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Drifters in the Gulf Stream

by G. G. McGrath[1], T. Rossby[2], and J. T. Merrill[2]

ABSTRACT

In the past, the Gulf Stream has frequently been viewed as essentially a barrier between the Slope and Sargasso seas. On the other hand, surface drifters have often been observed to leave the stream to the south. To gain a better understanding of surface flow of the Gulf Stream, we used drifter trajectory data to study their drift east and patterns of loss from the current. Two sets of drifter data were used, one from the 1995–1999 Georges Bank GLOBEC program and the other from the Global Drifter Program. We also made use of atmospheric wind stress estimates from a reanalysis data set to evaluate the effect of wind forcing on their movements. Without fail, all drifters that enter into the stream eventually detrain out of the current to the south, indicating significant cross-frontal transport at the surface. A first explanation of these detrainments relies on the Ekman drift to the south due to the westerly winds over the study area. However, the exits to the south are not uniformly distributed, but aggregate in three areas where the meandering is particularly sharp: the New England Seamount Chain, the Southeast Newfoundland Rise, and the 44°N trough in the North Atlantic Current. Although, intuitively, it would seem that the largest Ekman drift losses would occur in the winter, this study shows that the detrainment to the south occurs more effectively in the summer due to a minimum in the mixed layer depth.

1. Introduction

Most any satellite image of sea-surface temperature in the Gulf Stream (GS) region in the northwest Atlantic will reveal a well-defined pattern of cold water (slope waters) to the north and warm Sargasso Sea waters to the south with a distinct meandering band of warm water separating the two. Indeed, the strong contrasts in temperature and velocity across the northern edge or front of this band reinforce the view of the current as a strong barrier to cross-frontal exchange at and near the surface (Bower *et al.,* 1985). This sharp front, together with the band of warm water, conveys the impression of a well-defined transport flowing to the east. Yet all surface drifter trajectories in the stream will sooner or later exit to the south. This concept applies both when the drifter was already in the stream as it passes Cape Hatteras and when the drifter was entrained into the stream from the shelf or the waters to the immediate north of the GS. This raises the obvious question as to how and why drifters cross this rapidly moving stream with its maximum velocity of about 2 m s^{-1}

1. U.S. Coast Guard International Ice Patrol, 1 Chelsea Street, New London, Connecticut, 06320, U.S.A. ***email: gabrielle.g.mcgrath@uscg.mil***

2. Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island, 02882, U.S.A.

(e.g. Iselin and Fuglister, 1948; Johns *et al.,* 1995). This would seem at odds with the idea of a contiguous flow of warm water east toward the Grand Banks and north along the North Atlantic Current (NAC). Brambilla and Talley (2006) observed a similar pattern of exit from the North Atlantic Current to the warm side farther north in the North Atlantic. They noted that the rate of loss of drifters from the NAC vastly exceeded the downstream decrease in warm water transport toward Europe.

Two mechanisms causing drifters to leave the stream to the south come to mind, the most obvious one being Ekman drift. Given the westerly winds over the GS east of Cape Hatteras, the average Ekman transport should be approximately to the south. This should be the case even though the variability of the winds greatly exceeds its mean. A second mechanism for loss might result from the tendency for waters to be expelled from the stream primarily near meander extrema. Many studies have documented the formation of west-trending warm filaments at meander crests (e.g. Lillibridge *et al.,* 1990) and warm outbreaks that turn west from meander troughs (e.g. Cornillon *et al.,* 1986). While the filaments are highly visible against the cold waters, the warm outbreaks may actually have a larger volume exchange than do the warm filaments due to the deepening of the GS on the Sargasso Sea side. In possible support of this, Song *et al.* (1995) noted that Lagrangian floats deployed in the center of the GS on the $26.8\ \sigma_t$ surface (temperature = 15°C in the main thermocline) were more likely to exit the stream to the south than to the north. Of course, both mechanisms could contribute to the tendency for surface drifters to exit the stream to the south.

The warm GS meanders east past the New England Seamount Chain (NESC) where its mean path shifts roughly 1–1.5° to the north (Cornillon, 1986; Song *et al.,* 1995). The meandering structure steepens considerably over and to the east of the NESC. Southeast of the Grand Banks, the GS splits, with the most coherent part of the current turning north as the well-defined baroclinic NAC. Other waters continue southeast and cohere into the Azores Current (e.g. Klein and Siedler, 1989), and a significant portion curves broadly south and back west, as part of a prominent southern recirculation gyre (Hogg, 1992). The NAC continues north to about 50–52°N to what is known as the Northwest Corner (Worthington, 1976) where the current turns east as the Subpolar Front (SPF) and continues east across the mid-Atlantic Ridge toward Europe (Bower *et al.,* 2002; Brambilla and Talley, 2006).

The transport of water along the GS, NAC and SPF has been discussed in a number of studies (e.g. Hogg, 1992; Sato and Rossby, 1995; Perez-Brunius *et al.,* 2004), and while uncertainties exist about the accuracy of these transport estimates given that the currents vary over a wide range of time scales, there is no doubt about the continuity of the GS-NAC-SPF system: one does find subtropical waters in the northeast Atlantic. The total transport (0–2000 m) in the NAC is 20 Sv (1 Sverdrup = $1 \times 10^6\ m^3\ s^{-1}$) according to Perez-Brunius *et al.* (2004) compared to 88 Sv just east of Cape Hatteras (Halkin and Rossby, 1985). One might surmise from this that $O(1 \text{ in } 4)$ surface drifters in the core of the GS at Cape Hatteras might make it to the Northwest Corner. In fact, less than 1% of the drifters do so. Perhaps exploring where the losses take place might help us to determine the reasons why.

The objective of this paper is to develop as clear a picture as possible of where, when and how surface drifters cross the GS. In the next section we summarize the database for this study and the steps taken to bring all data into a consistent set. This section also describes the principal analysis tool used to quantify “drifter flux.” Section 3 presents the principal findings of the study, namely the dispersion of drifters and their loss to the south. Section 4 discusses further how they escape, while the last section provides a brief summary and discussion.

2. Data sets and analysis methods

The trajectory data for this study come from 233 GLOBEC (Global Ecosystem Dynamics Program) drifters and 1188 Global Drifter Program (GDP) drifters for a total of 1421 drifters. The GLOBEC drifters were deployed on Georges Bank during the years 1995–1999, typically in groups of five between January and June, the time of year of greatest interest to that program, so there is a deployment bias toward the first half of the year. The GDP drifters (obtained from the NOAA/AOML Drifter Assembly Center) come from a much larger group of drifters deployed in various areas of the North Atlantic. Those included here are those that come up with the Florida Current and continue east of Cape Hatteras in the GS. They pass by at any time of year. All drifters are of standard WOCE design (making use of a holey sock as drogue) except that most of the GLOBEC drifters were drogued at 10-m depth (with a few at 40-m depth) while the standard WOCE drifter has its drogue at 15-m depth. All drifter trajectories were low-pass filtered with a 30-hour half amplitude point to remove tidal and inertial oscillations, and re-sampled at 6-hour intervals. We use only trajectory data when the drogue is attached to avoid any bias to the trajectories due to the direct action of winds on the undrogued surface float.

a. Drifter data

The objective of creating a working data set for this study was to capture those drifters that entered and exited the Gulf Stream, so that the entire trajectory could be studied to identify where, when, and how the drifters cross the current. For this purpose we define a set of “picket” lines, first a Gulf Stream Entry Line (GSEL), and a set of segments along the southern edge of the GS that will define the Gulf Stream Demarcation Line (GSDL). The GSEL consists of a single long southwest to northeast line placed between 35.6°N, 73°W and 43°N, 64.5°W (Fig. 1). The principal requirement was that drifters, after they cross the line, show clear evidence of either being in or just about to join the stream. For this purpose we put the line as far west as possible to distinguish between drifters already in the GS at Cape Hatteras, and those that leave the mid-Atlantic Bight shelf (between Cape Hatteras and Georges Bank) and cross the slope waters (sometimes known as the Slope Sea) north of the GS and enter the stream from the north. These two groups will be known as the South and North group, respectively. A number of GLOBEC drifters deployed at Georges Bank

