# Lagrangian Observations of the Deep Western Boundary Current in the North Atlantic Ocean. Part II: The Gulf Stream–Deep Western Boundary Current Crossover*

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ABSTRACT

In this study, the authors analyze the trajectories of 18 RAFOS floats, launched in the deep western boundary current (DWBC) between the Grand Banks and Cape Hatteras to investigate the kinematics and dynamics in the region where the DWBC crosses under the Gulf Stream, near 36°N (the ''crossover region''). Floats deployed in the chlorofluorocarbon (CFC) maximum associated with upper Labrador Sea Water (depth ~800 m) illustrate the entrainment process of this water mass into the Gulf Stream. The behavior of the floats (and fluid parcels) in the crossover region is strongly dependent on the meandering of the Gulf Stream. When the stream is close to its mean position, fluid parcels entrained from the upper DWBC travel along the northern edge of the stream. When a meander trough is present downstream of the entrainment location, DWBC fluid parcels cross the Gulf Stream and sometimes are expelled on the south side. This represents a previously unrecognized mechanism for transporting upper Labrador Sea Water properties across the Gulf Stream. Floats deployed in the DWBC near the deep CFC maximum that identifies overflow water from the Nordic seas (depth ~3000 m) show a bifurcation in fluid parcel trajectories in the crossover region: fluid parcels that intersect the stream farther west tend to cross more directly and smoothly under the stream, while fluid parcels that hit the stream farther east exhibit more eddy motion and are more likely to be diverted into the interior along the Gulf Stream path. The deep float observations also reveal directly that the deep DWBC crosses under the Gulf Stream while conserving potential vorticity by sliding down the continental slope, as first conceptualized in a steady, two-layer model of the crossover. While potential vorticity is conserved along the deep float tracks on the short timescales associated with crossing under the Gulf Stream (up to a month), potential vorticity decreases over the longer timescales required for fluid parcels to transit the entire crossover region (several months to a year), consistent with what would be expected from eddy mixing.

## 1. Introduction

The deep western boundary current (DWBC) in the North Atlantic Ocean is the major conduit for the transport of recently ventilated water masses from northern latitudes toward the equator (Warren 1981). In recent years, it has become increasingly apparent that there are selected locations along the western boundary where the DWBC interacts more strongly with the ocean interior. One such site is located where the DWBC crosses under the Gulf Stream, near 36°N (the ''crossover region''). Here the Gulf Stream is flowing across the continental slope into deep water, and the western limbs of the northern recirculation gyre and the Worthington gyre are converging to form the deep Gulf Stream. The DWBC passes under the separating Gulf Stream between the western boundary and the recirculation gyres and enters the subtropical regime [see Hogg (1992) for a recent discussion]. Thus two branches of the thermohaline circulation cross each other, setting up the potential for interactions with basin-scale consequences.

A number of observational and modeling studies have been aimed at understanding the complex kinematics and dynamics in this critical area. Based on early observations of the DWBC, Hogg and Stommel (1985) represented the circulation in the crossover region in a steady, two-layer model with a southward flow along a slope in the lower layer (DWBC) and an eastward flow in the upper layer (Gulf Stream). They demonstrated that fluid parcels in the DWBC could cross under the Gulf Stream and still conserve potential vorticity by sliding down the slope. Once south of the stream, the DWBC would follow a new isobath that was deeper than the original isobath by the amount that the interface between the layers deepened across the Gulf Stream. Pickart and Watts (1990) observed a mean downslope

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flow near the bottom directly under the mean Gulf Stream path in current meter observations, consistent with the Hogg and Stommel model.

More recent studies have revealed the complex vertical structure of the DWBC in the crossover region. Pickart and Smethie (1993, hereafter PS93) reported on results from a detailed hydrographic and velocity survey of the crossover region, where they focused on the kinematics and dynamics of the upper and lower water mass components of the DWBC. These are upper Labrador Sea Water (ULSW), centered at about 800 m north of the Gulf Stream (Pickart et al. 1997), and overflow water (OW), which is a combination of Iceland–Scotland Overflow Water (ISOW) and Denmark Straits Overflow Water (DSOW). Overflow water is found from 2500 to 4000 m in the DWBC [see Pickart (1992) for a review of DWBC water masses]. Both ULSW and OW are distinguishable by high chlorofluorocarbon (CFC) concentrations due to their relatively recent contact with the atmosphere (DSOW contributes the most to the deep CFC maximum) (see, e.g., Smethie 1993; Fine 1995). PS93 found that a significant amount of ULSW is diverted away from the western boundary in the crossover region and entrained into the eastward flowing Gulf Stream. Only a narrow band of denser ULSW right against the continental slope crossed directly under the stream. In contrast, most of the OW appeared to follow the topography more closely and crossed directly under the Gulf Stream without being significantly diverted into the interior. Only the offshoremost edge of OW appeared to be diverted offshore.

