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Cross-Frontal Exchange in the Middle Atlantic Bight as Evidenced by Surface Drifters

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ABSTRACT

Surface drifters at 10 and 40 m are analyzed to assess cross-frontal exchange characteristics within the Middle Atlantic Bight. This Lagrangian analysis shows a shelfbreak jet characterized by strong and ubiquitous meandering. The drifters collectively demonstrate the continuity of the shelfbreak frontal jet from Georges Bank to Cape Hatteras. Along the length of the shelf break the drifters are detrained both onshore and offshore, yet offshore detrainment is predominant. The sites for offshore detrainment are distributed along the Bight, precluding the possibility that localized bathymetric features are the primary conduits for near-surface to mid-depth cross-frontal exchange. Finally, a strong seasonal asymmetry is noted in the drifter exchange pattern, with more offshore exchange in the winter than in the summer. However, the available data limits our interpretation of this feature.

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1. Introduction

At the continental shelf break offshore of the eastern United States, a sharp temperature and salinity front separates the relatively cool and fresh coastal waters from the warm and salty slope waters (Fig. 1a). Aligned with this front in the Middle Atlantic Bight is an alongshore current (Fig. 1b), which is part of a large-scale coastal current system that extends back into the Labrador Sea (Chapman and Beardsley 1989). The mean cross-frontal or cross-shelf velocities associated with the current in the Middle Atlantic Bight are weak, on the order of 0.01 m s^{-1} (Houghton et al. 1988), relative to the downstream velocities, on the order of 0.2–0.5 m s^{-1} (Linder and Gawarkiewicz 1998; Gawarkiewicz et al. 1996); yet there is clear evidence of strong cross-frontal exchange in the Middle Atlantic Bight. From hydrographic surveys, interleavings of slope and shelf waters on the order of 20–50 km have been observed in the Middle Atlantic Bight (Voorhis et al. 1976; Ramp et al. 1983; Houghton et al. 1986; Garvine et al. 1988), and Gulf Stream waters have been found on the continental shelf near Cape Hatteras, North Carolina (Churchill and Cornillon 1991; Gawarkiewicz et al. 1992, 1996). Based on the spatial and temporal scales of the observed variability, it is assumed that mesoscale processes are responsible for the observed onshore–offshore exchange. Candidates include the interaction of the frontal jet with warm core rings spawned from the Gulf Stream, surface mixed layer transport due to wind stress from synoptic weather systems, the influence of slope (or open ocean) variability, and the local instability of the current. To ascertain which of these processes are more likely than the others, a detailed look at the characteristics of the observed exchange is desirable. While the Eulerian-based observational studies mentioned above have immeasurably furthered our understanding of shelfbreak frontal characteristics, a Lagrangian view is especially beneficial for a study of cross-frontal exchange since the fundamental interest is centered on water parcel history.

The purpose of this note is to present a preliminary analysis of cross-frontal exchange across the shelfbreak front in the Middle Atlantic Bight by studying the Lagrangian characteristics of the system. Our understanding of cross-frontal exchange in the open ocean has benefited greatly from studies of SOFAR and RAFOS floats that have been released in the Gulf Stream over the past two decades (e.g., Bower and Rossby 1989; Owens 1984; Song et al. 1995, and references therein). Analyses of these trajectories have established the patterns of exchange across this open ocean front, including its strong depth dependence and have led to an understanding of the mechanisms of exchange (e.g., Bower 1991; Samelson 1992; Dutkiewicz et al. 1993; Pratt et al. 1995; Lozier et al. 1996, 1997). To determine which of the aforementioned mechanisms are responsible for cross-frontal exchange at the shelfbreak front, we plan to use Lagrangian data in conjunction with contemporaneous meteorological and advanced very high-resolution radiometer (AVHRR) data. We present our preliminary findings based on an analysis of the Lagrangian data alone. In this work we employ a set of drifter trajectories in the waters of the Middle Atlantic Bight to answer the specific questions: 1) Is there a preferred site for cross-frontal exchange in the Middle Atlantic Bight? 2) Is the exchange across this front symmetric? and 3) Is there a seasonality to the exchange pattern? It is hoped that this initial study, which establishes the basic pattern of exchange across a shelfbreak front, will provide some framework for studies on cross-frontal exchange mechanisms in the Middle Atlantic Bight, and perhaps in other dynamically similar regions.

