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Lagrangian flow patterns north of Cape Hatteras using near-surface drifters

Glen Gawarkiewicz *, Christopher A. Linder

Woods Hole Oceanographic Institution, Clark 343C, MS#21, Woods Hole, MA 02543, USA

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Abstract

Lagrangian flow patterns in the vicinity of Cape Hatteras are examined using the tracks of 42 drifters drogued at 10 m depth and initially deployed over Georges Bank. The drifters predominantly move southwestward over the continental shelf and slope. North of Cape Hatteras, the drifters become entrained in the Gulf Stream and are carried eastward into the central Atlantic Ocean. There are two types of entrainment, abrupt and gradual. The first is characterized by a rapid change in drifter speed and an abrupt shift in drifter direction to the east. During such entrainment events, the radius of curvature of the drifter track is less than 30 km. The second type of entrainment is characterized by a gradual change in drifter direction with little change in speed. The radius of curvature of drifter tracks during such entrainment events is large (typically 50 km). The latter type occurs more frequently in summer and fall, when stratification is stronger. The drifter tracks further reveal that entrainment from the shelfbreak front/slope water system into the Gulf Stream may occur a significant distance north of Cape Hatteras, occasionally as far north as 38 °N, 200 km north of Cape Hatteras. Only two drifter tracks extend along the shelf past Diamond Shoals into the South Atlantic Bight. Four drifters are ejected from the Gulf Stream and recirculate over the slope. The observed time scale of recirculation ranges over 1–3 months. These results suggest that there are a variety of processes that determine the maximum southward penetration of Mid-Atlantic Bight shelf water before entrainment into the Gulf Stream as well as the cross-slope speed of entrainment.

Keywords: Shelfbreak front; Cape Hatteras; Gulf stream; Fronts; Drifter; Continental slope

1. Introduction

Gabriel Csanady contributed a number of important papers on the structure of slope water circulation in the Middle Atlantic Bight and on the processes contributing to shelf/slope exchange. His leadership on a number of important experiments substantially added to our present day understanding of the slope water circulation and its complex interactions with both the Gulf Stream and the flow over the continental shelf.

* Corresponding author. Tel.: +1 508 289 2913; fax: +1 508 457 2181.
E-mail address: ggawarkiewicz@whoi.edu (G. Gawarkiewicz).

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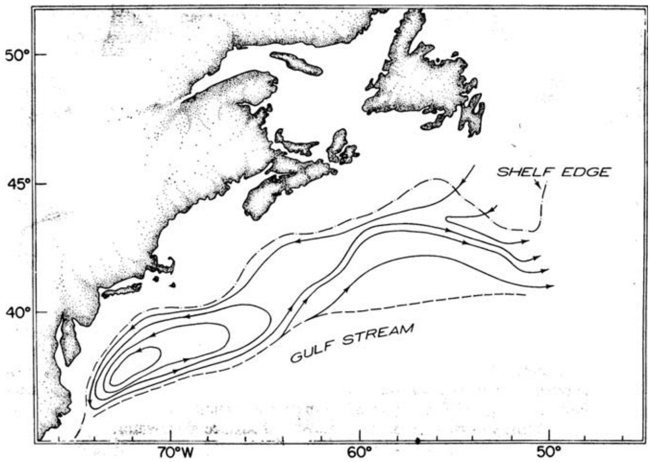

Fig. 1. A schematic figure of the slope gyre from Csanady and Hamilton (1988).

Two important papers that focused attention on slope water circulation and provided theory devoted to slope water flows were those of Csanady and Hamilton (1988) and Csanady (1988). Csanady and Hamilton (1988) defined the slope water circulation system and characterized its flow structure and transports (Fig. 1). Csanady (1988) summarized the observational understanding of slope water circulation and applied his dynamical insight into the implications of the ambient potential gradient associated with the topography. These two papers have largely determined our conceptual picture of slope water circulation north of the Gulf Stream in the Middle Atlantic Bight.

A significant scientific problem is the manner in which the slope water gyre interacts with the Gulf Stream and continental shelf. It has long been recognized (Ford et al., 1952; Fisher, 1972) that most of the flow over the continental shelf in the Middle Atlantic Bight does not extend into the South Atlantic Bight, and that the Gulf Stream entrains the vast majority of the shelf water (the "Ford water"). Lillibridge et al. (1990) carried out a high-resolution survey of entrained shelf water. They documented the subduction of the shelf water mass within the Gulf Stream and inferred mixing between shelf and ambient Gulf Stream water.

Despite our knowledge of the large scale structure of slope water circulation and the fate of the Middle Atlantic Bight shelf water, the details of shelf and slope water entrainment into the Gulf Stream are not well understood. Churchill and Cornillon (1991) described the complex interaction of Gulf Stream, slope, and shelf water over the upper slope north of Cape Hatteras. They also used remotely sensed sea surface temperature distributions to relate ephemeral surface fronts to near-surface geostrophic offshore flows. Churchill et al. (1993) also examined the potential for mixing between Gulf Stream and slope waters.

In order to clarify the details of entrainment of shelf and slope waters into the Gulf Stream near Cape Hatteras, we will use near-surface drifter tracks to examine the Lagrangian flow patterns in the southern Middle Atlantic Bight. The drifters were initially launched over and near Georges Bank as part of the GLOBEC (Global Ecosystems) Northwest Atlantic program. Their tracks have been used to examine flow around Georges Bank (Brink et al., 2003) and within the shelfbreak front (Lozier and Gawarkiewicz, 2001).

Below, we describe the data set and processing (Section 2), perform analysis of four typical trajectories illustrating entrainment (Section 3), and special cases including shelf flow past Cape Hatteras and recirculation from the Gulf Stream into the slope gyre (Section 4). The discussion of the results (Section 5) focuses on the meridional distribution of the cross-shelf flow, seasonal distribution and inferred cross-stream position within the Gulf Stream at 73°W. Results are summarized in Section 6.

2. Drifter methodology and data processing

The drifters we use for this study were deployed as part of the GLOBEC Northwest Atlantic Program by R. Limeburner, who kindly provided the data set that was processed and quality controlled. A general description of the drifter deployments, trajectories, and data processing are presented by Limeburner et al. (2000), while an analysis of the Lagrangian fields around Georges Bank is given by Brink et al. (2003). A brief summary of the drifter methodology is provided here.

The drifters were deployed over Georges Bank and in the area north of the Great South Channel from 1995–1999. Two hundred and three drifters, drogued at 10 m depth, were launched. The drifters contained an ARGOS satellite transmitter, and fixes were generally obtained six times per day. The satellite fixes were interpolated to positions at 6 h intervals using cubic splines, and were low-pass filtered using the PL66 filter, which has a half-power point at 38 h. Trajectories also were examined to remove erratic fixes. In addition to the position and velocity data, measurements of drifter temperature and submergence (transmitter below water) were also included in the drifter data base. While there were numerous failures in the temperature sensors, many of the drifters that passed into our study area did obtain reasonable temperature data.

