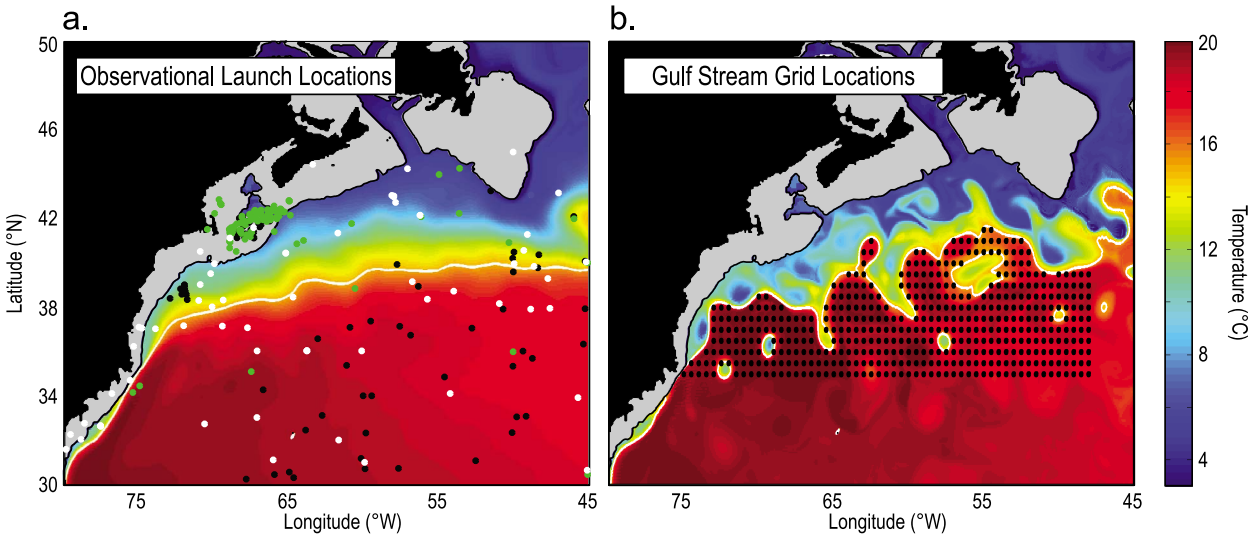


Figure 3. (a) Launch locations of observational drifters in the northwestern subtropical gyre superposed on the climatological mean temperature field at 200 m in FLAME. Black, green, and white dots indicate drifters launched between 1991 and 1995, 1996 and 2000, and 2001 and 2005, respectively. The white line indicates the climatological position of the 15°C isotherm at 200 m. (b) Sample launch locations of drifters launched within the Gulf Stream grid launching scheme superposed over the temperature field at 200 m at the time of the launch. The white line indicates the position of the 15°C isotherm at the time of the launch. In both plots, bathymetry less than 200 m is shaded gray.

kinetic energy (EKE) fields at 15 m from FLAME also compare favorably with EKE fields calculated from altimetry data and surface drifter velocity fields [*Fratantoni*, 2001] (Figure 2). Although small differences exist between the FLAME EKE fields and those of either observational measure, those differences are the same order of magnitude as the differences between the two observational records themselves. As such, we conclude that FLAME gives a reasonable representation of near-surface circulation and can be considered a reliable tool for this analysis.

[11] In this study, FLAME velocity fields are used to produce synthetic trajectories from two launch location schemes, shown in Figure 3. Details regarding the computation of these synthetic trajectories are described in *Gary et al.* [2011] and as such are not reproduced here. The first launch scheme, hereafter referred to as the "observational launch scheme," consists of drifter launch locations extracted from the Atlantic Oceanographic and Meteorological Laboratory, NOAA, global Lagrangian drifting buoy database south of 45°N (Figure 3a). The set of launch locations from 1990 to 2002 matches those used by BT; the set from 1991 to 2007 matches those used by HR. Unless otherwise noted, synthetic drifters at these locations are launched at 15 m in order to compare with the drifters in the observational record that were drogued to 15 m to prevent wind slippage [*Niiler et al.*, 1995; *Pazan and Niiler*, 2001]. For the second launch scheme (referred to as the "Gulf Stream grid") drifters are spread at 1/2° intervals within the Gulf Stream box (78°W–48°W, 35°N–47°N) utilized in the studies of BT and HR. However, to ensure that only subtropical drifters are included in this launch, a dynamical launch strategy is employed. Drifters are launched within this box only if they are located south of the Gulf Stream front, as defined by the position of the 15°C isotherm at 200 m [*Fuglister and Voorhis*, 1965] on the day of the launch. Thus, the launch pattern is temporally variable; one such pattern is depicted in Figure 3b. Finally, drifters launched with the two sampling schemes described above are considered to have entered the subpolar region when they cross 53°N. The high-latitude position of this boundary was chosen for consistency with previous studies (BT; HR) and to ensure that floats carried northward to subpolar latitudes are not mistakenly counted as "subpolar" prior to recirculating back to low latitudes. As will be shown in section 4, an inconsequential number of floats return to the subtropical gyre after crossing this latitude. Finally, we emphasize that our intent is to study how waters of subtropical origin reach the subpolar region. Toward that end, we consider cross-gyre exchange to have occurred when waters of subtropical origin reach the subpolar latitudes. Although some *cross-frontal* exchange may take place as part of this transformation, we are not strictly analyzing the movement of floats or water parcels across a front.

4. Results

[12] In this section, each of the questions posed in section 2 is investigated in turn within the context of the FLAME model.