2. Data and methods

The Lagrangian data used in this study stem from 10-m and 40-m drifters released over a 32-month period from January 1995 to August 1997 as part of the Global Ocean Ecosystems Dynamics (GLOBEC) Northwest Atlantic program (R. Beardsley and R. Limeburner 1999, personal communication). While these drifters were deployed to study flow over Georges Bank and the surrounding waters of the Gulf of Maine, a majority were eventually entrained into the offshore shelfbreak frontal jet and carried southwest into the Middle Atlantic Bight. Such entrainment is likely the result of the well-known tendency of constant-depth drogued drifters, such as those used in the GLOBEC program, to accumulate in frontal convergence zones (Loder et al. 1992). Thus, despite their deployment over Georges Bank, these drifters have facilitated this study of shelfbreak exchange.

The dataset used for this study consists of 36 10-m drifters launched in 1995, 36 launched in 1996, and 43 in 1997. Additionally, the study uses 5 40-m drifters that were launched in 1996 and 23 launched in 1997. Overall, there are 115 10-m drifter trajectories and 28 40-m drifter trajectories used in this analysis. After the drifters were launched in the waters of Georges Bank, their position and in situ temperature were interpolated to 6-h intervals using *ARGOS* satellite data. A spaghetti diagram of the 10-m drifter paths for 1996 is shown in Fig. 2a and all (from 1996 and 1997) 40-m drifter pathways are shown in Fig. 2b. Spaghetti diagrams for the 10-m drifters launched in 1995 and 1997 show similar distributions to those launched in 1996 and are thus not shown here. For the purpose of our study, our focus is on the drifter pathways within the Middle Atlantic Bight, specifically those within the vicinity of the shelfbreak.

Specific goals in this study of cross-frontal exchange were to determine whether, when, and where drifters were detrained from the frontal jet. Since all drifters were launched well inshore of the shelfbreak frontal jet, the first step in our study was to determine whether a drifter ever became entrained in the jet. Barring any quantitative measure to gauge whether a drifter was in or out of the jet, a qualitative assessment was made for each of the 115 drifter paths. A drifter was considered to have entered the shelfbreak frontal jet if it moved into the shelfbreak region (approximately designated as the region from the 50 to the 1000-m isobath), if it showed some acceleration as it moved into the region and if it moved generally southwestward in the direction of the shelfbreak jet, once it had entered the region. Significant changes in a drifter's temperature record were also an indicator of entrainment. Based on our analysis, 81 drifters at 10 m and 13 at 40 m joined the shelfbreak frontal jet.

Once it had been established which floats had joined the frontal jet, the next step was to assess if, where, and when a drifter crossed out of the jet. The assessment of whether a drifter was out of the jet was again based on the qualitative aspects of each drifter path. A drifter was judged to be out of the jet if it moved out of the shelfbreak region, if it showed a rapid deceleration, and if it showed a path orientation distinctly different than that of the expected southwestward orientation of the background frontal jet. Again, the drifter's temperature record was inspected for evidence of movement across the thermal front. To mark the downstream location where a drifter had left the frontal jet on the offshore side, we chose to mark the position (latitude and longitude) where it crossed the 1000-m isobath. The choice of this isobath was made as it approximately bounds the offshore side of the meandering envelope created by the shelfbreak frontal jet. Because this designation is somewhat arbitrary, we tested the sensitivity of our results to designations of the 500-m isobaths and of the 1500-m isobath and found little change. As will be discussed, some drifters that were detrained from the current were reentrained and then detrained again downstream. In such a case, a single drifter may have more than one crossing point. For each drifter information was collected on whether, when, and where the float joined the frontal jet and whether, when, and where the float crossed out of the frontal jet. From this information we were able to calculate the residence time for each drifter (number of days in the current) and its alongshelf displacement (distance between its initial entrainment location and its detrainment location). The results from the analysis of these data and calculations are presented in the next section.