The area we consider is bounded by 35 and 38 °N, and by 72–76 °W. A surprisingly large number of drifters, 42, entered this domain through the northern boundary, despite being launched well to the north over or near Georges Bank. The drifter tracks enable us to crudely consider the Lagrangian flow characteristics north of Cape Hatteras, but do not allow us to compute typical statistics such as particle-pair dispersion and eddy diffusivities. Our focus is on selected trajectories that are representative of the behavior of a number of drifters. In particular, we examine characteristics of these trajectories in relation to surface thermal fronts and wind forcing. Winds used in the analysis were obtained from the National Buoy Data Center meteorological buoy 44014 (Fig. 2), located at 36.61 °N, 74.84 °W in 47 m of water.

The entire ensemble of drifter trajectories that are entrained into the Gulf Stream appears in Fig. 2, broken into two categories that we will define in the next section. The majority of the drifters enter the domain over the continental slope. None of the drifters entrained into the Gulf Stream cross the Stream into the Sargasso Sea. Two drifters move southward over the continental shelf across Diamond Shoals and into the South Atlantic Bight. In the next two sections, we will examine typical drifter trajectories that represent differing modes of entrainment into the Gulf Stream, and will examine tracks of drifters that extend into the South Atlantic Bight and others that recirculate within a slope gyre.

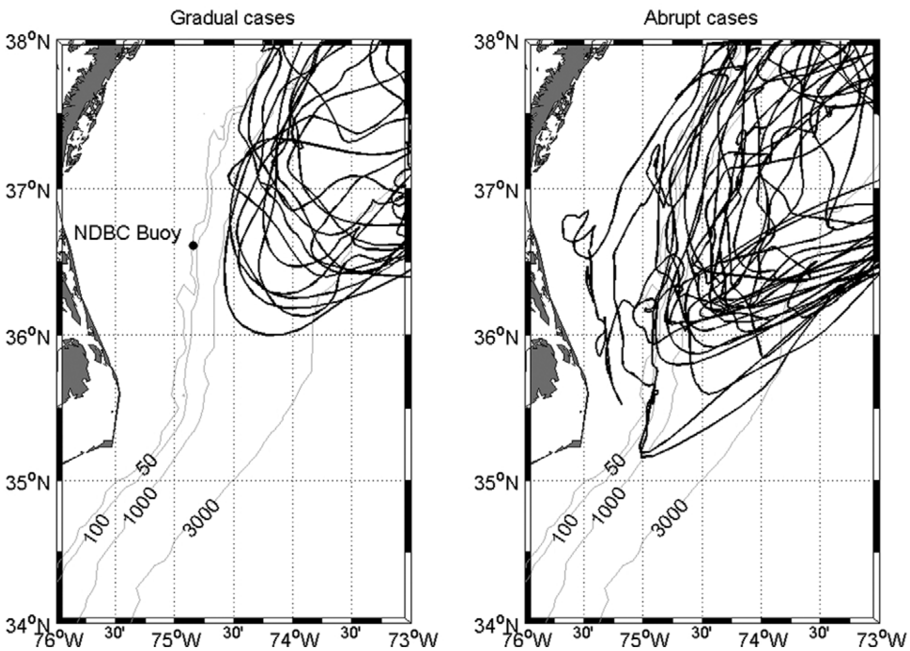

Fig. 2. A diagram containing all 42 trajectories of drifters passing within our study domain. All drifters were drogued to 10 m depth.

3. Typical trajectories and their relation to wind forcing and surface thermal features

All but one of the 42 trajectories depart the study domain through the eastern boundary. From examining these trajectories, we have determined that there are two primary types of entrainment. The first is marked by a very abrupt turn to the northeast and a rapid increase in drifter speed. The second type is marked by a very gradual turn to the northeast and a much lower rate of increase in speed. The latitudinal range over which these types of entrainment occur is large, with entrainment observed as far north as 38 °N (determining the boundaries of our study area). The trajectories indicate that the gradual entrainment is common in the northern portion of the study domain (north of 36 °N). South of 36 °N, drifter entrainment is always abrupt, and the path followed by drifters is often complicated as they approach Cape Hatteras. To illustrate the two different types of entrainment we will present four representative trajectories.

First, we consider an example of gradual entrainment in the northern portion of our study domain (Fig. 3). In this case, the drifter passes southwestward through the northern edge of the domain, and at 37.3 °N it turns offshore. The drifter's position as it enters the domain is in the area typically occupied by the shelfbreak front, and the drifter's speed of 20–30 cm/s is comparable to a climatological mean geostrophic flow in the frontal region (Linder and Gawarkiewicz (1998) show mean geostrophic velocities of up to 25 cm/s in their bimonthly climatology in this region). As it enters the study region, the temperature measured by the drifter is close to 12 °C.

After turning to the southeast, the drifter's temperature increases to 20 °C but the speed remains within a range of 20–30 cm/s. Near 36.5 °N, the drifter turns to the east and attains a speed of 70 cm/s. The temperature, however, actually decreases to 17 °C, suggesting that the drifter has not become entrained in the warmest Gulf Stream water mass. The drifter takes 6.25 days to cross the slope region between the shelfbreak front and the Gulf Stream with a turning radius of ≈100 km.

The second type of entrainment, an abrupt turn into the Gulf Stream, is illustrated by the track of a drifter that enters the study domain near the shelfbreak moving southward at ≈40 cm/s (Fig. 4). At 36.3 °N, the drifter takes an abrupt northeastward turn with a radius of curvature of only 20 km. As it approaches 36.3 °N, the drifter's speed declines to 5 cm/s suggesting it to be near a stagnation point between the shelfbreak front and Gulf Stream before becoming entrained in the Gulf Stream. After turning to the northeast, the drifter's speed rapidly increases, reaching a magnitude of 112 cm/s near 73 °W. The drifter temperatures steadily rise along

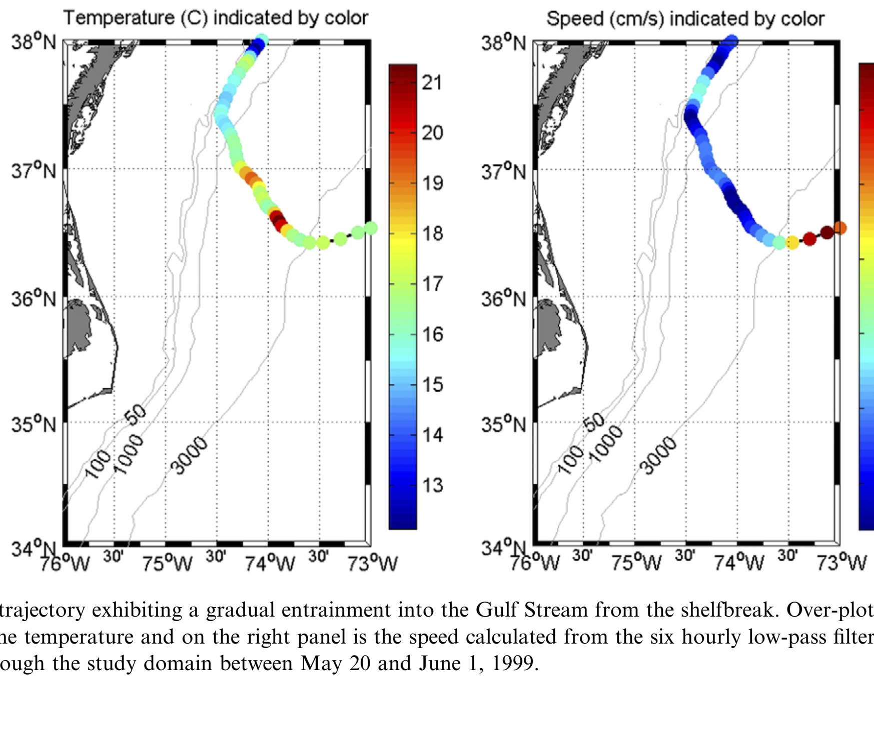

Fig. 3. A drifter trajectory exhibiting a gradual entrainment into the Gulf Stream from the shelfbreak. Over-plotted on the trajectory in the left panel is the temperature and on the right panel is the speed calculated from the six hourly low-pass filtered buoy positions. The drifter passed through the study domain between May 20 and June 1, 1999.