4.1. Can Surface Drifters From the Observational Record Provide an Accurate Assessment of Surface Intergyre Exchange and Its Temporal Variability?

[13] In this section, we use synthetic launches in FLAME to assess the ability of drifters within the observational record to accurately represent the amount of subtropical to

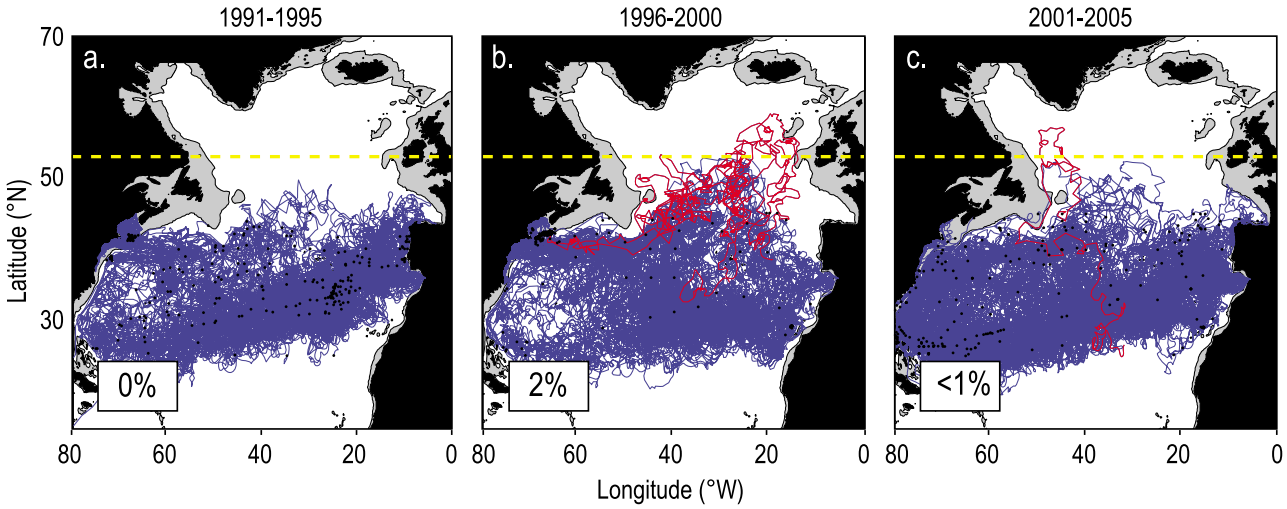


Figure 4. Synthetic drifters launched in FLAME at the observational launch locations (Figure 3a) for each of the three HR pentads (a) 1991–1995, (b) 1996–2000, and (c) 2001–2005 and advected through the instantaneous 15 m horizontal velocity fields from that pentad for 4 years. Transport values at 53°N for the three HR pentads are 10.35, 9.96, and 9.13 Sv, respectively. Red trajectories indicate those that crossed 53°N (yellow dashed line). Blue trajectories indicate drifters that remained south of 53°N. The percentage of drifters crossing 53°N is indicated in the white box. Bathymetry less than 500 m is shaded gray.

subpolar gyre exchange at the surface. In particular, the effects of (1) variable launch locations, (2) the constraint of drifter movement to a 2-D surface, and (3) Ekman drift are considered. In short, we demonstrate in sections 4.1.1 and 4.1.2 that the observational drifters, limited by their variable launch locations and inability to move in 3-D, are incapable of representing the nature of subtropical to subpolar gyre exchange. However, prior to addressing these three effects, we first assess exchange similarity between synthetic and observational drifters at 15 m and reexamine the impact of short drifter lifetime on intergyre exchange, previously investigated by BT, within FLAME. Our aim in repeating BT's analysis is to provide some model validation and to set the context for the following analyses. To that end, synthetic drifters were launched from the observational launch locations of three HR pentads (1991–1995, 1996–2000, and 2001–2005) and integrated forward through the time-varying 15 m horizontal velocity fields for 4 years. As seen in Figure 4, despite lifetimes of 4 years, these synthetic drifters exhibit very little intergyre exchange regardless of launch location or forcing. In fact, less than 2.5% of drifters reach 53°N within 4 years in all pentads (Figure 4), consistent with the results of BT and HR where minimal exchange was found. A more direct comparison with the results of BT is given by the statistics of synthetic trajectories with 600 day lifetimes, where less than 1.1% of drifters reach 53°N in all pentads. This exchange is slightly smaller than the amount of intergyre exchange of the 600 day drifters in the BT study (4%–5%), however the difference is likely due in part to the artificial linkage of trajectories separated in both space and time by BT. However, though small differences exist, the conclusion reached by this simple modeling experiment is the same as that reached by BT: although short drifter lifetime may cause a slight underestimation of the amount of intergyre exchange at 15 m, the degree of connectivity between the surface waters in the subtropical and subpolar gyres appears to be small.

4.1.1. What Are the Effects of Variable Launch Locations and the Constraint of Drifter Movement to a 2-D Surface on the Measure of Intergyre Exchange?