3. Results

The spaghetti diagrams of the 10-m and 40-m drifter paths (Figs. 2a,b) show a remarkably coherent view of a shelfbreak frontal jet in the Middle Atlantic Bight. Overall, the drifter pathways at both depths delineate a generally southwestward flow along the shelfbreak after they were launched in the waters of Georges Bank. Such a picture is consistent with recent studies (e.g., Pickart et al. 1999; Gawarkiewicz et al. 2001; Linder and Gawarkiewicz 1998) that have suggested the presence of a frontal jet that stretches the entirety of the Middle Atlantic Bight shelf break. After the drifters were launched in the waters of Georges Bank a majority were entrained into the shelfbreak frontal jet from the shoalward side of the front. These drifters generally moved westward south of Nantucket Shoals and then, following the 100-m isobath, flowed southwestward toward Cape Hatteras. The trajectories show a considerable amount of entrainment and detrainment along their paths, especially on the offshore edge of the shelfbreak frontal jet. At Cape Hatteras the drifters are swept into the surface waters on the northern side of the Gulf Stream, consistent with the flow of shelf water in that vicinity as observed from hydrographic surveys (e.g., Gawarkiewicz et al. 1996). Finally, we note the relatively wide envelope created by these trajectories, which suggests that the shelfbreak jet is not strongly trapped to a particular isobath. While the areal coverage of the 40-m drifter tracks is reduced relative to the 10-m drifters (attributable to the reduced speed at 40 m), the general pattern is similar at both depths.

a. Individual trajectories

An examination of the individual trajectories in the 10-m and 40-m drifter datasets reveals some characteristic features, shown in Fig. 3 for the 10-m drifters. The color of each drifter position denotes its temperature in order to facilitate an assessment of cross-frontal movement. Of those drifters entrained into the shelfbreak frontal jet, some were expelled onshore (Fig. 3a), some were pulled offshore by Gulf Stream rings (Fig. 3b), some were carried down the length of the Middle Atlantic Bight and then pulled into the Gulf Stream (Fig. 3c), while others were expelled offshore before the shelfbreak frontal jet intersected the surface Gulf Stream waters (Fig. 3d). Many of the individual trajectory paths illustrate quite clearly the continuity of the shelfbreak jet within the Middle Atlantic Bight. As will be shown later, a significant fraction of the drifters are carried downstream with little or no detrainment from the jet.

In addition to showing the continuity of the shelfbreak frontal jet, the drifters also display the ubiquity of meandering associated with this front. Meandering paths are persistent over the seasons and over the entire spatial domain of the Middle Atlantic Bight. Features of the trajectories provide evidence that traveling, rather than stationary, waves are responsible for the meandering pathways. Crested meander patterns (as seen in Figs. 3c, and 3d) are characteristic of flow regimes where the phase speed of a wave approaches the magnitude of the local flow velocity (Lozier et al. 1997), and small loops in the trajectories (as seen in Fig. 3c) also suggest the presence of a traveling wave field, as demonstrated for Gulf Stream trajectories by Lozier et al. (1997).

It is important to note that, while it was apparent that warm core rings are able to “pull” a drifter from the shelfbreak jet into the slope water region, floats were more often than not expelled in the absence of such a ring. Expulsion of water parcels from a meandering current has been explained in the context of flow kinematics whereby cross-stream motion results from the presence of a propagating meander and or a meander exhibiting growth or decay (Bower 1991; Song et al. 1995; Lozier et al. 1996). If propagating meanders are present along the length of the shelf break, then cross-shelf exchange would be expected to be present along the length of the shelf break as well. This issue is explored in the next section.

b. Locations of detrainment

As evident from the spaghetti diagrams in Fig. 2, and as quantified in section 3d, many more drifters were “lost” to the offshore side of the shelfbreak frontal jet than to the onshore side of the current, indicating a strong asymmetry in cross-frontal exchange in the Middle Atlantic Bight. Such asymmetry is consistent with previous ideas about offshore losses of shelf water to the continental slope based on analyses of water masses (e.g., Mountain 1991). The focus of this section is on the predominant offshore exchange.