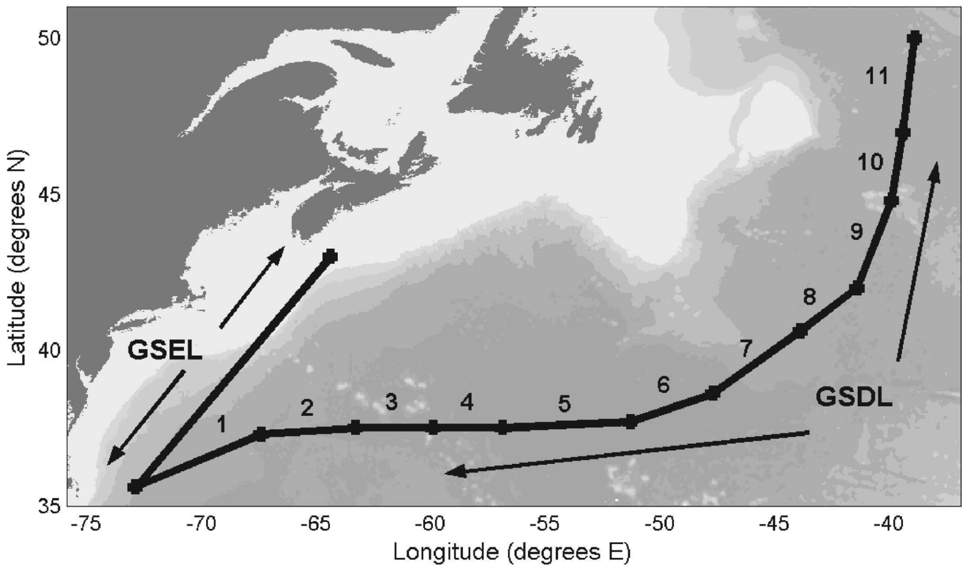

Figure 1. Location of Gulf Stream Entry Line (GSEL) and the 11 segments of the Gulf Stream Demarcation Line (GSDL). Bathymetric shading in 1000 m steps from 1000 to 5000 m depth. The New England Seamount chain shows up clearly north of segments 2 and 3 and the Southeast Newfoundland Rise (SENR) is the shoaling ridge just northwest of segment 7.

drifted south on the shelf first before being entrained into the GS right off of Cape Hatteras. This pattern has been observed in earlier studies (Lozier and Garwarkiewicz, 2001). Thus, the two groups, North and South, have not to do with their origin, but with where they cross the GSEL. Each and every drifter was examined for both temperature and velocity to ensure that it really was in (the southern group) or joined the GS (northern group) after crossing the Slope Sea. These criteria eliminated quite a few drifters, leading to 191 drifters, 113 drifters from the GLOBEC data set and 78 drifters from the GDP data set.

The GSDL consists of 11 roughly 350-km long segments designed to identify where loss from the stream takes place; this required locating the line as close to the GS as possible. But we also had to be mindful of large amplitude meandering and did not want drifters in deep troughs to register as (brief temporary) exits from the GS. The set of segments defining the GSDL in Figure 1 separates the southern limit of the meandering stream from waters that have left or are clearly outside the stream. It was adjusted laterally to be as close to the southern limit of GS meandering as possible without intercepting any drifters actually still flowing in the stream. After deciding on a final location, select drifter trajectories were also examined at the point where they crossed the line to ensure that the corresponding velocities reflected detrainment from the stream to the south, indicated by slower drift velocities. No drifters detrained permanently from the stream to the north. A few drifters traveled north in meanders or as part of warm core rings, but in all cases these rejoined the main flow of the stream within days. Nearly 40 drifters stopped transmitting before they exited the stream, further reducing the working data set to a final total of 153 drifters. Of these, 74 were drogued at 10 m depth, 71 at 15 m depth, and eight at 40 m depth. The North subset contained 51 drifters (38 GLOBEC and 13 GDP), and the South subset contained 102 drifters (42 GLOBEC and 60 GDP).

To see if drogue depth had any effect on where drifters left the stream, we looked at the distribution of first crossings for the three groups of drifters. The 40-m drifters subset was too small to show any clear pattern. Because the majority of the GDP drifters (all drogued at 15-m depth) entered the stream in the vicinity of Cape Hatteras, these drifters were already in the core if not to the south of the jet axis when crossing the GSEL. As we will see, this position across the jet axis created a preferential tendency for the drifters to quickly exit to the south. In comparing the 10-m and 15-m drifter subsets, no distinct differences were observed within the study area, outside of those clearly related to where the drifters were initially deployed. This tendency was related to location in the stream rather than to the depth of the drogue. Even though this comparison is less than rigorous, all drifters in the working data set were treated the same with regard to drogue depth.

b. Atmospheric data

The atmospheric data used in this analysis were produced by the European Center for Medium-Range Weather Forecasting (ECMWF). The ECMWF 40-year Reanalysis (hereafter referred to as ERA40; Uppala *et al.,* 2005) fields were archived four times daily, on the same time interval as the drifter data. The purpose here will be to estimate the Ekman drift contribution to drifter movement. ECMWF data are used in many drifter studies as they have been found to have no bias in wind direction when compared to the local winds (Niiler and Paduan, 1995). We use ERA40 data from the 1995–1999 period, as it was decided that the five years of atmospheric data would be adequate for this study. The fields available to us were on a reduced Gaussian grid which we interpolated to a regular grid at 1.125° spacing. The fields of interest include the east-west and north-south accumulated wind stress, the east-west and north-south instantaneous wind stress, the east-west and north-south wind component velocity at 10 m above the sea surface (the standard elevation for wind velocity measurements), sea-surface temperature 2 m below the sea surface, and the mean sea level pressure. For this study, Ekman transports were estimated using the 6-hour accumulated wind stress which after dividing by the time interval, gives an average transport for the period. This averaging was judged preferable to using an instantaneous wind stress value every 6 hours. By dividing transport by mixed layer depth (MLD), we obtain Ekman velocity. The resulting Ekman drifts are finally summed and averaged in $2° \times 2°$ boxes, a spatial resolution we thought would be quite adequate given the large scale of the wind systems.

3. Results

This study seeks to determine the characteristics of the trajectories of surface drifters in the GS, and in particular where and after how long they leave the stream. We begin with an overall spaghetti diagram and continue with a closer look at spatial and temporal patterns.