[14] Synthetic drifters are next used to examine the possibility that the drifter-observed exchange is biased by variability in launch locations and the fact that indications of temporal variability in that exchange are likewise biased. HR concluded from changes in surface drifter trajectories between 1990 and 2007 that a new subtropical to subpolar pathway had opened, allowing increasing amounts of subtropical water to reach the subpolar basin. However, the surface drifters considered by HR had varying launch locations, which may have artificially increased or decreased the amount of exchange measured from one HR pentad to the next. Specifically, in the HR study, subtropical drifters were defined either by passage through a box surrounding the Gulf Stream (35°N–47°N, 78°W–48°W) or by their low-latitude launch location (south of 45°N). Each of these definitions encloses a large region north of the Gulf Stream where subpolar waters are recirculated [*Hogg et al.*, 1986]. As evident in Figure 3a, a number of drifters in the observational data set were not launched in subtropical waters but instead launched in the recirculation gyre located north of the Gulf Stream front. Drifters launched north of the Gulf Stream would not need to cross the Gulf Stream–North Atlantic Current front in order to reach 53°N, and as a result, may have biased the amount of measured exchange [*Lozier and Riser*, 1990; *Bower and Lozier*, 1994].

[15] To examine whether the attribution of temporally variable exchange could be biased by variable launch locations, synthetic drifters were launched from the obser-

Table 1. Percent of Drifters Drogued to 15 m Reaching 53°N[a]

	1991–1995 Forcing	1996–2000 Forcing	2001–2005 Forcing
1991–1995 Launch Locations	0.0%	1.6%	0.8%
1996–2000 Launch Locations	0.5%	2.0%	1.6%
2001–2005 Launch Locations	2.3%	2.3%	0.4%

[a]Percent of drifters when launched from various launch locations (rows) and advected through various horizontal velocity fields (columns).

vational launch locations at 15 m for each HR pentad and then advected through the horizontal velocity field for each pentad for 4 years. In other words, nine cases were run: drifters were initialized at the launch locations for pentad 1 and then advected forward using the velocity fields for pentads 1, 2, and 3 to yield three measures of intergyre exchange. The launch locations for pentads 2 and 3 were similarly tested. The amount of exchange measured by the surface drifters within each of these nine scenarios is shown in Table 1. Notably, regardless of launch location or forcing, only a small amount of exchange was measured. However, Table 1 indicates that variability in launch location is able to produce as much variability in the amount of exchange measured as variability in the velocity fields through which the drifters are advected (2.3% and 1.9%, respectively). This finding suggests that the variability in the amount of intergyre exchange previously attributed to temporal variability in drifter pathways could just as easily be attributed to variability in drifter launch location. When drifters from the same launch locations are advected through changing velocity fields (as shown in Table 1), no trend in the amount of exchange can be reasonably extracted. This result calls attention to the need for careful documentation of surface drifter launch positions relative to the dynamic axis of the Gulf Stream so that resultant trajectories can be assessed in the context of their initial position. However, before these results can be used to interpret the likelihood that there was or was not a trend in the intergyre exchange measured by the North Atlantic surface drifters, we must first assess whether drifters constrained to a depth of 15 m can reliably measure intergyre exchange.

[16] The constraint imposed by the 2-D motion of surface drifters on the measure of intergyre exchange is examined by repeating the test described above (with results shown in Table 1) using the full 3-D velocity field for integration of the pathways rather than just the horizontal velocity field. For this run, synthetic drifters, when allowed to move in 3-D, become synthetic floats. As seen in Table 2, regardless of launch location or forcing, the number of synthetic floats reaching 53°N increases dramatically relative to the number of surface-constrained drifters reaching that latitude when launched under the same conditions. Whereas a maximum of 2.3% of surface drifters (at 15 m) reached 53°N, the percentage of floats reaching that latitude ranged from 6% to 29%, depending upon launch location and forcing. These results clearly indicate that BT's conjecture was likely correct: the inability of surface drifters to move in 3-D inhibits their ability to mimic the pathway of water parcels. Thus, these results suggest that in order to accurately measure intergyre exchange in the upper ocean, observational floats and drifters must be Lagrangian in nature, and in the reconstruction of such pathways using model data, the 3-D velocity field must be used. Additionally, these results highlight the bias introduced by variable launch locations in the assessment of temporal changes. Though intergyre exchange for a fixed launch location scheme varies across the HR pentads (by ~6%–7% for all launch location schemes), the total variability in the percent of floats reaching 53°N is dominated by variability in launch location. Regardless of the velocity field through which floats were advected, floats launched from the 1991–1995 and 2001–2005 pentads measured a maximum of 14.0% exchange. However, floats launched from the 1996–2000 locations and advected through the velocity fields from each of the HR pentads measured from 21.7% to 29.1% exchange. As described previously, launches from the second HR pentad contain a number of launch locations north of the GS front (Figure 3a). As such, the amount of exchange measured by the 3-D floats shown in Table 2 for this pentad is likely an overestimate.

[17] In answer to the question posed at the beginning of section 4.1.1, we conclude that the results from the synthetic drifter launches in FLAME indicate that intergyre exchange measured by observed drifters is likely constrained by limited drifter lifetimes, but even more likely limited by the inability of the drifters to move away from the 15 m surface. Furthermore, the modeling experiments suggest that variability in launch location prohibits an assessment of temporal variability in subtropical to subpolar pathways from the observational record.

4.1.2. Could the Removal of Ekman Velocities Allow for a Meaningful Measure of Exchange by Surface Drifters?

[18] On the basis of BT's conjecture that Ekman transport inhibits surface exchange, we investigate in this section the possibility that the removal of the Ekman velocity field (calculated from the observed wind field) could yield an estimate of throughput from the observed drifters. The depth of the fair weather Ekman layer in stratified, midlatitude regions of the North Atlantic has been estimated to be 20 m or less [*Price and Sundermeyer*, 1999]. As such, the tests

Table 2. Percent of Floats Launched at 15 m Reaching 53°N[a]

	1991–1995 Forcing	1996–2000 Forcing	2001–2005 Forcing
1991–1995 Launch Locations	10.1%	6.1%	12.2%
1996–2000 Launch Locations	21.7%	28.0%	29.1%
2001–2005 Launch Locations	7.4%	10.1%	14.0%

[a]Percent of floats launched at 15 m that reach 53°N when launched from various launch locations (rows) and advected in 3-D through various velocity fields (columns).