Preferential sites for the detrainment of water parcels from the shelfbreak jet might result if riverine input creates a large offshore local transport, if there is a preferential site for the intersection of warm core rings with the shelfbreak jet, and/or if cross-shelf exchange is affected by local bathymetry, such as canyons. The locations of all cross points (as defined in section 2) for the 10-m and 40-m drifters are shown in Figs. 4a and 4b, respectively. First cross points are designated with a black star, while second cross points are designated with a red dot. (The reader is reminded that a drifter may cross into and out of the jet more than once and as such it may have more than one associated cross point.) From this distribution it is apparent that there is not a preferential site for offshore exchange since the detrainment sites are distributed along the length of the Middle Atlantic Bight. Given that all drifters were entrained into the shelfbreak frontal jet at the upstream site east of Georges Bank, it might be expected that a much larger number would be expelled upstream simply based on probability estimates; fewer drifters are available at downstream sites for detrainment. Had the drifters all been placed in the center of the jet or on the offshore side of the jet, perhaps more would have escaped further upstream than downstream. However, these drifters were all initially entrained from the jet's onshore side and thus they were not all in a position for offshore exchange at the upstream sites. Using only the first cross points produces a pattern with fewer downstream locations, illustrating that some of the evenness of the distribution in Fig. 4 can be attributed to reentrainment. Finally, we note that such a distribution for cross-shelf exchange sites implies that the process(es) responsible for the variability are present along the length of the shelfbreak frontal jet. Possible candidates include frontal instability, as well as wind-driven offshore transport. We conclude that it is unlikely that canyons or other localized bathymetric features affect the spatial distribution of upper shelf water ejection onto the continental slope in the Middle Atlantic Bight. However, the bathymetric influence on detrainment from the shelfbreak jet at depths below these 10-m and 40-m drifters remains unknown. Finally, we note that our conclusion regarding the topographic influence applies to its effect on offshore detrainment in the Middle Atlantic Bight. The much-studied and strong influence of bathymetry on flow in the Gulf of Maine/Georges Bank region is quite evident in Fig. 2.

c. Seasonality

Past observations have noted a seasonal asymmetry in the exchange across the shelfbreak front in the Middle Atlantic Bight. Wright (1976) found that shelf parcels were present on the slope over 90% of the time during the late spring and summer and were present less than 10% of the time during winter. Houghton et al. (1988) measured the heat flux across the shelfbreak front south of New England and found a seasonal variation; the flux increases as the summer progresses due to the contribution from eddy fluxes. In an effort to assess any seasonality associated with the drifter data, the 10-m drifters were subdivided into 2-month bins. Shown in Fig. 5a is the spaghetti diagram for those drifters that were in the shelfbreak jet during the months of January and February (1995, 1996, and 1997) and shown in Fig. 5b is the spaghetti diagram for those drifters that were in the current during the months of June and July (1995, 1996, and 1997). We note that these months do not represent the launch months, but rather the months during which the drifters were transiting the shelfbreak jet. Depending on the season, there can be a one, two, or even three month lag from the time a drifter is launched until it is entrained into the shelfbreak jet.

The patterns from the winter and summer trajectories are markedly different. A higher percentage of drifters were drawn offshore prior to reaching the Gulf Stream confluence during the months of January and February in the Middle Atlantic Bight (92% of those in the stream) than during the months of June and July (25% of those in the stream). Such a difference is reflected in the average residence times, 15.1 days in the winter and 41.8 days in the summer, and in the average displacements, 184 km in the winter and 478 km in the summer. In addition, as the drifters progress southwestward they are located farther offshore in the winter compared to the summer. Perhaps the most striking difference is the character of the trajectory paths near their launch sites. During the summer months the launch site for these 10-m drifters is in the midst of an anticyclonic gyre that encircles Georges Bank and essentially traps the drifters for up to several months, as discussed by Limeburner and Beardsley (1996). An inspection of the four other seasonal plots shows that there is a progression leading to the winter/summer difference displayed in Fig. 5. During the late winter and early spring months, the drifter trajectories move onshore and less exchange with the offshore waters is evident. The drifter paths in the late summer and early fall show the opposite: The envelope of trajectories moves offshore relative to the summer positions and more exchange with the offshore waters is seen.