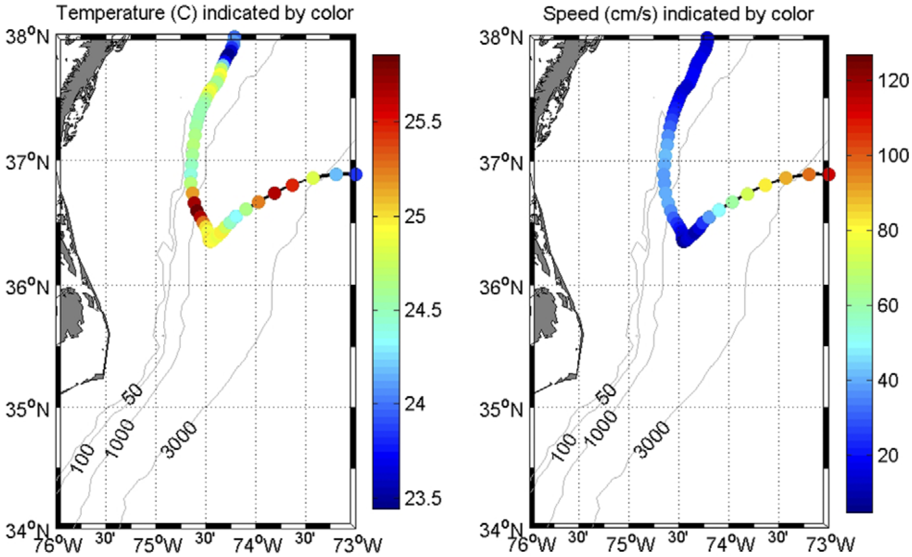

Fig. 4. Same as Fig. 3, except showing a drifter trajectory exhibiting an abrupt entrainment into the Gulf Stream in the northern area of the study domain. The drifter passed through the study domain between August 21 and September 3, 1996.

the northeastward portion of the trajectory, reaching 25.5 °C, indicating entry into Gulf Stream core water masses.

Entrainment in the southern portion of the domain can be quite dramatic as illustrated by the track of a drifter that moves southward along the 100 m isobath until turning abruptly into the Gulf Stream, with a turning radius ~5 km, at 35.1 °N (Fig. 5). In the process of turning, the drifter temperature rises from 14 to 22 °C over an along-isobath distance of 20 km. This temperature increase is consistent with passage into the Gulf Stream water mass in winter. Following the turn, the drifter speed rapidly increases from 20 to 136 cm/s over a horizontal distance of 40 km.

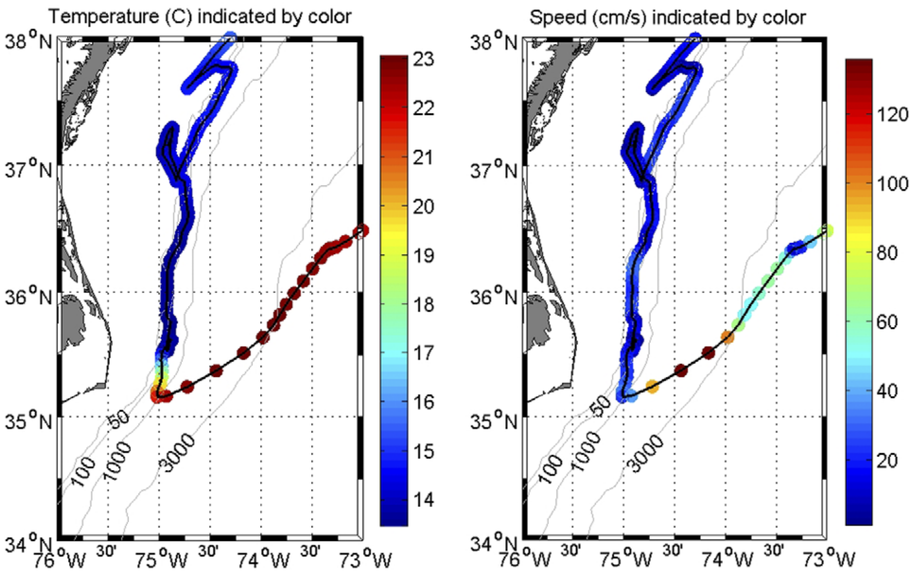

Fig. 5. Same as Fig. 3, except showing a drifter trajectory with abrupt entrainment into the Gulf Stream in the southern area of the study domain. The drifter passed through the study domain between November 14, 1998 and January 1, 1999. Note the large thermal gradients along the outer shelf near the entrainment region.

A second example of abrupt entrainment in the southern portion of the domain is more complicated (Fig. 6). In this example, the drifter passes along the middle of the continental shelf at approximately the 30 m isobath. Near 35.75 °N, the drifter is carried offshore by 20 km before turning southward, presumably in the flow associated with the shelfbreak front. At 35.1 °N, the drifter turns abruptly to the northeast, and experiences a rapid increase in speed, from 10 to 156 cm/s. In contrast to the previous example, the drifter's temperature remains fairly constant in the region of abrupt entrainment, at around 22 °C. After the drifter's entrainment into the Gulf Stream, the temperature increases, to 25 °C by the time it reaches 73.5 °W. This trajectory is from the summer, which explains the lack of strong thermal gradients at 10 m depth.

We now consider the impact of wind forcing on the trajectories. For the first case (Fig. 7(a)), a gradual turn from the shelf-edge into the Gulf Stream within the northern portion of the study domain, wind forcing appears to play an important role in the initial off-shelf motion of the drifter. As the drifter travels between 37.5 and 37 °N, the winds are from the south, giving rise to an eastward component of Ekman transport. As the drifter proceeds south of 37 °N the winds shift to the southwest and weaken substantially. The drifter continues at roughly the same speed and direction even after the decrease in wind speed. The lower half of the southeastward-directed portion of the drifter's trajectory is in the vicinity of a thermal front (Fig. 7(b)). Thermal (and density) fronts frequently cross the slope topography in this region, as previously documented by Churchill et al. (1993). In this case, the drifter's initial departure from the along-isobathflow at the shelf-edge appears to be initiated by the wind forcing. It then presumably continues in a geostrophic cross-isobath flow.

For the second case—abrupt entrainment in the northern portion of the study region—wind forcing does not appear to play a significant role in the drifter's movement into the Gulf Stream (Fig. 8(a)). There is no significant wind forcing as the drifter moves along the upper slope. During its abrupt turn to the northeast, the Ekman transport is to the west, opposite to the direction that the drifter turns. The surface thermal front associated with the Gulf Stream was located very close to the position at which the abrupt change in direction occurred (Fig. 8(b)).