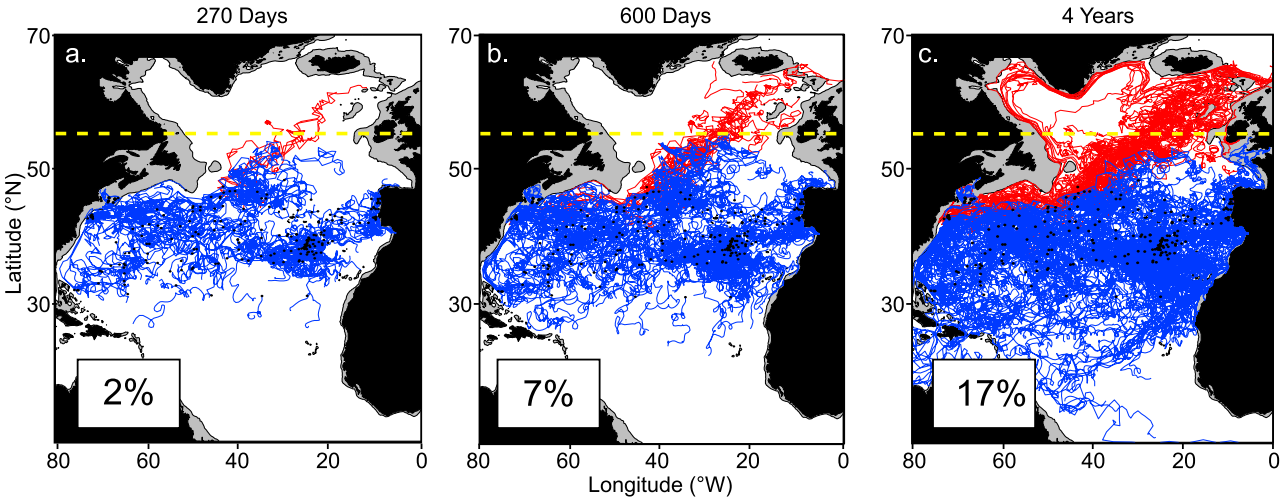


Figure 5. Synthetic drifters released below the Ekman layer (50 m) from the observational launch locations (Figure 3a) for the first HR pentad (1991–1995) and advected through the instantaneous horizontal velocity fields for (a) 270 days (average lifetime of the drifters in the observational record), (b) 600 days (long lifetime run used in BT study), and (c) 4 years. Colors are as in Figure 4. Bathymetry less than 500 m is shaded gray.

conducted in section 4.1.1 are duplicated in this section for synthetic drifters launched at 50 m, sufficiently deep to be below the depth of the midlatitude Ekman layer and advected through the 2-D velocity fields. Essentially, with this modeling experiment we ask, given the other observational constraints of limited drifter lifetime and variable launch locations, whether an accurate measure of the intergyre exchange and its temporal variability can be retrieved with the removal of the Ekman velocity field. Despite the results from section 4.1.1 that showed the importance of integrating the surface drifters with the 3-D velocity field, we conduct these experiments using the 2-D velocity field in order to assess the degree to which useful information about intergyre exchange can be extracted from the observational data set. With this choice, we are assessing whether the observational database is sufficient to recover the subsurface (50 m) pathways from the subtropical to the subpolar gyre.

[19] The effect of drifter lifetime is first retested by launching synthetic drifters at 50 m from the launch locations of each HR pentad and integrating forward in time for 4 years. The results, shown in Figure 5, clearly indicate that the amount of exchange below the Ekman layer exceeds that at the surface: whereas 17% of drifters with lifetimes of 4 years enter the subpolar gyre at 50 m (Figure 5c), none of the drifters launched from the same launch locations and advected through the same velocity fields reach the subpolar gyre when launched at 15 m (Figure 4a). Furthermore, drifter lifetime appears to play a much more substantial role in the amount of measured exchange at 50 m than it did at the surface. As shown in Figure 5, only 2% of drifters with lifetimes of 270 days (the mean lifetime of drifters in the observational record) enter the subpolar gyre when launched at 50 m, while 7% (17%) of drifters with lifetimes of 600 days (4 years) do so. This dramatic increase in exchange with drifter lifetime at 50 m clearly indicates that drifter lifetimes of 270 days are insufficient to capture intergyre pathways below the Ekman layer. Furthermore, this trend was found to be consistent for drifters launched in all HR pentads and from all locations (not shown).

[20] Given the insufficiency of the observed drifter lifetimes to measure intergyre exchange and its temporal variability, we ask next whether a measure of exchange could be recovered from the observed data set if the observed drifter lifetime was extended via BT's "linkage" method described in section 2. Toward this end, the nine-part modeling experiment described in section 4.1.1 (with results shown in Table 1) is repeated for drifters launched below the Ekman layer (at 50 m) and allowed to run for 4 years. Again, nine runs are made, whereby pathways are initiated from each of the observational launch schemes and integrated forward with the velocity fields from each of the three pentads. An inspection of Figure 6 demonstrates that, as with drifters launched within the Ekman layer, the effect of launch location proves to be much more influential in establishing the number of drifters reaching the subpolar gyre than temporal variability in the velocity fields through which they are advected. For example, the amount of exchange measured for drifters launched from the 1991–1995 observational launch locations and advected through the velocity fields from each of the HR pentads measures 17%, 14%, and 11% (Figure 6, top). In contrast, the amount of exchange measured by drifters launched from each of the three sets of observational launch locations and advected through the 1991–1995 velocity fields yields a 17%, 54%, and 16% rate of exchange, respectively (Figure 6, left). Once again, drifters launched from the launch locations of the second HR pentad (1996–2000) yield the greatest rate of exchange.