The differences between the winter and summer trajectories can potentially be attributed to two factors. During the winter, the wind stress is much stronger than in summer, and thus offshore Ekman transport within the surface mixed layer is likely to be much more important in winter. This may also explain the wider envelope of trajectories within the shelfbreak frontal jet during the winter. However, a second, and more subtle, difference is the manner in which the drifters cross from Georges Bank to Nantucket Shoals. During the summer the drifters appear to cross the Great South Channel in a more northerly position than in the winter. It is likely that during summer the drifters are actually carried within the tidal mixing front over Nantucket Shoals rather than in the shelfbreak frontal jet. The tidal mixing front is typically near the 60-m isobath (see Fig. 15 of Limeburner and Beardsley 1982), which is about 30–40 km shoreward of the 100-m isobath. This seasonal shift in transport across the Great South Channel is also apparent in model simulations (Naimie et al. 2000), where particles cross the channel farther northward during summer than in winter.

The seasonal differences noted here are interesting and they raise many questions, but we are limited in our inferences on several accounts. One is that the winter and summer drifters would need to have the same initial cross-stream position within the shelfbreak jet for us to assess the differences in their subsequent offshore/onshore position. Another is that the drifters are isobaric, and as such their exchange may differ from water parcels, which would presumably lie principally on surfaces of constant density. In addition, these differences might be influenced by seasonal differences in transport; however, such seasonality is not well established. Finally, the uncertainty as to whether or not the drifters are in the shelfbreak frontal jet during the summer complicates the seasonal comparison of offshore exchange. Because of these limitations to our interpretation, it is difficult to reconcile these results with results from previous studies (mentioned above) that found enhanced mixing in the summer months. While the drifter patterns imply more exchange between the shelf and slope waters in the winter months, the extent to which this Lagrangian exchange is associated with Eulerian property fluxes across the front remains to be determined.

d. Overall exchange pattern

The overall pattern of exchange for the 10-m and 40-m drifters is shown schematically in Figs. 6a and 6b, respectively. Of the 81 10-m drifters that joined the current (Fig. 6a), 61 exited on the offshore side of the front and 7 exited on the onshore side of the front, with the remaining 13 still in the current at the end of their mission. Such preference for offshore exchange could result from a distributed offshore transport that results from the freshwater input to the shelf region. The offshore transport is consistent with Wright (1976), who found half the shelf water, defined by salinity, to be present over the continental slope. It is also consistent with the water mass analysis by Mountain (1991) and transport estimates by Biscaye et al. (1994), which suggest that half of the transport entering the Middle Atlantic Bight (~ 0.4 Sv; Beardsley et al. 1985) is lost by the time the flow reaches Chesapeake Bay. It is interesting to note that despite the diminution of the alongshelf transport, offshore detrainment in the lower reaches of the Middle Atlantic Bight is still predominant. The increased offshore exchange evidenced by the drifters may also reflect enhanced exchange between the shelfbreak jet and the shelf waters due to the strong variability of the slope waters. In other words, had there been drifters placed initially offshore, there could have been significant entrainment of these drifters into the shelfbreak jet. This possibility is reinforced by the observation that, of the 50 floats lost to the offshore side prior to Cape Hatteras, 12 were reentrained into the current. This is consistent with the results of Dragos et al. (1996) in which drifters were initially launched over the slope and many were entrained into the shelfbreak jet. Though the numbers are small, it is interesting to note that none of the drifters lost to the onshore side were reentrained.