For the two southern cases of abrupt entrainment, the wind does not play an important role. For the third case (Fig. 9(a)), the Ekman transport is to the west as the drifter abruptly turns to the northeast. Cloud cover limited the availability of thermal images coincident with this drifter's track, but an image from several days before its entrainment shows the Gulf Stream thermal front in close proximity to the position of the drifter's abrupt change in direction (Fig. 9(b)). For the fourth case, in which the drifter passes over the mid-shelf before shifting position to the shelfbreak and then abruptly entraining into the Gulf Stream, the winds did not appear

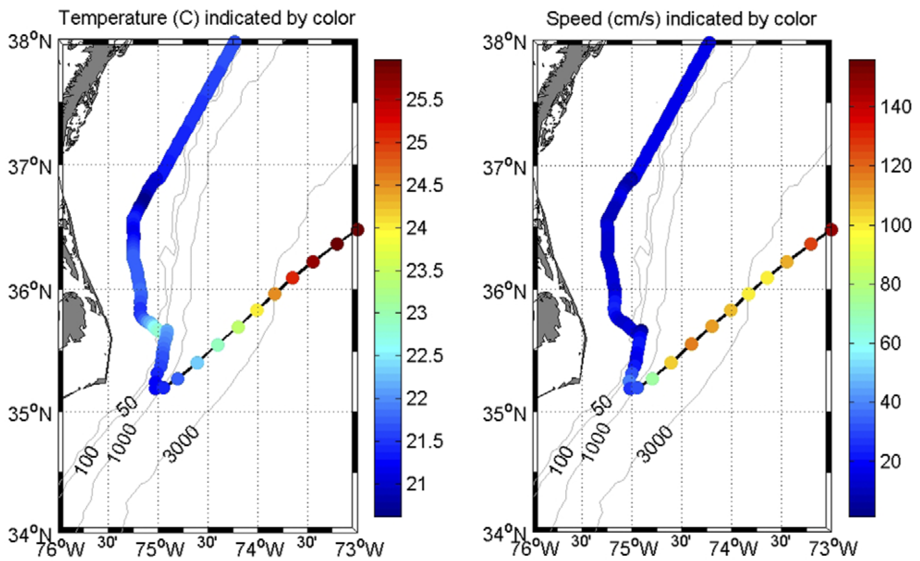

Fig. 6. A drifter trajectory showing two entrainment events, first offshore into the shelfbreak frontal jet and then into the Gulf Stream. The drifter trajectory spanned September 21 to October 22, 1997.

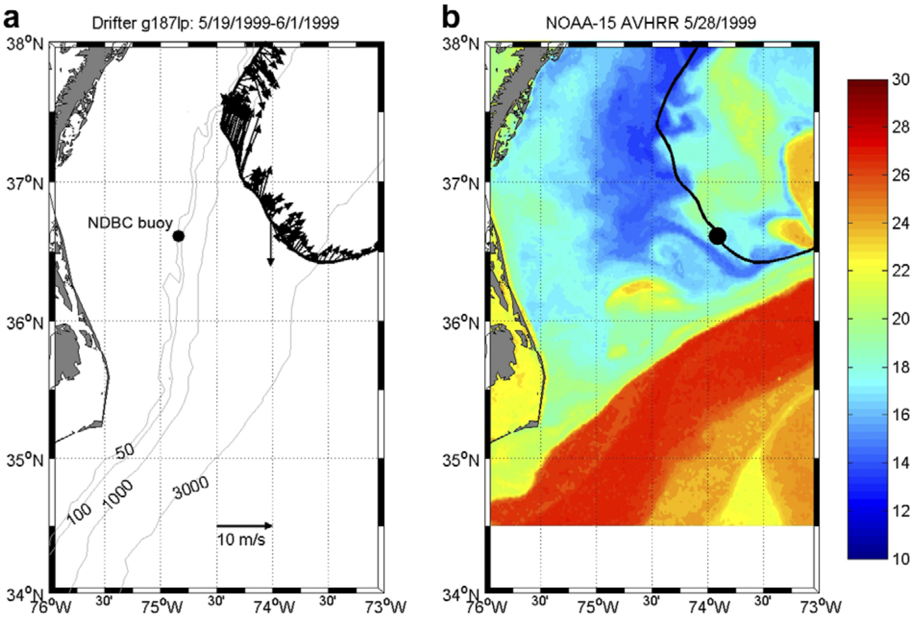

Fig. 7. (a) The trajectory of the drifter shown in Fig. 2 with winds from NDBC buoy 44009 over-plotted as a function of time. (b) The same trajectory over-plotted on an image of sea surface temperature produced by the NOAA Coastwatch program. The position of the drifter when the image was taken is denoted by the large black dot.

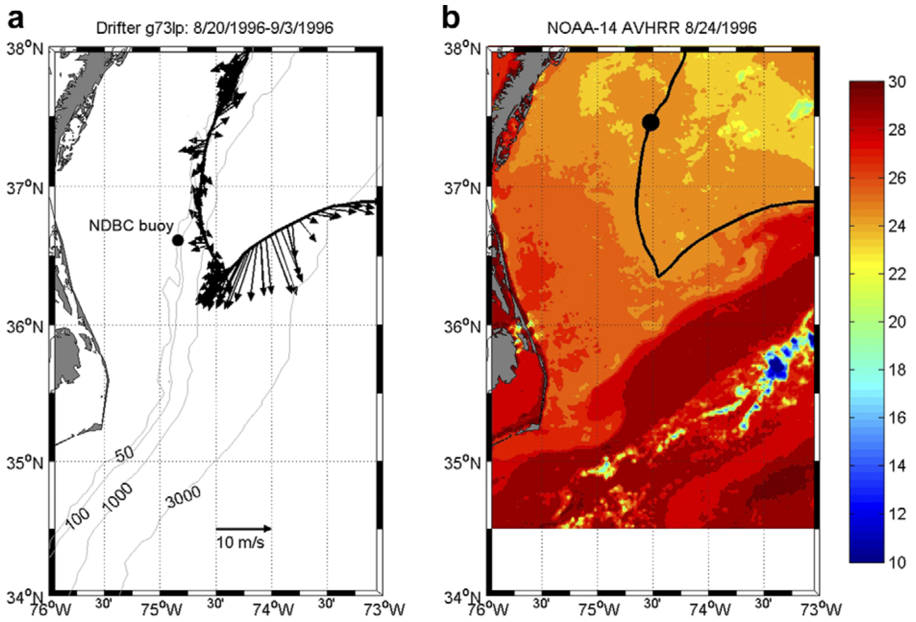

Fig. 8. (a) Winds over-plotted for the drifter trajectory shown in Fig. 3. The sea surface temperature is over-plotted in (b).

to play a role. The first cross-shelf shift in position, from the 30 m isobath to the shelfbreak, occurs as the winds blow from the north giving rise to a westward Ekman transport (Fig. 10(a)). Similarly, during the abrupt entrainment into the Gulf Stream, winds are from the northeast, also giving rise to an Ekman transport opposed to the shift in the drifter's path. As in the previous case, the Gulf Stream surface thermal front is in close proximity to the point of abrupt entrainment (Fig. 10(b)).