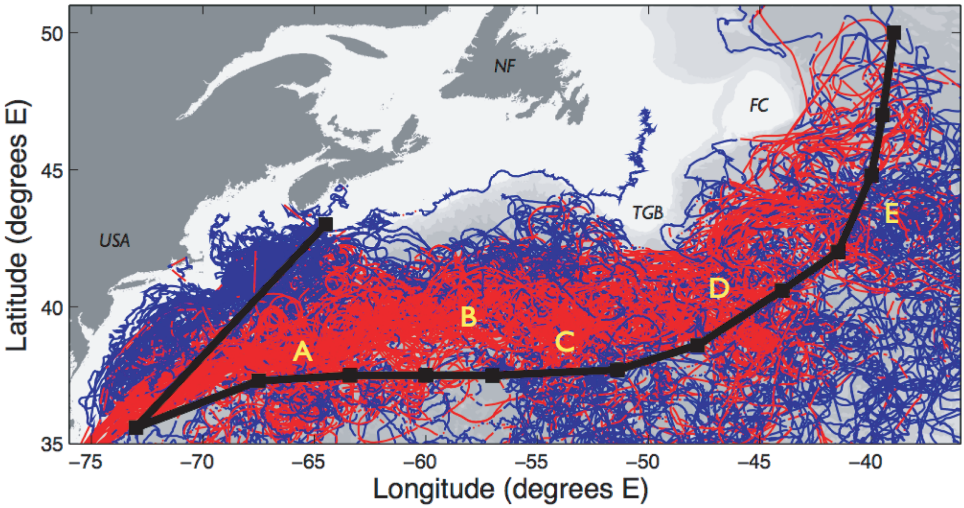

Figure 2. Overall spaghetti diagram of surface drifters used in this study. Trajectories are colored in red for speeds >0.5 m s^{-1}, else in blue. A, D, and E mark areas of preferred expulsion from the Gulf Stream. B is a section where little expulsion occurs, and C is an area where both exits and reentrainment occur. (NF = Newfoundland, TGB = Tail of Grand Banks, FC = Flemish Cap).

a. The spaghetti diagram

The overall spaghetti diagram in Figure 2 shows all drifter tracks used in this study. The figure illustrates four regions where drifters preferentially leave the GS: a region of very steep meandering at and just west of the NESC, labeled A; an area well east of the NESC labeled C; the Southeast Newfoundland Rise (SENR) labeled D; and the 44°N Trough (Kearns and Rossby, 1998), labeled E. The data from region B reveal a circulation pattern not previously documented in the literature. We will from now on use this A–E labeling. These four A, C, D, E exit areas stand in contrast to the white areas in between, areas of little trajectory activity.

Exit area A is perhaps the cleanest or easiest one to describe since the trajectories west of here have relatively straight or gently curving paths. Expulsions here occur quite abruptly due to the development of a sharp displacement to the south of a trough with quite tight cyclonic curvature. In the absence of this trough, drifters continue east. The ensemble of trajectories indicates that the path of the GS shifts north by about 1–1.5° at about 65°W consistent with earlier studies (Cornillon, 1986; Song *et al.,* 1995; Fratantoni, 2001). However, just east of this step the drifters reveal a character not seen in the just cited papers. Instead of continued steep meandering, many drifter tracks in region B run unexpectedly "straight" with relatively few southward extensions or meanders and evidently only modest loss of drifters in this region. We return to this in Section 5.

Between C and D, some drifters flowing east toward D, will turn south across segment 7 and back to the west and northwest to cross segment 5 to complete what one might call a

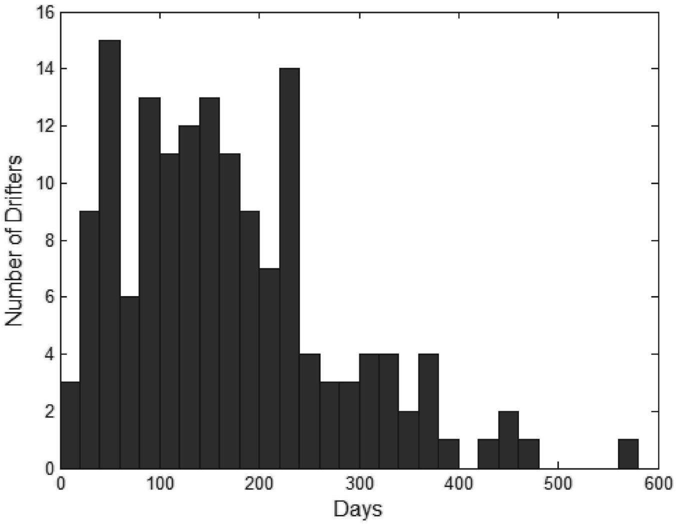

Figure 3. Histogram of residence time (including temporary expulsions) for drifters in the Gulf Stream. Mean residence or transit time was 159 days.

"50°W recirculation." Note that the region just to the southeast of segment 6 of the GSDL is relatively open and free of trajectories. The drifter speeds in the northern half of this circulation are fast (speeds ≥0.5 m s^{-1} are shown in red) indicating their advection by the stream, while speeds in the southern half are slow, indicating departure from the stream.

In the vicinity of D the GS bifurcates with part of the stream turning north as the baroclinic NAC. The NAC continues nearly 10°N to the Northwest Corner (Worthington, 1976; Lazier, 1994; Woityra and Rossby, 2008) where it makes a sharp turn to the east. As the NAC passes through the 44°N trough (region E), a number of drifters exit the current across segment 9. Just south of E (between D and E) sits the Mann Eddy where few drifter expulsions occur. Only one drifter actually reaches and passes through the Northwest Corner despite the fact that both surface drifters and subsurface RAFOS floats indicate considerable directional stability to the velocity field all along the NAC to the Northwest Corner (Carr and Rossby, 2001).

The residence or transit time for drifters in the stream varied enormously between a minimum of three and a maximum of 570 days with an overall mean of 159 days (Fig. 3). The larger residence times include temporary expulsions where the drifters remained so close to the stream that they became re-entrained. The mean speeds between entry and exit were calculated based on entry across the GSEL and final exit across the GSDL. The mean speed for all drifters was 0.253 m s^{-1} with a maximum mean speed of 1.707 m s^{-1} and a minimum mean speed of 0.022 m s^{-1} over the mean residence time of 159 days.

The Eulerian mean fields of velocity and eddy kinetic energy (EKE) have been estimated by many so we will be brief here and note only that our results match others quite well (e.g.

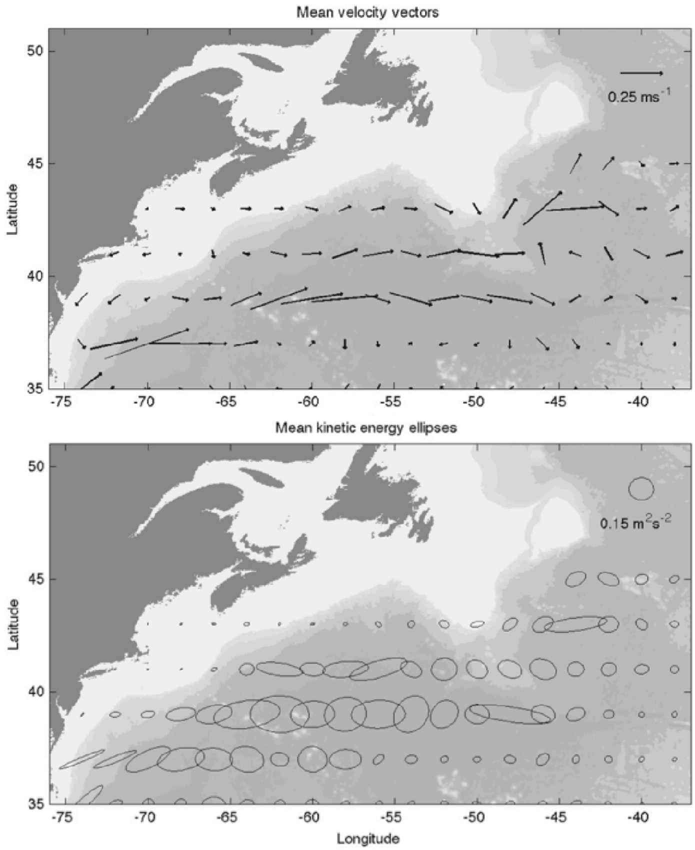

Figure 4. Mean velocity and eddy kinetic energy in 2° × 2° boxes for the entire GS area. The scale arrow and ellipse in upper right corners =0.25 m s^{-1} and 0.15 m^2 s^{-2}, respectively.