[21] In summary, these modeling experiments suggest that the irregularity and variability of the initial launch locations as well as the inability of the floats to move in 3-D space pose large obstacles to obtaining a realistic assessment of the observed Lagrangian intergyre exchange and its temporal variability from the observational data set. Even if the

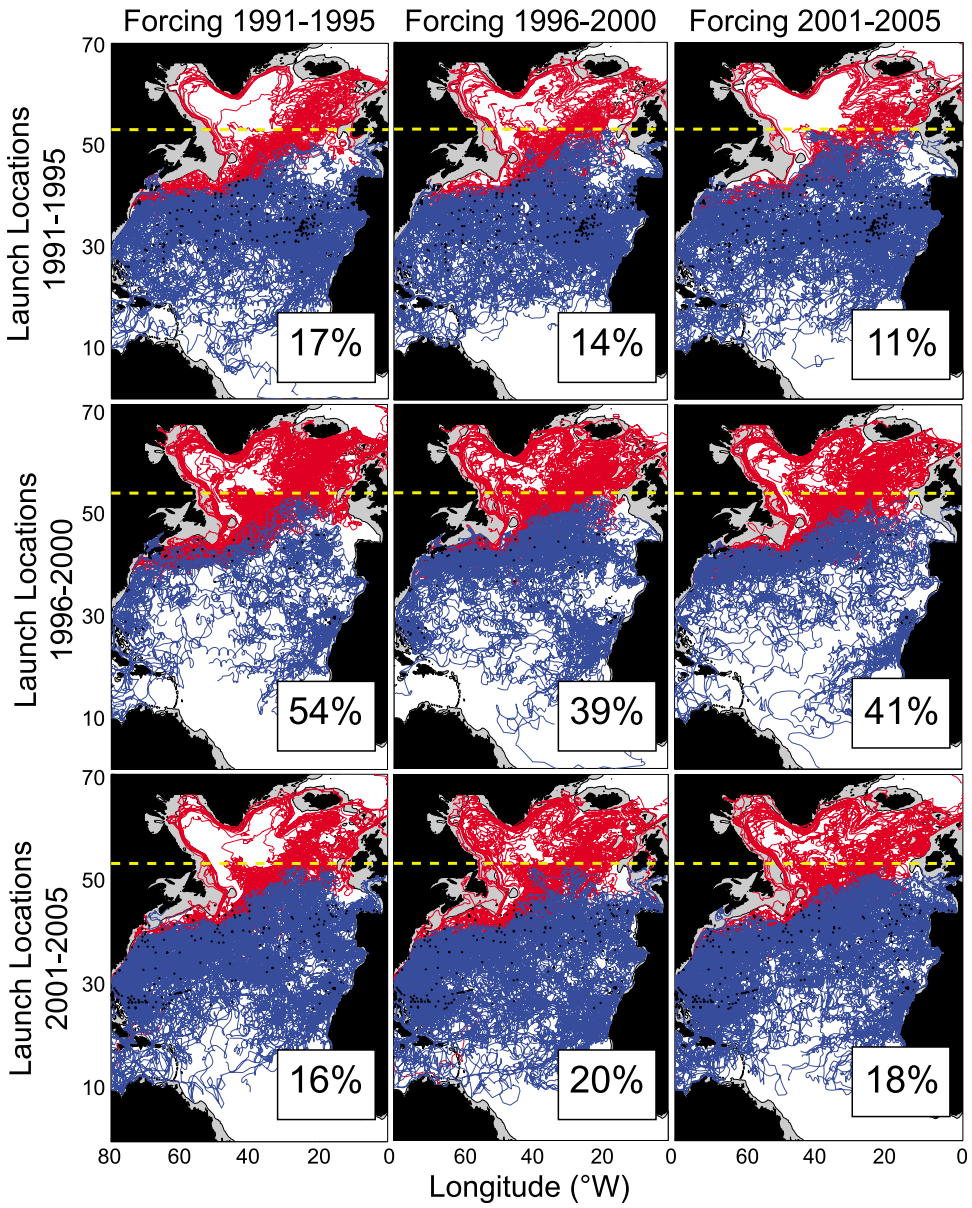


Figure 6. Synthetic drifters launched in FLAME at the observational launch locations (Figure 3a) for each of the three HR pentads (top) 1991–1995, (middle) 1996–2000, and (bottom) 2001–2005 and advected through the instantaneous 50 m horizontal velocity fields from (left) 1991–1995, (middle) 1996–2000, and (right) 2001–2005 for 4 years. Colors are as in Figure 4. Bathymetry less than 500 m is shaded gray.

effect of limited drifter lifetime can be alleviated and the Ekman velocity field removed, the observational drifter data set is sufficiently hampered by these constraints to preclude reliable estimates of exchange. With this conclusion and that from section 4.1.1 regarding the importance of 3-D pathways, we can no longer look to the current observational database for a depiction of intergyre exchange from a Lagrangian viewpoint. As such, we continue our study within the context of FLAME using synthetic floats advected with the 3-D velocity field and launched from a regular grid within subtropical waters. We do not suppose that the model will yield the North Atlantic's subtropical to subpolar exchange, rather that a comparison of the model's subsurface to surface exchange will provide context for the rather sparse observational data set.