Of note in this pipe diagram (Fig. 6a) are the 23 drifters that traveled the length of the Middle Atlantic Bight only to be exported to the surface waters of the Gulf Stream and the 13 drifters that were left in the current when their last position was recorded. Considering the high degree of variability in this region, it is striking that over half (46 out of 81) of the drifters that joined the shelfbreak jet upstream either ended up in the current or were exported at the end of the “pipeline.” If we were to count only those drifters which stayed in the current for their entire journey (with no entrainment or detrainment), the count would drop to 24 of the 81 drifters, or one-third of the total. Such numbers are testimony to the continuity of the shelfbreak frontal jet in this region. The view of this continuity illustrates the advantage of Lagrangian data in the assessment of water parcel history.

The pipe diagram for the 40-m drifters (Fig. 6b) shows the same overall pattern of exchange as the 10-m drifters, yet here the numbers are insufficient to draw firm conclusions. More offshore than onshore exchange is noted and, again, almost half (6 of the 13) of the 40-m floats that joined the shelfbreak jet either were throughput to the Gulf Stream near Cape Hatteras or they were in the jet when their last position was recorded. Accounting for entrainment/detrainment the number of floats at 40 m that stayed in the current for their entire mission was 5 (of the 13). This could suggest weak entrainment at this level, yet the small number of 40-m drifters precludes any certainty of this suggestion.

The residence time and alongstream displacement were calculated for each drifter in order to gain some insight into the temporal and spatial scales of the exchange process. Shown in Figs. 7a and 7b are the histograms for the calculated displacements and residence times, respectively, for those drifters that were detrained offshore. The majority of the drifters were detrained within 30 days of their entrainment, yet some were in the shelfbreak region for close to 100 days. The average residence time was 28.6 days, with a relatively large standard deviation of 24.5 days. The alongstream displacements spanned from approximately 30 km to approximately 790 km, with an average displacement of 319 km, with a standard deviation of 202 km. The large range in these values stems from the large difference in the downstream advection for a drifter at the edge of the current compared to one that is centered in the swiftly moving center. Our analysis of the synoptic velocities associated with these drifters shows a range from just several kilometers per day to close to 80 km day^{-1}. Interestingly, the average advection speed, based on a computation of the displacement length for each drifter divided by the residence time of each drifter, yields a value of 14.2 km day^{-1}, with a range from 4.8 to 38.2 km day^{-1} and a standard deviation of 6.7 km day^{-1}. Obviously, no drifter in our study maintains a velocity of 80 km day^{-1} for the duration of its residence in the shelfbreak current. Instead, the drifters meander across the stream, moving from a relatively high speed core to the slower moving edges of the current. Thus, the large differences in residence times result from the differences in how each drifter's duration in the center, and at the edges of the current, is partitioned. The temporal scale of approximately 30 days and the spatial scale of approximately 300 km are far larger than decorrelation scales measured by fixed moorings (Garvine et al. 1989) and recent high-resolution hydrography (Gawarkiewicz et al. 2001). This difference implies that much of the variability at a fixed location is due to frontal meandering, whereby particles, in Lagrangian space, largely remain within the current. Particle detainment occurs infrequently relative to frontal meandering, hence the larger residence times relative to the synoptic temporal decorrelation scale. The temporal and spatial scales we have calculated from the drifters are the scales for offshore detrainment and, as such, are based on when the float has left the shelfbreak region completely, not just when it has changed its position relative to the stream. Finally, we note that the average residence time in summer (~ 41 days) far exceeded the average winter residence time (~ 15 days), in agreement with the seasonal differences in offshore exchange described earlier.