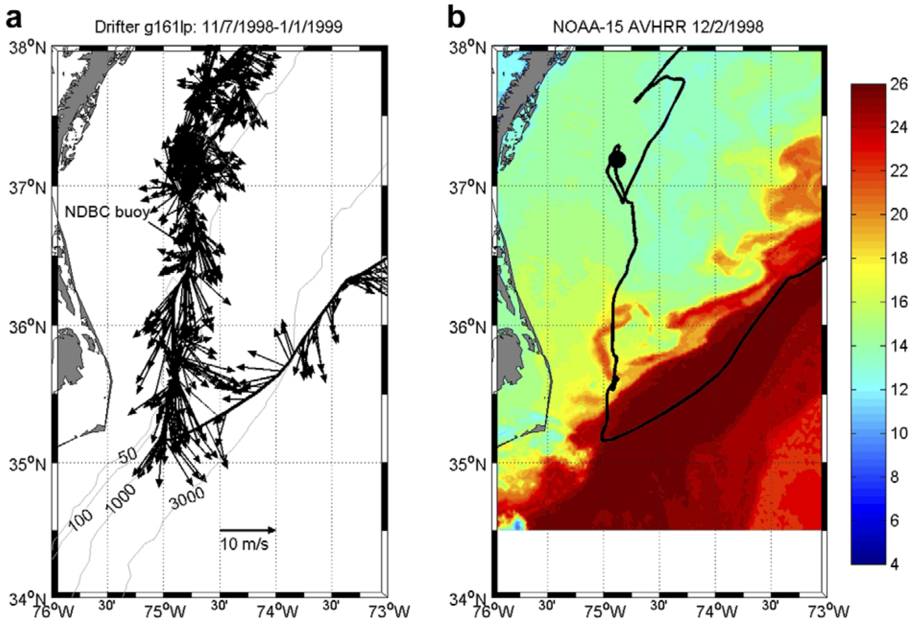

Fig. 9. (a) Winds and (b) sea surface temperature for the drifter trajectory shown in Fig. 4.

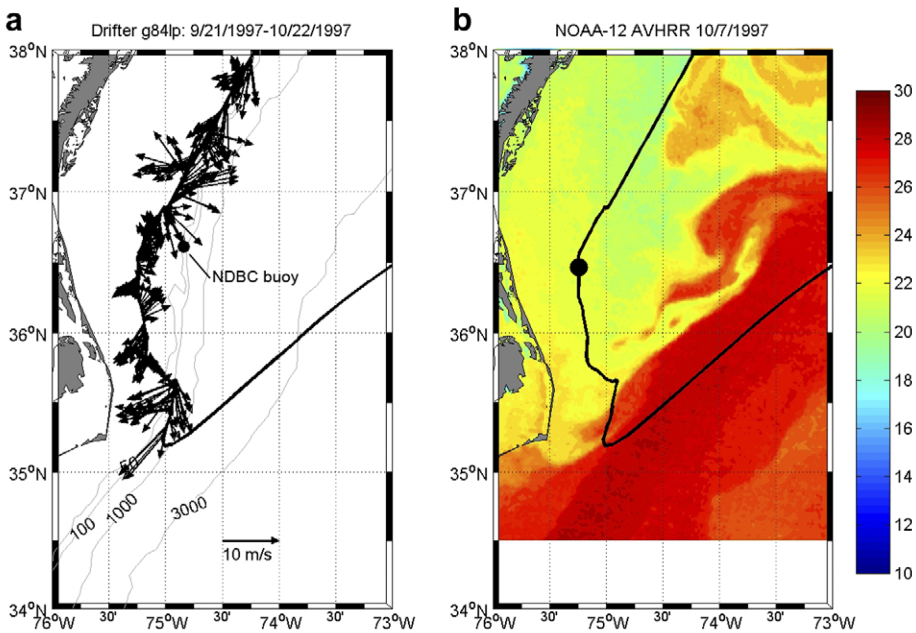

Fig. 10. (a) Winds and (b) sea surface temperature for the drifter trajectory shown in Fig. 5.

There is a substantial shift in the zonal distribution of drifter position as a function of latitude. In the north (Fig. 11(a)), the drifters are fairly evenly distributed zonally. Further south, however, the zonal distribution of the southward passing drifters is concentrated between 74 and 75.5°W, with no drifters east of 74°W (Fig. 11(b)). The drifters passing further onshore thus travel into the southern portion of the domain, while the drifters passing further offshore are all entrained into the Gulf Stream and do not reach the southern portion of the domain.