4.2. Is the Amount of Intergyre Exchange at the Surface Representative of the Overall Subtropical to Subpolar Exchange?

[22] In order to investigate the nature of subtropical to subpolar exchange within FLAME, synthetic floats were launched dynamically within the Gulf Stream grid (described in section 3) and integrated forward in time for 4 years using the time-varying 3-D velocity field. Floats were repeatedly launched every 2 months between 1990 and 2000 (launches after 2000 would not yield 4 year trajectories). As described previously, care was taken to ensure that only floats whose

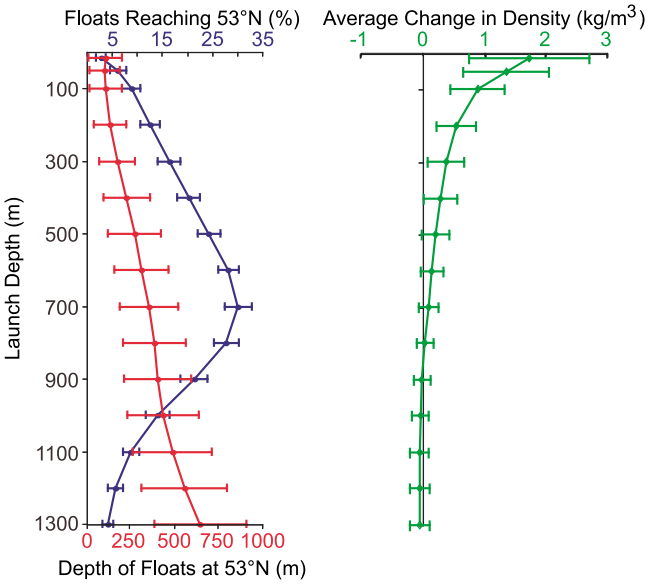


Figure 7. (left, blue) Mean percent of synthetic floats launched at various depths which reach 53°N when advected through the 3-D velocity field for 4 years. Error bars indicate the standard deviation of the percent of measured exchange recorded by floats from each of the launches initiated between 1990 and 2000. (left, red) Mean depth of all floats reaching 53°N when they arrive at 53°N. Error bars indicate the standard deviation of float depths when they arrive at 53°N. (right, green) Average density change of all floats reaching 53°N between the time of their launch and the time that they cross 53°N. Error bars indicate the standard deviation of float density change.

initial position lay south of the instantaneous Gulf Stream front were considered. Finally, floats were launched at 15 m, 50 m, and also at 100 m intervals between 100 and 1300 m in order to assess the vertical profile of intergyre exchange for the upper water column.

[23] The model runs described above produce the vertical profile of Lagrangian intergyre exchange shown in Figure 7, where error bars are derived from repeated launches. A sample of the resultant trajectories from these launches can be seen plotted according to launch depth in Figure 8a. As evident in Figures 7 and 8a, the exchange measured by the floats launched at 15 m, whose northward transport is inhibited both by their launch positions south of the Gulf Stream front and, at least initially, by Ekman drift is small: only 3% (±1%) of floats reach 53°N within 4 years. However, below the Ekman layer the number of floats reaching the subpolar gyre increases steadily until reaching a subsurface maximum of 30% (±3%) for floats launched at 700 m.

[24] *Spall* [1992] demonstrated that cooling of subtropical surface waters in a non-eddy-resolving model with steady forcing can produce velocities that spiral cyclonically with depth beneath the Gulf Stream's eastward extension. To examine whether the enhanced exchange with depth observed within FLAME (described in the preceding paragraph) can be explained by such a cooling spiral, the vertical structure of the mean velocity field in FLAME was examined at several locations along a launch transect at 48°W (Figure 8a). Shown in Figure 8b is the mean velocity hodograph along that transect at 38°N, which is just south of the climatological position of the Gulf Stream front (Figure 3a) and within the region of strong wintertime cooling. A cyclonic rotation with depth of the upper water column (only velocities below the Ekman depth are plotted in Figure 8b since the cooling spiral pertains to the geostrophic velocities) is evident, however the rotation is weaker and shallower than that predicted by *Spall* [1992] for the subtropical gyre. The spiral shown in Figure 8b has a rotation of just 5.35° from 50 to 200 m, compared to a predicted rotation of 27° over 450 m. Below 200 m an anticyclonic beta spiral [*Schott and Stommel*, 1978] is recovered. Inspections of hodographs at other locations along the transect produced similar results. Interestingly, the spiral in the model's winter velocity field is weaker (~1° from 100 to 300 m) than that shown in Figure 8b, lending some doubt to the supposition that the cooling is responsible for the observed spiral and, consequently, for the differences in exchange with depth. Furthermore, if the escape of the floats considered in Figure 7 was primarily determined by the presence of a wintertime cooling spiral, some seasonality in the arrival into the subpolar gyre would be expected. However, an examination of the arrival time of floats in the subpolar gyre (not shown) indicated none of the expected seasonal variability and, perhaps more relevant, there was no preference when the floats that arrived at 53°N were sorted by the season of their launch. Finally, we note that the increase in float exchange with depth extends to 700 m, at which point the exchange is maximized. Thus, it is difficult to attribute exchange characteristics within the model to a weak cooling spiral that extends to only 200 m in the mean and one that is not consistent with seasonal expectations.