Richardson, 1983; Fratantoni, 2001) albeit in greater detail thanks to the larger database. All available drifter velocity data for the entire data set of 1421 drifters have been binned into 2° × 2° boxes such that each box has a minimum of 20 data points. The mean velocity field (Fig. 4, top) shows the robust flow of the GS off of Cape Hatteras, the northward shift of the GS as it approaches the NESC, and its turn north as the NAC just beyond the SENR. Even though the number of drifters still in the stream has decreased, the Eulerian mean velocity field reveals clearly both the Mann Eddy at 42°N and the 44°N Trough. The variance ellipses, which indicate EKE, vary enormously with location (Fig. 4, bottom). The steadiness of the flow off Cape Hatteras shows up as a low EKE polarized in the direction of mean flow whereas at A, the first major expulsion region, EKE reaches as much as 0.3 m^2 s^{-2}. High EKE values, all typically at the 0.3 to 0.5 m^2 s^{-2} levels, occur all along the GSDL, but there is little hint of the specific expulsion patterns noted above.

b. Trajectory evolution

We extend the concept of a "domain of occupation" (Kupferman and Moore, 1981) to examine the temporal development of the spaghetti diagram. As in a spaghetti diagram, one superimposes all trajectories, but as a set of panels, each one spanning a longer period of time. This approach provides a measure of how they spread, how they fill out an expanding "domain of occupation," The three panels in Figure 5 show the spread of all trajectories after one, two, and four weeks from the time the drifters cross the GSEL. We see thus that the North group does not immediately enter the GS, but must first cross the Slope Sea. Most of the South group drifters are in the GS upstream of Cape Hatteras. During the first week, the South group tracks extend relatively straight or gently curved such that the drifters remain in the core of the GS and reach the first steep meander trough near 68°W rather quickly. The panel reveals that after only one week a few drifters are leaving the stream to the south. After two weeks, a majority of drifters will be crossing the NESC. After four weeks in the stream, a few drifters have started reaching the SENR, but preferred areas of exit have not yet shown up, except for A in the west. The North group exhibits a very different pattern since they are all in the Slope Sea. The near-surface geostrophic currents in the Slope Sea follow the bathymetry to the west (Rossby *et al.,* 2005) at $O(0.1)$ m s^{-1}. These westward currents notwithstanding, the surface drifters exhibit a variable, but mostly southeastward drift across the Slope Sea toward the GS. They all enter the GS—at various points along the stream, and virtually all of them west of ~60°W.

c. Drifter exit patterns

Figure 6 (top) summarizes the exit patterns in terms of GSDL segment crossings while the lower left and right panels show the histograms to first and final exits, respectively. Note that the sum of the exits in the top panel adds up to more than the number of drifters. This larger number includes local exit and re-entrainment across the GSDL one or multiple times before final exit from the GS farther downstream. As the spaghetti diagram in Figure 2 shows, drifters escape the stream to the south in four principal areas. Region D exhibits the highest activity with 53 crossings, followed by region A with 38 crossings, and region E with 37 crossings. The three western regions of highest crossing activity (A, C, D) emphasize first exits A and D from the stream; as drifters re-enter and continue in the stream, the final exit locations shift farther to the east (D and E). This pattern can be seen in the right panel. When examining both the first and final exits of drifters along the GSDL, regions A, D, and E (segments 2, 7 and 9) stand out as preferential sites for expulsion from the Gulf Stream. Region C is a bit broader and one where some drifters recirculate back into the GS from D. These and other drifters will eventually exit the stream farther downstream in region E.

When we compare drifter patterns in North and South groups we find that North drifters exit the stream to the south farther to the east (Fig. 7). This figure confirms the three regions of high drifter exits: A, D, and E. West of D, 52% of the South subset exit the stream compared to only 23.5% of the North subset reflecting the fact that the latter subset needs to

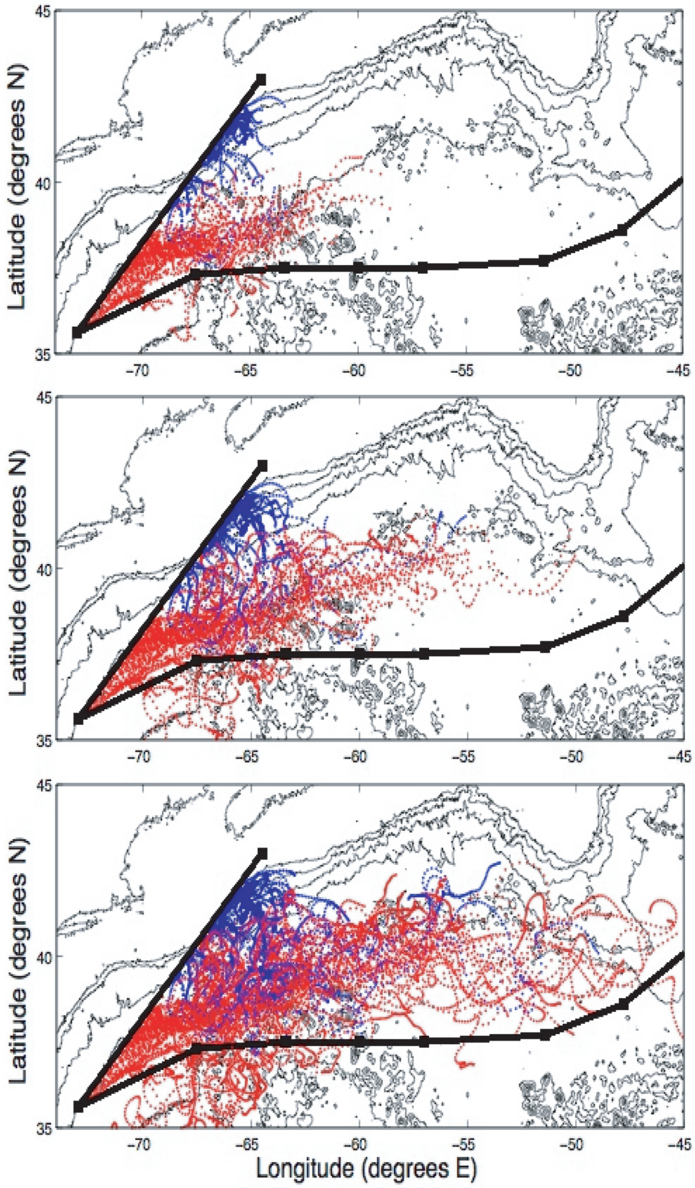

Figure 5. Domain of occupation after 1, 2, and 4 weeks. Tracks in red and blue belong to the South and North subgroups, respectively. Positions plotted 4× per day.

cross the Slope Sea and the full GS in order to exit to the south. The majority of the South drifters, more broadly distributed in the core of the stream when they cross the GSEL, require less additional displacement to exit to the south; thus their first exit occurs farther west than for the North drifters.