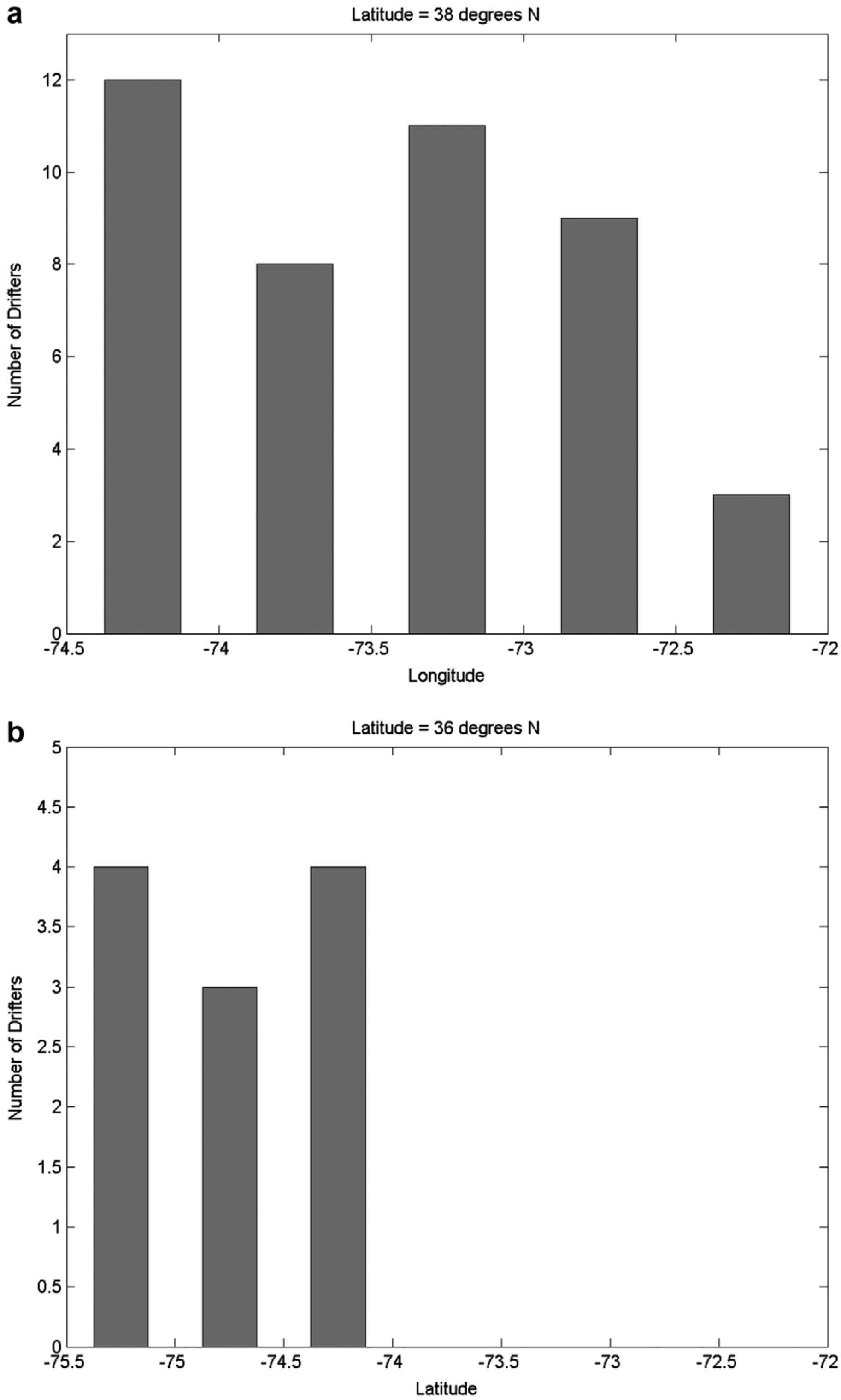

Fig. 11. The distribution of the longitude of drifters crossing (a) 38°N and (b) 36°N. Note that the distribution is much more evenly distributed in (a), but is strongly concentrated in the west in (b).

Examination of the trajectories shows that a majority of the entrainment events can be categorized as abrupt events (24 out of 41). The remaining 17 can be classified as gradual.

4. Two special cases – Passage into the South Atlantic Bight and recirculation

Only two drifter trajectories pass Diamond Shoals and enter the South Atlantic Bight. One of these drifters eventually becomes entrained in the Gulf Stream (Fig. 12(a)). Unfortunately, there is no thermistor record from this drifter in our study domain, and the drifter position record has long gaps due to transmitter difficulties. The time intervals between drifter speed estimates are thus long and irregular. This drifter penetrates the South Atlantic Bight as far south as 34.56 °N before becoming entrained into the Gulf Stream. Its movement into the South Atlantic Bight is rapid, passing from 35.92 °N to 34.6 °N in 3.25 days, at an average speed of 52 cm/s. After turning into the Gulf Stream, the drifter's trajectory is in close proximity to the Stream's surface thermal front (Fig. 12(c)). The most likely reason for the drifter's penetration into the South Atlantic Bight is an extended time period of southward winds (Fig. 12(b)). Pietrafesa et al. (1994) found that Middle Atlantic Bight shelf water (and Virginia Coastal Water) was normally found in the South Atlantic Bight during times of southward winds. They showed that these downwelling favorable winds accelerate the coastal current and allow it to penetrate the shelf region south of Diamond Shoals. In this case, the drifter enters the South Atlantic Bight due to forcing by the southward wind, but only reaches 50 km south of Diamond Shoals.

The second drifter trajectory that crosses Diamond Shoals penetrates much further into the South Atlantic Bight (Fig. 13(a)). Unfortunately, due to transmitter failure, this trajectory ends at 33.74 °N, 140 km south of Cape Hatteras. The drifter approaches Cape Hatteras at a rapid speed, moving between 36 and 35 °N in 1.75 days at an average speed of 77 cm/s. The movement of this drifter into the South Atlantic Bight also appears to be associated with southward winds. Winds are directed to the southwest during the time when the drifter passes through the southern Mid-Atlantic Bight into the South Atlantic Bight (Fig. 13(b)). It is interesting to note that the temperature record of this drifter (Fig. 13(a)) shows fairly uniform temperatures in the Cape Hatteras shelf region, in contrast to the temperature records of many other drifters (Fig. 5). Churchill and Berger (1998) identified the Hatteras Front as the southern boundary of the Middle Atlantic Bight shelf water. The lack of thermal gradients along the trajectory of this drifter would imply that the front was south of Hatteras, a situation also described in Savidge (2002). Unfortunately, clouds obscured the satellite thermal imagery at

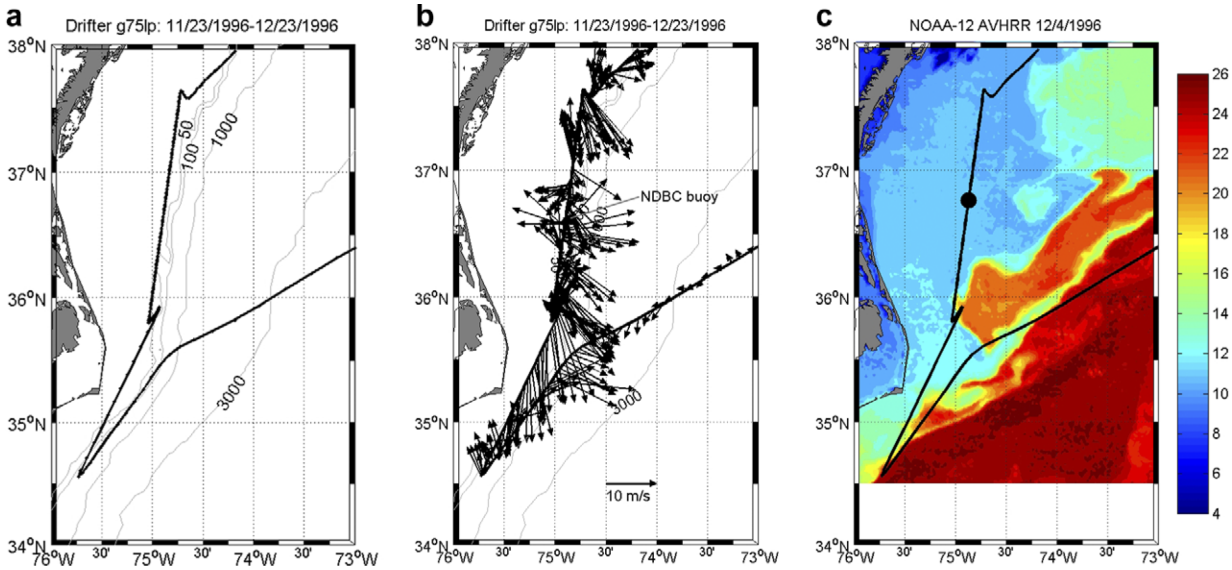

Fig. 12. The trajectory of a drifter which passed southward across Cape Hatteras. The trajectory is plotted in (a), with winds over-plotted in (b) and sea surface temperature over-plotted in (c). The temperature probe failed on this drifter, and the position fixes were intermittent. The drifter passed through the domain between November 23 and December 23, 1996.