[25] The depths at which floats within the Gulf Stream grid arrive at 53°N (hereinafter, the target depth of the floats) are indicated by the red line in Figure 7. An examination of float target depths indicates that, with the exception of floats launched at 15, 50, and 100 m (each of which have average target depths of ~100 m), the floats shoal significantly as they move northward, often arriving hundreds of meters shallower than their launch depth. For example, the average target depth of floats launched at 700 m is 350 m (±166 m). This shoaling of float positions is supported by the mean position of isopycnals along 40°W between 25°N and 60°N (Figure 9), where strong shoaling of the isopycnals across the subtropical-subpolar front is evident. Interestingly, the shallowest density surfaces along 40°W are restricted to low latitudes, outcropping at the surface south of the mean position of the NAC (depicted by the vertical gray bars in Figure 9), suggesting that surface waters within the subtropical gyre are largely recirculated. However, the isopycnals found at depth in the subtropical gyre, including the σ_Θ = 27.1 surface (shown by the white line in Figure 9) cross the NAC as they shoal and outcrop north of the front.

[26] From Figure 7 it appears that floats arrive at 53°N at the depth which their launch isopycnal resides. In other words, it appears as though the change in depth of the floats from their launch location to 53°N can be attributed to the

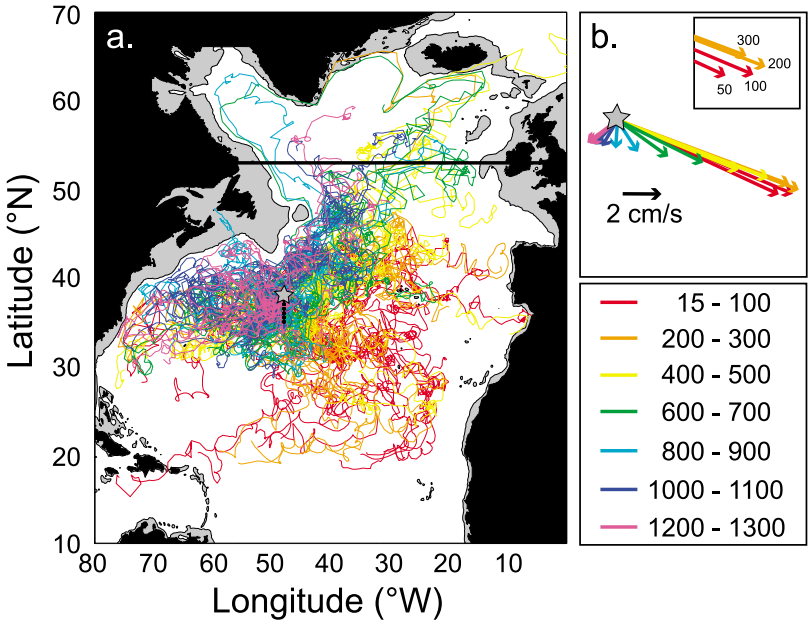


Figure 8. (a) Trajectories of synthetic floats launched along a transect at 48°W within the Gulf Stream grid and advected through the instantaneous 3-D velocity fields for 4 years. Colors indicate the depth of the float at the time of its launch. Bathymetry less than 500 m is shaded gray. Gray star indicates the location of the mean velocity profiles shown in Figure 8b. (b) Mean velocities from 50 to 1300 m at 48°W, 38°N.

shoaling of the isopycnals from the subtropical to the subpolar gyre. However, the target depths of the floats at 53°N are slightly deeper than the depth of the launch isopycnals, indicating that some densification occurs along float pathways (Figure 7). This densification likely results from cooling due to the strong loss of heat to the atmosphere along the pathway of the NAC [*McCartney and Talley*, 1982] and mixing with denser water masses as the floats make their way to the north. While the surface water densification is substantial (more than the density change across the front at their launch location; see Figure 9), it is important to note that the floats launched at deeper levels, which comprise the bulk of the floats reaching the subpolar gyre, remain close to their original densities. For example, floats launched at 700 m experience only ~0.1 kg/m^3 densification between their launch locations and 53°N (Figure 7),

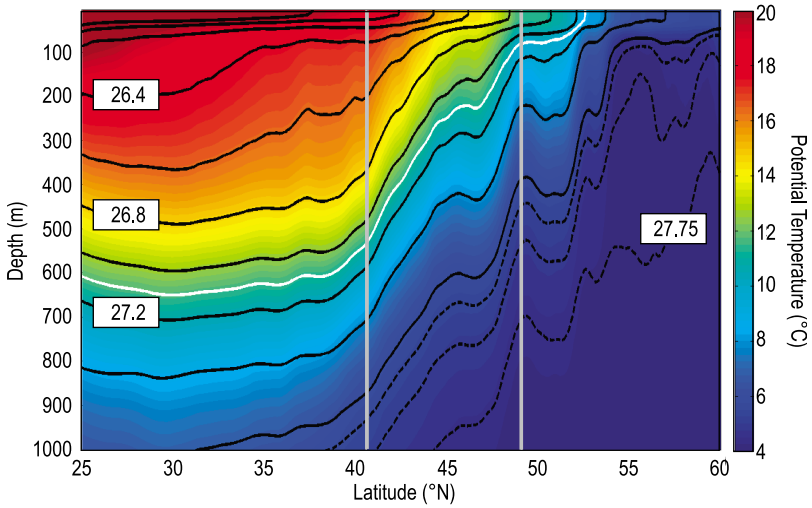


Figure 9. Mean potential density superposed over mean potential temperature along a meridional section at 40°W in FLAME. Contour interval is 0.2 kg/m^3 and 0.05 kg/m^3 for solid and dashed black lines, respectively. White contour line indicates the σ_Θ = 27.1 isopycnal. Vertical gray bars indicate the mean position of the NAC at 40°W.