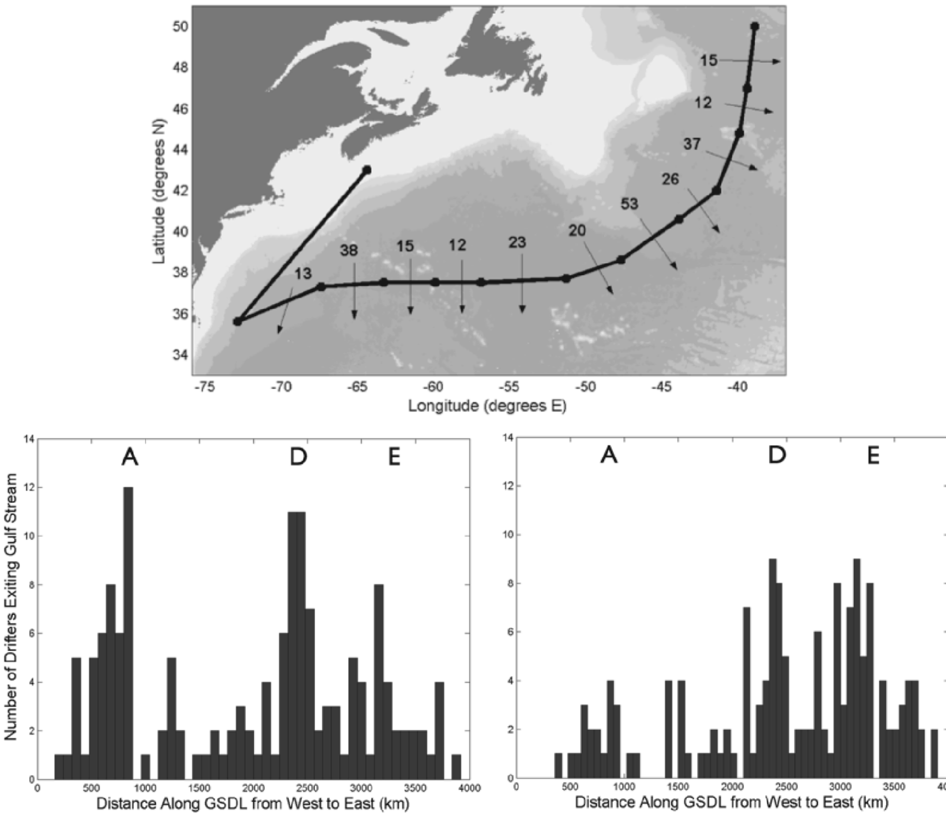

Figure 6. Top panel: GSDL with number of exits to the south across each segment. The lower left panel shows the distribution pattern for first exit from the GS while the right panel shows the corresponding pattern for final exit. The regions of highest first crossing activity occur in the west (A and D in lower left panel) whereas final exit occurs farther to the east (D and E in lower right panel).

4. How do drifters cross the Gulf Stream?

The geographical distribution of enhanced loss from the GS provides some helpful clues to the mechanisms involved. Two striking patterns have emerged thus far: (1) All drifters exited the stream to the south, and (2) the southward exits appear to aggregate in regions known for their large amplitude meanders. Two mechanisms consistent with the above are wind-driven Ekman transport and exchange processes associated with large-scale meanders. We consider first the role or impact of meandering, but preface this by noting that the prevailing winds impose a general surface drift to the south throughout the area of interest. This wind stress "preconditions" or biases all surface motion to the south regardless of what other processes may be taking place. We return to a more detailed discussion of Ekman drift in Section 4b.

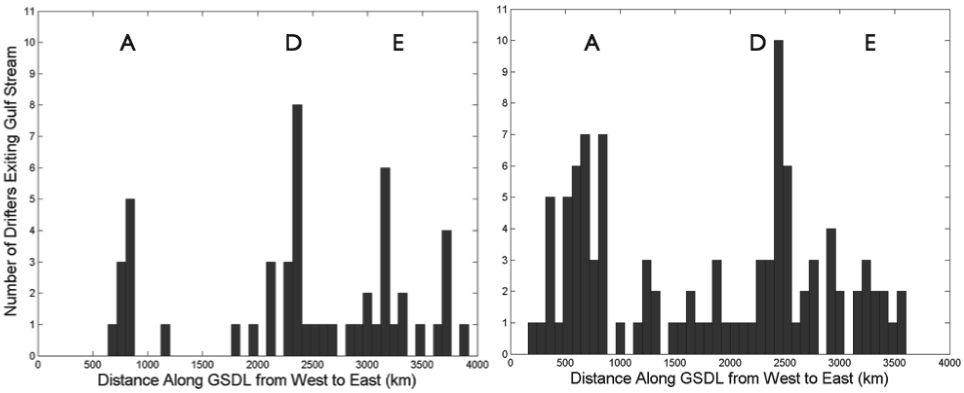

Figure 7. Histogram of first exits for North and South groups, respectively (left and right panels). Note how the northern group crosses the GSDL farther east.

a. Meandering

The characteristics of meanders in the study area fall into either the free meandering of the zonally-flowing GS (Richardson, 1983), or the topographically-locked meandering of the NAC dictated by the shape of the continental escarpment where it flows northeastward east of Canada (Kearns and Paldor, 2000). However, despite their different meandering behavior, both currents have been historically viewed as barriers to cross-frontal exchange at the surface. From an analysis of an extensive hydrographic survey of the GS in 1960 (Fuglister, 1963), Bower *et al.* (1985) suggested that the GS be viewed as a barrier to cross-frontal exchange on shallow isopycnal surfaces. As evidence of this, they showed the coincidence all along the GS to 50°W of a sharp water mass boundary with the path of the current itself. Using an isopycnal dissolved oxygen budget, Bower *et al.* (1985) estimated that a cross-frontal eddy oxygen flux had to be included in order to obtain reasonable closure. They found that the hypothesized formation of cold core rings as pinched-off meander troughs did not suffice to balance fluxes and losses in the Sargasso Sea. Subsequent Lagrangian studies showed how meander-induced circulation enables an important mechanism for cross-stream exchange. Explained in more detail by Song and Rossby (1997), the jet begins to meander, inducing a centrifugal force pulling the water parcels from the center to the edge of the current, and allowing some of these water parcels to be detrained from the jet completely. Bower (1989), Bower and Rossby (1989), Bower (1991), Dutkiewicz *et al.* (2001), Bower and Lozier (1994), Song *et al.* (1995), Song and Rossby (1997), Lozier *et al.* (1997), Rajamony *et al.* (2001), and Schollaert *et al.* (2004) all describe the role of meander-induced cross-current movement to the exchange of water mass and properties across the GS. While most of the above studies apply to isopycnal pathways, the same applies at the surface. Parcels will far more likely detrain from the meandering current when the meanders are steep. To illustrate this we superimpose the trajectory of GLOBEC drifter #53 on sea-surface temperature at the time it is exiting

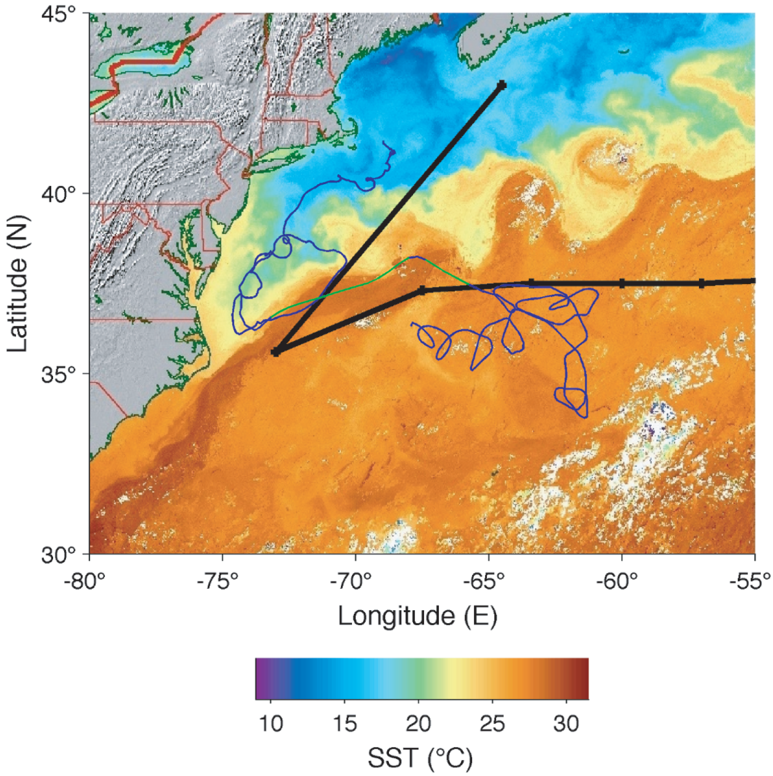

Figure 8. Trajectory of one surface drifter superimposed on sea-surface temperature (SST) at the time of this drifter's escape from a meander trough. The track is shown in green for speeds >0.9 m s^{-1}. SST image for Sept. 23, 1996 from the remote sensing group at APL/JHU (http://fermi.jhuapl.edu/avhrr/gs).

the stream (Fig. 8). The color-coding of the speed of the drifter track illustrates its entrance and expulsion from the GS with the green trajectory (speeds greater than or equal to 0.9 m s^{-1}) representing its time in the current. The pattern of sea-surface temperature at the time of its exit (September 23, 1996) shows, as one might expect, a steep trough where the drifter left the stream.