4. Summary

The pattern created by the drifter trajectories presented in this analysis establishes the shelfbreak frontal jet as an important conduit for the export of shelf waters to the open ocean. Some export is achieved by offshore detrainment along the length of the Middle Atlantic Bight, while other parcels of water are carried to the open ocean when the shelfbreak jet converges with the Gulf Stream surface waters near Cape Hatteras. In this regard, the shelfbreak jet can be characterized as a “leaky pipe.” However, the “pipeline” for this exchange is a strongly meandering jet that is not as trapped to topography as the name implies. Additionally, the overall offshore exchange involves a complex set of processes that creates both detrainment and reentrainment along the length of the Middle Atlantic Bight. The pattern of ejection points from the shelfbreak jet to the continental slope suggests that canyons and other local bathymetric features do not cause the bulk of near-surface to middepth shelf/slope exchange. Despite the losses to the slope, half of the drifters entrained into the shelfbreak jet either reached Cape Hatteras or had their final position recorded within the shelfbreak jet. This strongly suggests that, despite periodic losses to the continental slope, the shelfbreak frontal jet is a continuous feature running from the south flank of Georges Bank to Cape Hatteras, and is extremely important in advecting water parcels to the southwest in the Middle Atlantic Bight.

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Figures

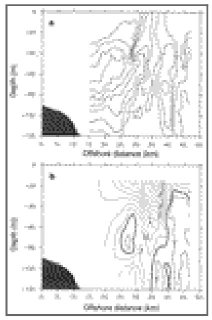

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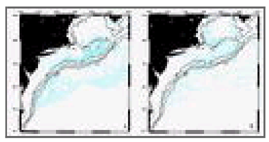
FIG. 1. A cross-shelf transect of (a) temperature and (b) alongshelf velocity from the shelfbreak south of New England on 9 May 1996. The temperature is contoured in intervals of 1°C, while the velocity is contoured in 0.05 m s^{-1} intervals, with negative (dashed) values indicating flow to the west. The location of this section is shown as the red line in Fig. 2a



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>>FIG. 2. (a) Spaghetti diagram of 10-m drifters released in the vicinity of Georges Bank during 1996 as part of the GLOBEC program. (b) Same as for (a) but for 40-m drifters released in 1995, 1996, and 1997. Deployment locations are marked with a red star. The red line marks the approximate position of the section shown in Fig. 1. All drifter positions were low-pass filtered following the method used by Brink et al. (2000) for drifters in the California Current

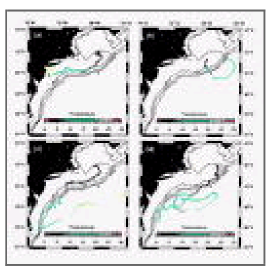

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FIG. 3. Representative 10-m drifter trajectory paths along the Middle Atlantic Bight. Deployment location is marked with a red star and positions are plotted every 6 hours

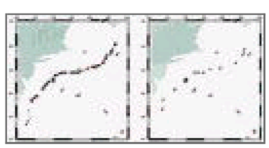

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FIG. 4. Locations where the (a) 10-m and (b) 40-m drifters were ejected offshore from the shelfbreak current. Stars represent the locations where drifters are first detrained from the current, while dots show subsequent detrainments

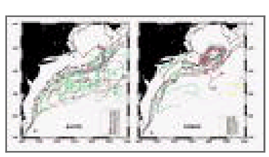

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FIG. 5. Seasonal difference in cross-frontal exchange in the Middle Atlantic Bight. Spaghetti diagram of those 10-m drifters that were in the shelfbreak current during the months of (a) Jan and Feb, and (b) Jun and Jul. Colors are used to differentiate the drifter paths from one another. The color code shows the drifter number and the year of its launch

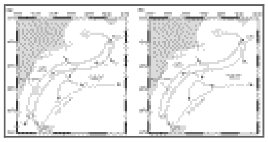

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FIG. 6. Schematic showing the downstream fate of the (a) 10-m and (b) 40-m drifters

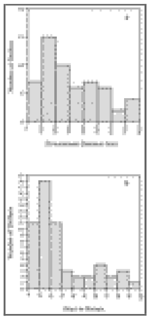

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FIG. 7. (a) Histogram showing the distribution of 10-m drifters according to the distance the drifter traveled downstream, defined as the alongshelf distance between the detrainment and entrainment locations. (b) Histogram showing the distribution of 10-m drifters according to the number of days spent in the shelfbreak current, defined as the date of detrainment minus the date of entrainment

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