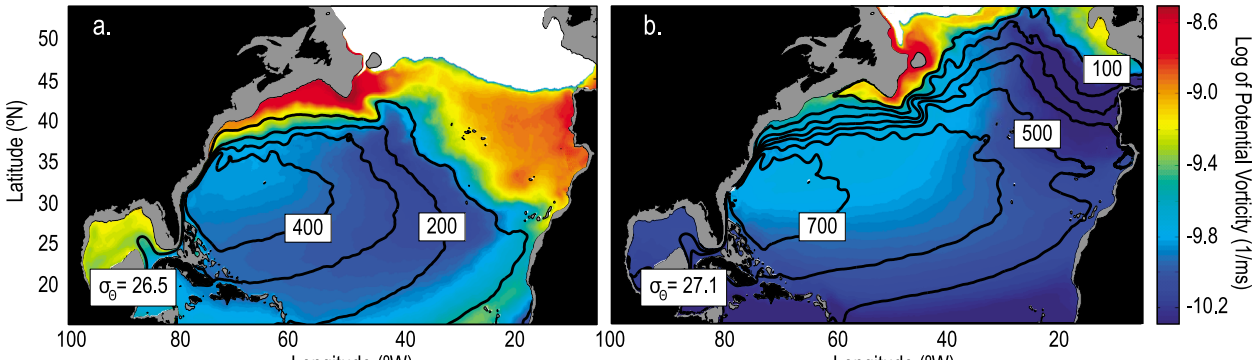


Figure 10. Mean depth (m) of the (a) σ_Θ = 26.5 and (b) σ_Θ = 27.1 isopycnal surfaces superposed on mean potential vorticity fields along those isopycnals in FLAME. Depth contour interval is 100 m. Bathymetry below 500 m is shaded gray.

which is about 1/5 of the cross-stream density gradient at their launch location (Figure 9). Thus, though some densification does occur along pathways, these modeling experiments suggest that subtropical waters entering the subpolar gyre are primarily subsurface waters that shoal along density surfaces as they move northward.

[27] To complement the cross-section of temperature and density in Figure 9, plan views of depth and potential vorticity on two selected isopycnals are shown in Figure 10. As emphasized above, the depth contours on the shallow isopycnal (Figure 10a) indicate that waters this light are absent north of ~45°N [*Lozier et al.*, 1995]. Instead these relatively shallow waters recirculate within the subtropical gyre, as indicated by the float pathways in Figure 8a, but also indicated by the potential vorticity field in this basin. Prior modeling work has demonstrated the constraint placed on Lagrangian pathways by the mean potential vorticity in a subtropical basin [*Lozier and Riser*, 1990]. For the deeper isopycnal, at the approximate depth where Lagrangian pathways are most likely to lead from the subtropical launch region to the subpolar latitudes, the potential vorticity field is consistent with a bifurcation at the exit of the Gulf Stream. Such a bifurcation (long noted in past studies of hydrographic fields) suggests a flow field that contains a branch that recirculates anticyclonically in the subtropical basin and another that extends to subpolar latitudes; consistent with the Lagrangian pathways. This extension is, in effect, the throughput of subtropical waters as part of the basin scale meridional overturning.

5. Summary

[28] For decades the Gulf Stream–North Atlantic Current system has been considered the dominant pathway by which subtropical waters are advected to high latitudes. The visual connectivity between the subtropical and subpolar gyres, apparent in surface velocity and sea surface temperature fields, has led to the supposition of a strong surface throughput. As such, previous studies have used surface drifter records in an attempt to understand both the mean and the time-varying pathways by which subtropical waters are transported to the subpolar gyre.

[29] In this study, an eddy-resolving OGCM was used to demonstrate that drifters from the observational record are more than likely incapable of capturing the true pathways by which subtropical waters are transported to high-latitude regions of deep convection as a result of their short lifetimes (as demonstrated previously by BT), variable launch locations, and restriction to movement in 2-D. Synthetic floats were repeatedly launched from a standard grid and integrated for 4 years with the model's 3-D velocity field to study intergyre exchange. From the modeling results, we suggest that subtropical waters in the North Atlantic are primarily transported to high latitudes at depth along shoaling density surfaces. Surface waters in the subtropical gyre, sampled by the drifters in the observational record, are largely absent in the intergyre exchange process and are instead recirculated within the subtropical gyre.

[30] Recent evidence regarding the impact of wind and eddy fields on the circulation of the North Atlantic has revealed that the "conveyor belt" model greatly oversimplifies the large-scale overturning of the ocean [*Lozier*, 2010, and references therein]. This study reinforces the complexity of the overturning since it calls into question the expectation that the conveyor belt has a strong surface expression in the intergyre transport in the North Atlantic. The implication of this result for our understanding of how overturning variability impacts the spatial and temporal variability of the North Atlantic's sea surface temperature remains unanswered.

[31] **Acknowledgments.** The authors gratefully acknowledge NSF for the support of this work, Claus Böning (IFM-GEOMAR) for access to FLAME model output, and two anonymous reviewers for their thoughtful comments. K.C.B. thanks Stefan Gary for his generosity with codes for the analysis of FLAME output and for many helpful conversations.

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K. C. Burkholder and M. S. Lozier, Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Old Chemistry Building, Rm. 103, Box 90227, Durham, NC 27708, USA. (kristin.burkholder@duke.edu)