Bower (1991) developed an elegant kinematic model to elucidate fluid pathways in a meandering jet. By specifying a two-dimensional stream function of the jet in the frame of the propagating meander, cyclic boundary conditions apply such that flow out of the field of view re-enters on the opposite side. By prescribing realistic meander wavelength and propagation rate (which appears as a reverse flow outside the stream), jet velocity and width, one can then examine retention in the stream as a function of only one parameter, namely meander amplitude. Dynamical mechanisms would need to be included in a complete analysis of these phenomena, but here we use Bower's model to illustrate how expulsion can take place at meander trough A.

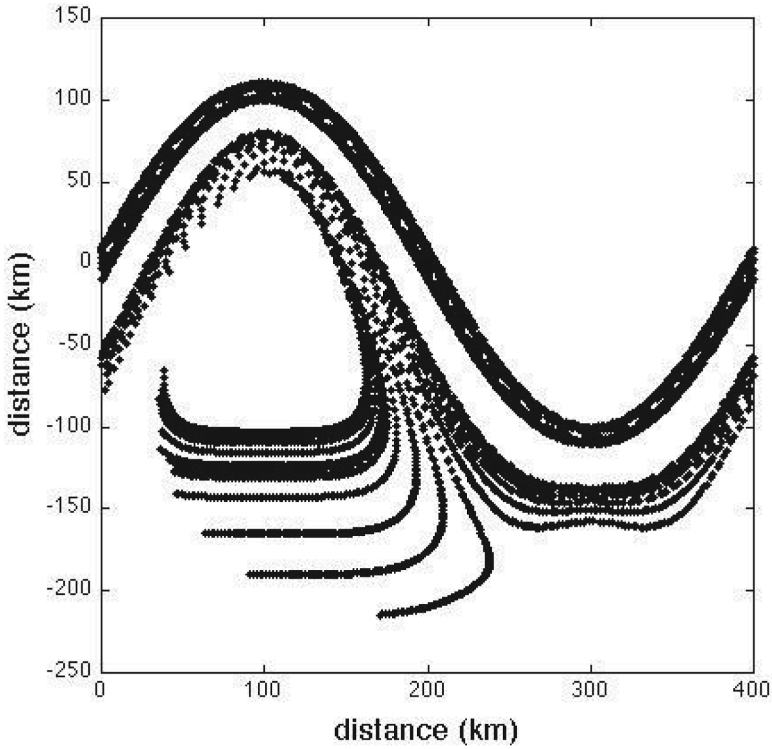

Figure 9. The Bower kinematic model applied to a steep meander. The meander wavelength and amplitudes are 400 and 100 km, respectively. Peak speed is 200 km day^{-1} and the phase velocity is 10 km day^{-1}. “Drifters” were deployed along the axis of the current and 40 km to the south thereof. After 18 days a significant fraction of the southern drifters have been expelled and started recycling in the retrograde direction. The centerline drifters remain tightly arranged along the axis of the current. (Cyclic boundary conditions have been applied.)

We choose 400-km wavelength (Lee and Cornillon, 1995), a phase velocity of 10-km day^{-1} based on Gilman (1988), a peak speed in the current of 200-km day^{-1} and a scale width for the current of 40 km (somewhat larger than the 34-km radius of deformation for the anticyclonic side of the current, Rossby and Zhang, 2001) and a meander amplitude of 100 km. “Drifters” were deployed every 10 km along two lines, the current axis and 40 km to the south thereof. Figure 9 shows the spread of the drifters. The center-line remains distinctly in the center of the current for the 18 days. The southern line shows clear evidence of drifter detrainment and retrograde drift, which reflects the fact that the coordinate system is not fixed in space but follows the phase propagation of the meander (Bower, 1991). Two points can be made here: detrainment from the current on the southern side is clearly evident, but the continuity of the centerline means no fluid can get across the current with the parameters chosen here. Even a larger meander (150 km amplitude) has an unbroken string of drifters along the centerline.

The 44°N trough presents a different situation for, as its name implies, the trough does not propagate; it remains stationary at that latitude. Since downstream meandering provides the fundamental mechanism for fluid loss as discussed in the previous paragraph, stationary meanders imply retention in the stream from a kinematic point of view. And, in fact, observations have shown how some drifters and subsurface floats have passed through a remarkably deep (or steep) 44°N trough (e.g. Carr and Rossby, 2001). However, one can still show how kinematic loss of fluid could take place, by decreasing the meander amplitude during a fluid parcel's transit through the trough. Since the Bower model does not include time-dependence in the meander frame we impose time-dependence by reducing the meander amplitude at an exponential rate from 100 km to 15 km during a similar 18-day period. The rate is arbitrary, but attempts to be realistic. We choose the same 400-km wavelength, but with no phase propagation. The peak speed was reduced to 80-km day^{-1} reflecting the slower surface speeds in the NAC. Figure 10 shows the initial and final centerlines of the meander as dotted and solid lines, respectively. Drifters were deployed along the same two lines shown in Figure 9. The final distribution of drifters is shown. The entire center group is still in the high-speed center (indicated by the thin black line), all drifting at speeds between 70- and 80-km day^{-1}. The southern line has mostly left the current, with half the drifters moving at speeds of 10-km day^{-1} or less. There is no overlap between the two groups. Even though the time dependence differs from the previous case, time-dependent meandering increases exchange between the current and surrounding waters.

b. Ekman drift

We now address the question of almost perfect asymmetry of loss from the stream. Both Bower (1989) and Bower and Lozier (1994) had shown how RAFOS floats can exit the GS to either side of the current due to their deceleration as they drift toward the edge of the current upstream of meander crests and troughs, respectively. But, as we have seen, surface drifters show a very strong preference for expulsion to the south. The losses appear to be related to meander activity, but why the striking asymmetry? The answer, we suggest, lies in the Ekman drift.

The predominantly westerly winds in the study area impose a generally southward Ekman drift. Several factors point to this. First, the North group of drifters with their drift east and south across the Slope Sea in a direction quite different from the generally westward flow there, would be hard to understand unless it results from a wind-driven Ekman drift. This wind-driven drift, when applied to the narrow width of the GS, can also explain the ease with which the drifters subsequently can cross over from one side to the other.

Many methods exist for the estimation of Ekman velocity, but for the purposes of this study it will suffice to use the slab model approach (McNally and White, 1985; Rudnick, 2003) where the slab represents the surface mixed layer. Therefore, the actual velocity will depend upon both wind stress and slab thickness or mixed layer depth (MLD). Information on the latter can be obtained from the report by Monterey and Levitus (1997). For the