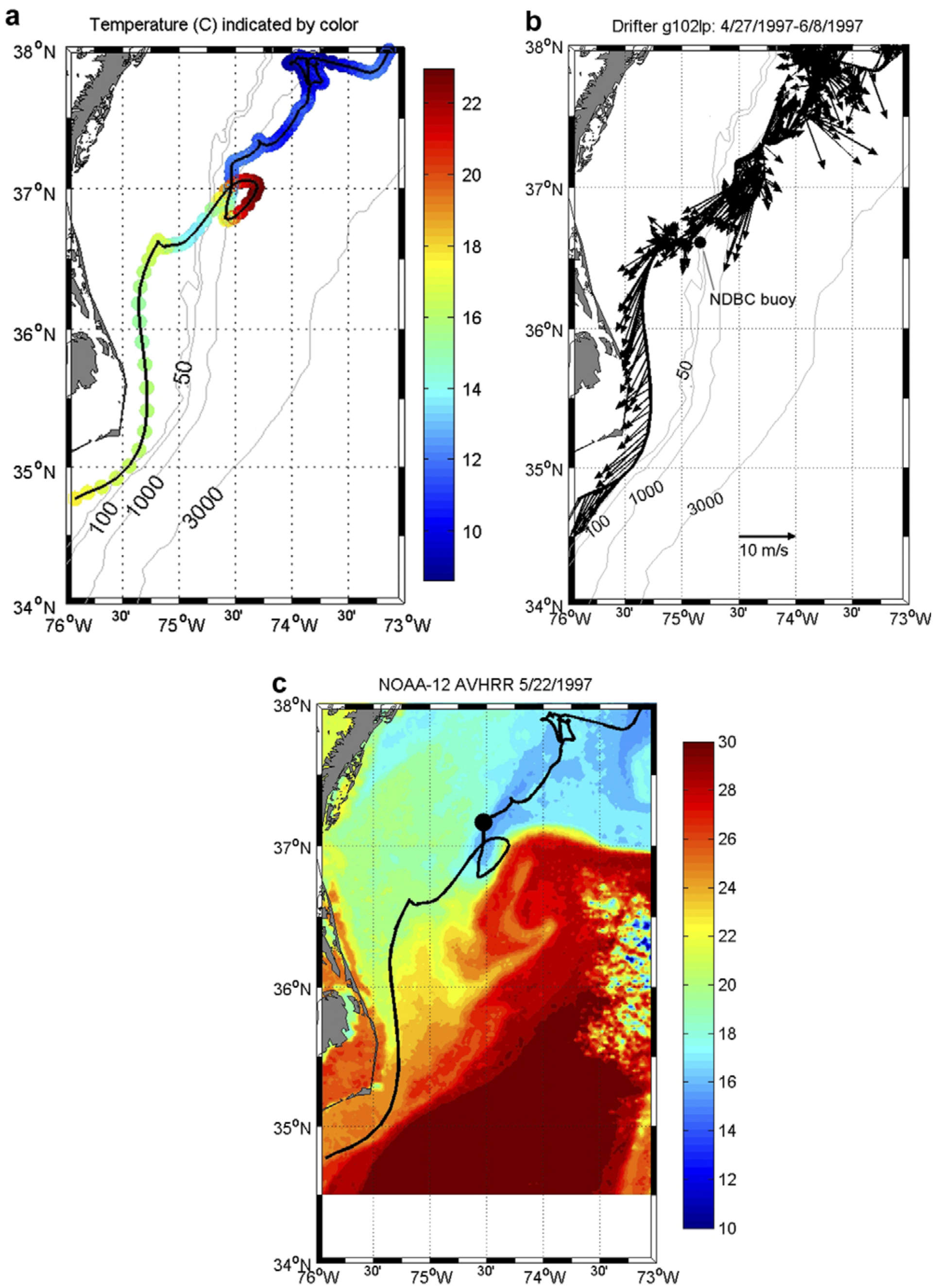

Fig. 13. The trajectory of a second drifter which passed southward across Cape Hatteras. The temperature and speed are over-plotted in (a), the winds in (b), and the sea surface temperature in (c). The drifter passed through the domain between April 27 and June 8, 1997.

the time of the drifter's passage of Cape Hatteras, so that the presence of the Hatteras Front cannot be confirmed through the satellite imagery.

Another unusual class of trajectories is formed by those of drifters that pass through the domain more than once as they recirculate within a slope gyre. An example of this is provided by the drifter track shown in Fig. 14. After ejection from the Gulf Stream near 70 °W, this drifter loops back to the shelf-edge region, crossing the slope and arriving at the shelf-edge near 37.5 °N. It is then entrained a second time in the southern part of the study domain. The track of this drifter illustrates the two types of entrainment, a gradual entrainment in

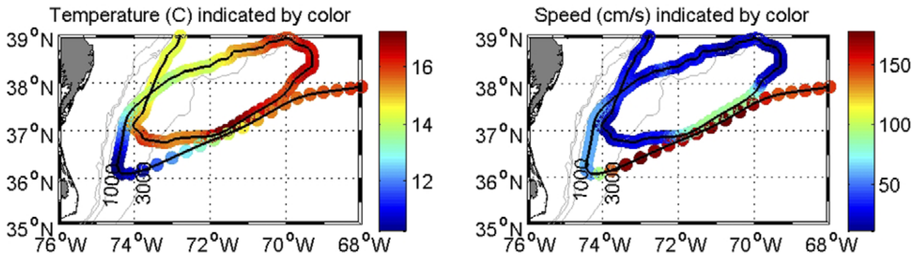

Fig. 14. The trajectory of a drifter which recirculated across the slope region and returned to the shelfbreak area north of Cape Hatteras. Temperature is over-plotted in the left panel and speed in the right panel.

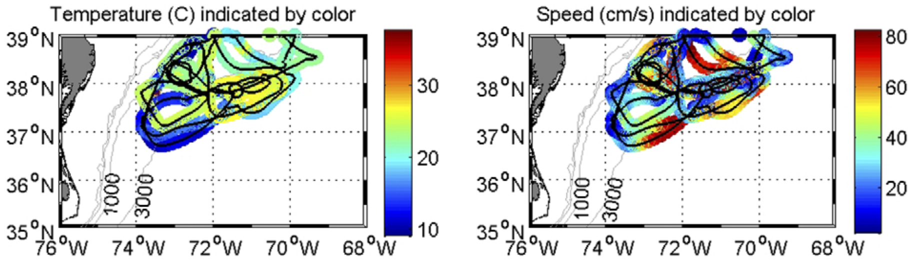

Fig. 15. The trajectory of a drifter with a much more complicated trajectory which recirculated to the shelfbreak.

the northern part of the study domain and an abrupt entrainment in the southern part of the domain. The drifter returned to 38 °N after 41 days. Two other studies have also documented transport from the Gulf Stream to the edge of the continental shelf on short time scales (Hare et al., 2002; Rasmussen et al., 2005). As Hare et al. (2002) noted cross-slope flow may be important for the transport of larval fish between the South Atlantic Bight and estuaries of the Middle Atlantic Bight.

Altogether four drifters reenter the study domain through recirculation in a slope water gyre. A second example of recirculation in the slope region (Fig. 15) is much more complicated than the previous one. In this case, the drifter appears to move in and out of various slope water eddies and traverses a number of shelf and slope water masses. The time interval between crossings of 38 °N is 106 days, significantly larger than the previous case. These two examples reveal a wide range of times for recirculation in the slope region north of Cape Hatteras.

The small numbers of drifters that recirculate is a contrast to previous findings from Berger et al. (1996). Using drifters launched at the 106-Mile Dumpsite off New York, they found that 15 out of 72 drifters recirculated—21% of the total launched. The percentage of drifters that recirculate in our case is 9.5%—less than half the percentage of the 106-Mile Dumpsite drifters. It is unclear if this is due to temporal shifts in the intensity of the slope circulation or to the difference in the launch position within the dumpsite relative to the more onshore position of the drifters selectively examined in this study. Further information about the dumpsite drifters are given by Dragos et al. (1996), who show that 15% of the drifters were carried westward from the launch site to the shelfbreak front, but that none of the surface drifters reached the continental shelf shoreward of the shelfbreak.