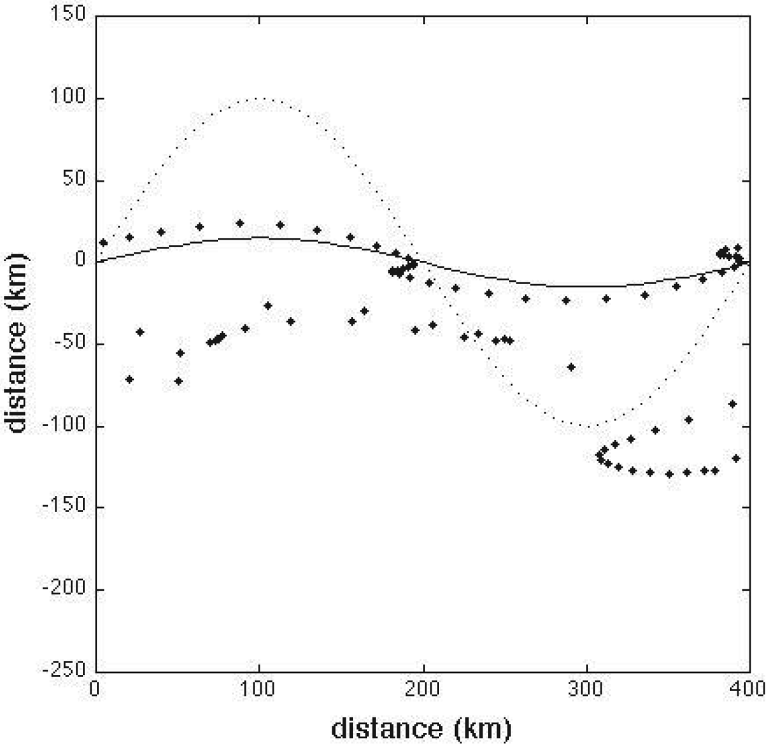

Figure 10. The Bower kinematic model applied to the 44°N Trough. This meander is stationary, and peak speed in the jet is modeled at 80 km day^{-1}. Drifter deployment is the same as in Figure 9. Time dependence is introduced by decreasing the meander amplitude exponentially from 100 to 15 km over 18 days. Note how the centerline drifters remain near the centerline (solid line) as it decays, whereas ~1/2 of the southern drifters have left the decaying meander. (Cyclic boundary conditions have been applied.)

purposes of the study MLD is based on a variable density change from the ocean surface corresponding to a 0.5°C temperature change and thus takes into account the large variability of seawater's thermal expansion coefficient. These MLD values were provided for the 15th of each month throughout the entire year. Figure 11 (top panel) shows the annually averaged Ekman velocity vectors. To obtain these, we first estimate the monthly mean drift velocities. For each month we first obtain Ekman mass transport (normal to the wind): $M = \langle\tau\rangle/f$ (kg m^{-1} s^{-1}), where $\langle\tau\rangle$ is mean monthly windstress and f is the Coriolis parameter. We divide this by density and layer thickness to obtain Ekman slab velocity across the area of interest. These monthly estimates are then averaged to yield the annual mean velocity in Figure 11 (top panel), which shows that the overall mean Ekman velocity is 0.02 m s^{-1} almost due south. This is not a large velocity compared to typical speeds in the GS, but it is on average to the south. Given that the width of the stream where velocities are $>$0.5 m s^{-1} is only 90 km (Rossby and Zhang, 2001), it would take only $O(1)$ month to

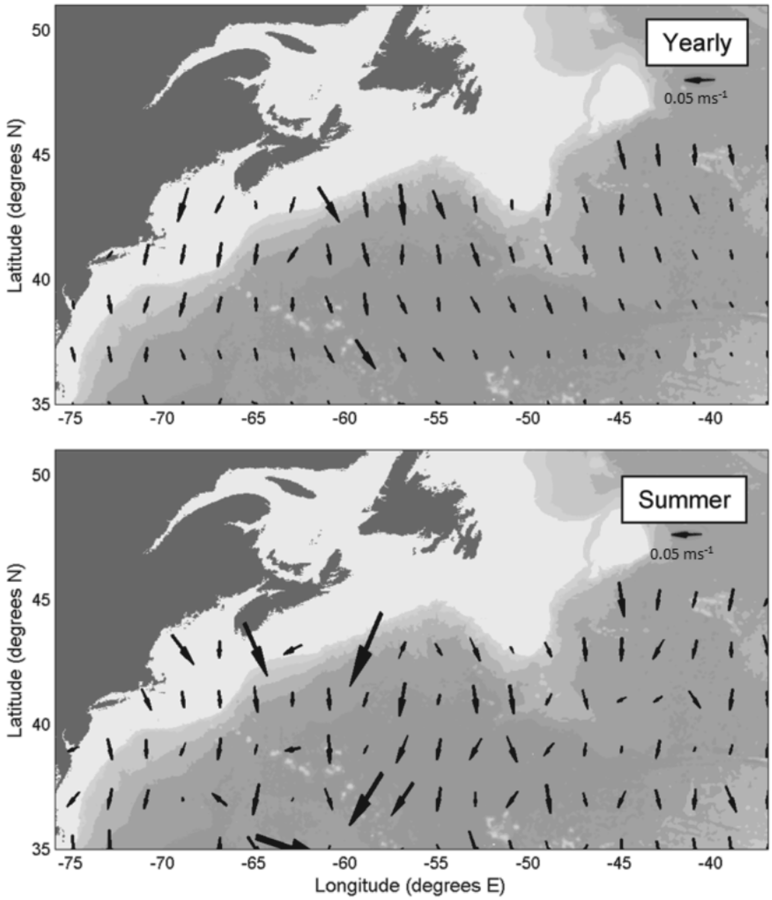

Figure 11. Mean Ekman velocity calculated from windstress at all drifter locations and binned into $2° \times 2°$ boxes. A near uniform distribution of Ekman velocity can be seen over the entire study area. The overall mean drift to the south is 0.02 m s^{-1}. The bottom panel shows corresponding Ekman velocities for the June-July-August summer months only. The same scale factor is used for both panels.

make the crossing. Given the large scale of the wind systems and the averaging over many years, the uniformity of drift without any areas of preferentially large or small Ekman velocity comes as no surprise. This further reinforces the view that the locations of preferential expulsion from the stream as seen in Figure 7 reflect areas of intense meander activity and not the winds.

Knowing that winds have a pronounced seasonal cycle we now consider whether this impacts the GS exit patterns. Intuitively, one might expect the Ekman velocities to be largest in winter due to the large wind stress over the North Atlantic during this season. For the ERA40 data during the period 1995–1999, the east-west wind stress peaks in December, remains high through the winter with a spike in April (in this 5-year data set).

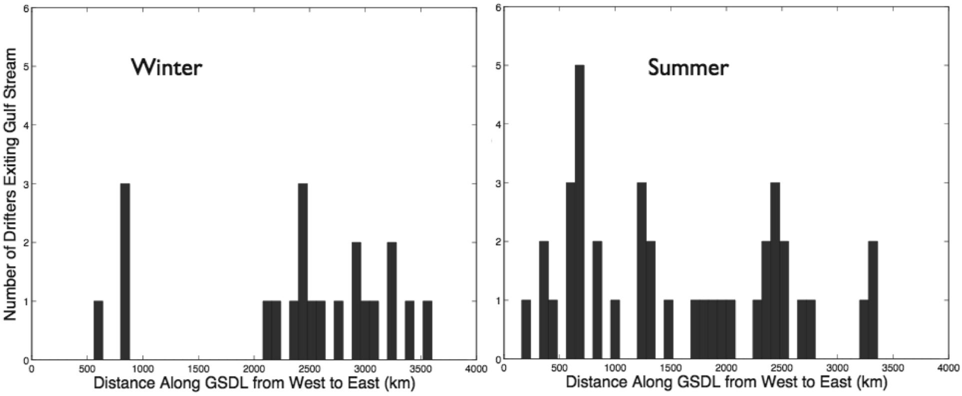

Figure 12. Histograms of first exits of the South subset of drifters that entered the stream in winter months Dec-Jan-Feb (left panel) and those that entered the stream during the Jun-Jul-Aug summer months (right panel). The summer group shows a heavier distribution of exits to the west than does the winter group.

This seasonal pattern can also be seen in the Lindau (2001) climate atlas. MLD decreases toward summer, and on a fractional basis it thins much more than the decrease in Ekman transport. As a result the computed Ekman velocity actually increases in summer (Fig. 11, bottom). A zonal average of Ekman velocity to the south along 37 and 39°N yields 0.024 and 0.031 m s^{-1} during the three winter (JFM) and three summer (JJA) months, respectively, showing a 29% larger Ekman velocity in summer than in winter.

In order to determine whether the drifter data exhibit a similar pattern, we examine the exits of drifters from the larger South subset with its distribution throughout the core of the stream when they cross the GSEL. We further split this group into two subsets, the "Winter" subset consisting of **39** drifters that entered the stream across the GSEL between January and March, the months of the deepest MLD, and the "Summer" subset consisting of **21** drifters that entered the stream across the GSEL between June and August, the months of the shallowest MLD. Figure 12 shows the results. A suggestion of seasonality can be seen in the 0–2000 km range: From entry to region D, 64% of the summer drifters exit, compared to only 19% of the winter drifters, with a particularly significant increase in the number of summer exits in area A. Another way to express the above can be seen in Figure 13 which shows the time to exit for all drifters. The median residence time for a winter drifter was 113 days compared to the median residence time in the summer of only 40 days. Because of the thin MLD and greater southward Ekman velocity in the summer, drifters will exit the stream sooner and farther to the west. In winter, with a deeper MLD, and despite the larger Ekman transport, the drifters remain in the stream farther to the east.

5. Discussion and summary

We have shown from surface drifter trajectory data that surface waters in the GS do not remain in the current but slip out of it to the south. Using two sets of drifters, a set of

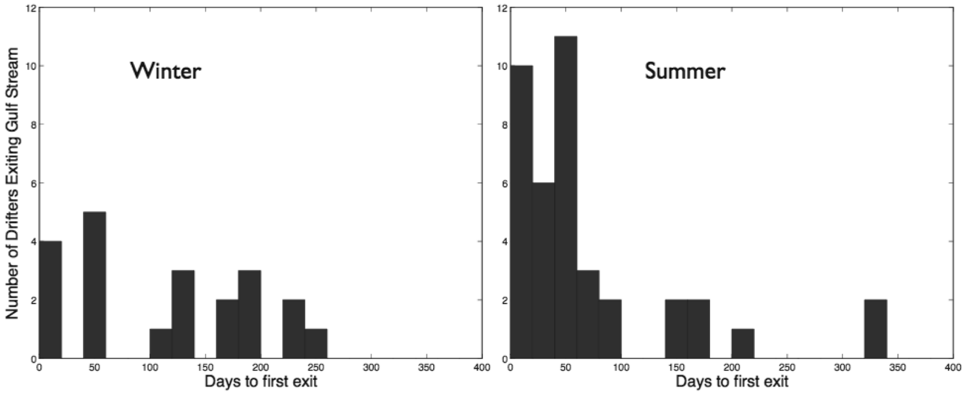

Figure 13. The same set of drifters as in previous figure but now from a temporal perspective showing time to first escape. The median time to expulsion was 113 days in winter compared to 40 days in summer. For both groups the numbers are limited so the results should be seen as suggestive only.

drifters already in the stream at Cape Hatteras and a set of drifters initially well north of the stream, we show that both will eventually exit the current to the south, the latter farther to the east than the former. We show that the action of winds appears to be responsible. In further support of this we show that this drift to the south takes place more rapidly in summer, and that the reason for this is the much thinner mixed layer resulting in larger Ekman layer *velocities* despite lower Ekman *transports.*

Given the large scale of the wind systems one might expect that the losses from the GS to the south would be rather uniformly distributed. We find instead that exit from the GS takes place primarily in three areas: region A (the NESC), region D (the SENR), and region E (the 44°N Trough), at each of which the rapid current exhibits strong cyclonic curvature. Region A is where the GS first develops the first steep meanders east of Cape Hatteras. We do not *know* that the New England Seamount Chain is responsible, but it seems plausible. It is also here that the GS shifts north about 1.5°. At region D the GS turns to the northeast upon crossing the SENR, and finally at region E the NAC flows through the 44°N trough, a steep (or sharp) meander that sits between the essentially permanent Mann Eddy at 42°N and Flemish Cap. This meander does not propagate; it is locked in place. But it does expand and contract considerably over a wide range of time scales (Kearns and Rossby, 1998). Considerable exchange takes place at region C as well. There is some indication that this region also re-entrains some water forming a local anticyclonic recirculation between C and D.

One may perhaps be able to argue that in these three regions the meander troughs are particularly steep. If a drifter "survives" meander transit here, it most likely was not near the edge of the current and thus may survive modest-sized meanders until it reaches the next "steep" meander region. This would help explain the lack of loss in between. These drifter loss patterns could apply equally well to the cross-stream exchange and mixing of nutrients and phytoplankton from the Slope to Sargasso Seas. The likelihood of exchange in the opposite direction could be much lower. One can see evidence for similar loss patterns in an earlier study by Richardson (1983). Although that study had only 110 drifters to work with, regions A and D show up as areas of loss from the stream, with perhaps some activity near, but somewhat to the west of C as well.

The Mean Dynamic Topography (MDT) prepared by AVISO (http://www.aviso.oceanobs.com/es/data/products/auxiliary-products/mdt/comparison-of-global-mdt/index.html) represents a significant improvement over earlier products, especially in terms of total sea level difference across the GS at 70°W, now about 1.25 m compared to an earlier 0.8 m. Of specific relevance here, it also exhibits a number of local dynamic height maxima along the offshore limit of the GS and NAC, one between Cape Hatteras and roughly region A, and another between 60° and region D. The Mann Eddy and region E show up clearly as well as a NAC path similar to what has been reported in the past (e.g. Rossby, 1996). While this figure differs from our results with respect to the shape/length of the recirculation between region C and D, it points to the existence of local recirculation gyres that superimpose along-stream variations in transport. This raises the concern that estimates of transport, however accurately obtained, cannot immediately be compared with estimates at other sites without knowledge of these local patterns.

This study shows clearly that Ekman forcing plays the central role in forcing surface drifters to the south across the GS toward the Sargasso Sea. We have also shown that drifters in the cool Slope Sea are forced south into the warm GS. This begs the question how to reconcile the cross-frontal flow with the existence of a well-defined band of warm water coursing its way east from Cape Hatteras; i.e., why doesn't cold water from the Slope Sea just cover the GS as one proceeds east? There are several issues here such that a detailed analysis goes well beyond the intent of this study, but it can be noted that the Ekman velocity is still small compared to the downstream velocity of the GS such that as surface water from the Slope Sea is pushed by the winds into the stream, it is immediately sheared and mixed into the rapid flow of warm water and thereby assumes the properties of the GS. This mixing may be further enhanced by the fact that Slope Sea–surface water is generally denser (especially in winter) than that of the GS resulting in additional convective overturning. As an aside it might be noted that the warm band gradually weakens in both width and thermal contrast in the downstream direction, and the demarcation between the cold Slope Sea and the generally warm waters of the GS becomes increasingly complex or convoluted. Intense heat loss to the atmosphere and meander-induced exchange with the Sargasso Sea also contribute to the weakening of the warm band.

The fractional loss of drifters to the Sargasso Sea between Cape Hatteras and the SENR greatly exceeds any decrease in downstream mass transport. The reason for this pattern must be seen in the fact that the drifters all lie in the Ekman layer: they are representing that thin layer, not the underlying downstream flow of the GS. The total Ekman mass transport across the GS per unit length is approximately $M = \langle \tau \rangle / f$ (kg m^{-1} s^{-1}) = 0.06

(N m^{-2})/1 $\times 10^{-4} = 600$ kg m^{-1} s^{-1}. Dividing this by the density of water (10^3 kg m^{-3}) and multiplying by the distance from Cape Hatteras to the SENR (~2000 km) yields 1.2 Sv. The effect of this small transport, compared to the 88 Sv just east of Cape Hatteras (Halkin and Rossby, 1985) is greatly magnified because it takes place at the surface.

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