5. Discussion

We will briefly discuss the meridional distribution of offshore flow. This will be examined using a criterion developed by Lozier and Gawarkiewicz (2001), defined as the point at which a trajectory crossed the 1000 m isobath. Next we will describe the seasonal distribution of abrupt versus gradual entrainment. Finally we will place the drifter trajectories in the context of the mean cross-stream structure of along-stream flow to contrast the relative cross-stream positions of our representative abrupt and gradual entrainment examples.

The spatial distribution of the drifter positions as they cross the 1000 m isobath appears in Fig. 16(a). The drifters cross this isobath over nearly the full range of the study area, from 35.16 °N to 37.98 °N. Twenty six of the 42 drifters passing through this area originated shoreward of the 1000 m isobath. Of these, only two passed across the 1000 m isobath south of 35.5 °N. One of the two (Fig. 12(a)) was entrained into the Gulf Stream south of Cape Hatteras. The crossing positions are more evenly distributed north of 35.5 °N. The gradual entrainment events occur only north of 36.5 °N. The abrupt entrainment events, however, occur over the full range of latitude.

The latitudinal distribution of the crossing points (Fig. 16(b)) shows that half of the 26 drifters cross the 1000 m isobath north of 37.4 °N. The drifters that cross south of 35.5 °N are both located over mid-shelf, near the 30 m isobath, as they cross 35.5 °N. The overall mean in the latitudinal distribution is 36.87 °N. The loss of drifters is much larger than would be expected from the narrowing of the shelf alone. To illustrate this, the normalized shelf/slope width (the distance between the coast and the 100 m and 1000 m isobaths) between 35 and 38 °N is plotted in Fig. 16(b). This shows that the drifters cross the 1000 m isobath much more rapidly than would be expected solely due to a narrowing of the shelf, particularly between 37 and 38 °N.

The distribution of crossing points is surprising in the sense that one might have expected a pronounced peak in the latitudinal distribution near the mean position of the Gulf Stream if the abrupt entrainment type dominated. The distribution suggests that the gradual type of entrainment is very important and may occur significantly northward of Cape Hatteras. Further work is clearly necessary to determine the underlying hydrographic structure over the slope during these northern gradual entrainment events, as well as a theoretical understanding of why the shelfbreak front should separate or fragment near these crossing points. The distribution also implies that the type of thermal front that crosses the continental slope observed by Churchill et al. (1993) may be a fairly frequent event south of 38 °N.

Two final points regarding the contrast between the abrupt and gradual entrainment events are worth mentioning. First, it appears that the abrupt entrainment events are relatively evenly distributed by season, with slightly over half (13 of 24) in the summer/fall as opposed to the winter/spring. For the gradual entrainment, the majority of the events occur in summer/fall (13 of 17). While this is not statistically reliable, it does suggest

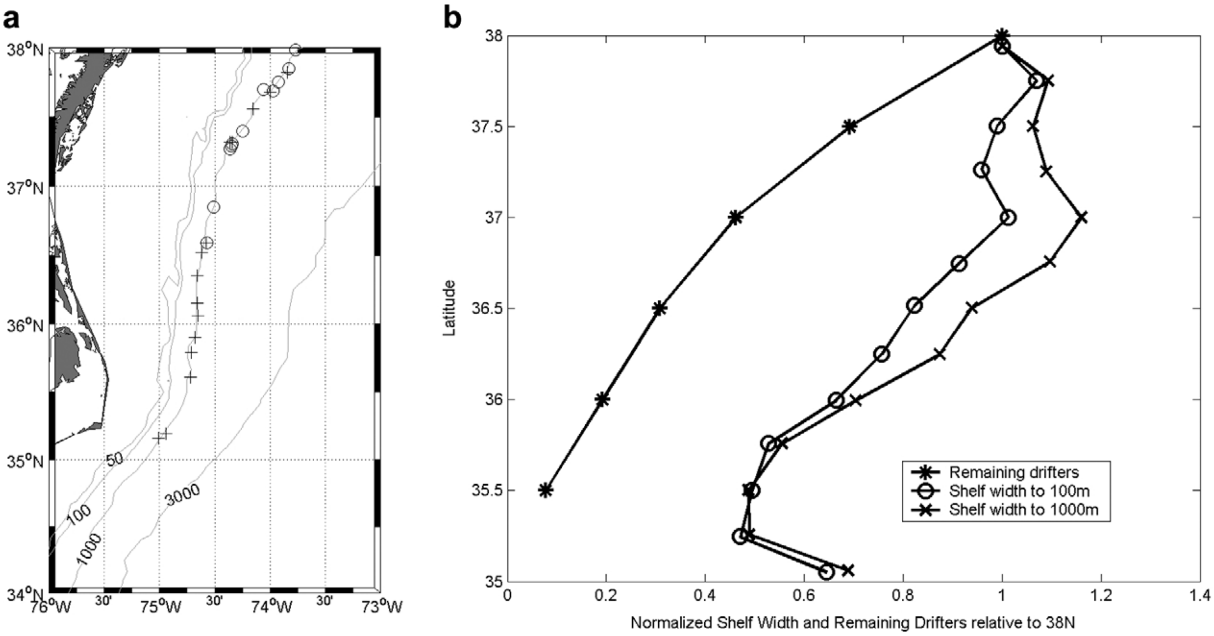

Fig. 16. (a) The distribution of positions at which drifters moved offshore across the 1000 m isobath. Circles denote gradual entrainment while crosses denote abrupt entrainment. (b) A histogram of the crossing points distributed by latitude, showing a clear decrease in frequency with southward position. The drifter losses are normalized by the number of drifters at 38 °N and the shelf/slope width is normalized by the distance between the coast and the 100 m and 1000 m isobaths at 38 °N.

that the gradual events tend to occur when stratification is strong. Second, the drifters that exhibit abrupt entrainment appear to be carried downstream much more closely to the core of the Gulf Stream. Halkin and Rossby (1985) defined the cross-stream distribution of the along-stream velocity at 25 m depth along 73 °W. For the three abrupt entrainment cases presented in Section 3, the maximum velocities after entrainment were 127, 136, and 156 cm/s, while for the gradual case presented the maximum velocity after entrainment was 76 cm/s. The long-term mean maximum near-surface velocity within the core as measured by Halkin and Rossby was 169 cm/s, which implies that the drifters with abrupt entrainment may have been fairly close to the core of the Gulf Stream.

6. Summary

Analysis of drifter trajectories over the shelf and slope north of Cape Hatteras indicates that there are two types of entrainment into the Gulf Stream, abrupt and gradual. The events of abrupt drifter entrainment are characterized by a sharp change in drifter direction with a rapid increase in speed, while drifter trajectories of the gradual entrainment events have a large radius of curvature and small speed increases. Two drifter trajectories pass south of Cape Hatteras into the South Atlantic Bight shelf region, and a slightly larger number (4 of 42) are ejected from the Gulf Stream and return to the shelfbreak. The results strongly suggest that entrainment into the Gulf Stream occurs over a large latitudinal band and that different processes contribute to entrainment.

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