Spall (1996a), motivated by the vertical gradient in DWBC water properties and inferred fluid parcel pathways observed by PS93, represented the Gulf Stream in the upper layer and the DWBC in two lower layers of a three-layer regional primitive equation model of the crossover. He demonstrated that the mean southward flow in the intermediate layer, representing ULSW, split into two pathways at the crossover: one diverted slightly offshore before returning to the boundary and continuing southward and the other flowing eastward under the model Gulf Stream. A divergence of the eddy potential vorticity flux at the bifurcation point, caused by intermittent formation of upper DWBC eddies, balanced the eastward mean flow across mean potential vorticity contours. In the lowest layer of the model, the DWBC more closely followed the topography and continued southward without being diverted significantly into the interior.

Following on the pioneering work of Swallow and Worthington (1961), who experimentally confirmed the existence of the DWBC using neutrally bouyant floats, we have undertaken a major experiment to directly observe long-term fluid parcel pathways in the DWBC, especially in the crossover region, using Lagrangian drifters. In Part I of our study (Bower and Hunt 2000 hereafter BH00), we analyzed the tracks of 26 Range and Fixing of Sound (RAFOS) floats that were deployed in the DWBC between the Grand Banks and Cape Hatteras to investigate the large-scale pathways and spreading rates of recently ventilated water masses that are transported by the DWBC. We found that the pathways of fluid parcel were strongly influenced by the Gulf Stream in the crossover region. In Part II, we focus attention on the float observations just in the crossover region. While the PS93 study significantly improved the description of the complex circulation and dynamics in this critical area, they could only infer fluid parcel pathways by assuming the velocity field observed in their synoptic survey was stationary. In the following analysis, we describe directly observed fluid parcel pathways and, in particular, investigate the effects of time dependence on those pathways.

This Lagrangian study is part of a collaborative effort with R. Pickart (WHOI) and W. Smethie (LDEO) to investigate the variability of the DWBC based on hydrographic, tracer, and float measurements. The field program was called the Boundary Current Experiment (BOUNCE). In the next section, the float dataset collected during BOUNCE is described. In section 3, we show how the fluid parcel pathways in the upper DWBC are sensitive to the time-dependent meandering of the Gulf Stream. We also demonstrate that the deep DWBC is deflected offshore at the crossover in order to conserve potential vorticity, as suggested by Hogg and Stommel (1985). The findings are discussed in terms of previous observational and modeling results in section 4, and summarized in section 5.

## 2. Data

Detailed descriptions of the RAFOS floats used in this study, launch locations, and sampling strategy can be found in BH00 and in Hunt and Bower (1998). In brief, 30 RAFOS floats were deployed in the DWBC between the Grand Banks and Cape Hatteras during two hydrographic survey cruises, the first in November–December 1994 on the R/V *Endeavor* (EN257, BOUNCE I), and the second in May–June 1995 on the R/V *Oceanus* (OC269, BOUNCE II). Half of the floats, referred to hereafter as ''shallow'' floats, were designed to be isopycnal-following (Rossby et al. 1985; BH00), and ballasted for the CFC maximum associated with ULSW. This maximum is centered at $\sigma_t = 27.73$, which is at about 800 dbar north of the Gulf Stream (PS93; Pickart et al. 1997). Isopycnal floats follow the three-dimensional motion of fluid parcels more accurately in regions where density surfaces slope steeply, such as in the crossover region. To make the floats isopycnal, spring-backed pistons were added to give the floats nearly the same compressibility as seawater (Rossby et al. 1985). Because of the relatively low stratification at the depth of these floats, they were designed to be slightly less compressible than seawater (by 10%–15%) to avoid unstable behavior (BH00). The other 15 floats, referred to as ''deep'' floats, were isobaric, ballasted for 3000 dbar.

This is near the deep CFC maximum associated with the OW from the Nordic seas. The deep floats could not be rendered isopycnal due to the low stratification and extreme hydrostatic pressures in the deep ocean (Rossby et al. 1985). All the floats were programmed to collect acoustic tracking data from moored sound sources, as well as pressure and temperature measurements, once daily for two years. See Rossby et al. (1986) for a more detailed description of the RAFOS float system.

The floats were deployed along CTD sections across the DWBC, the shallow floats mostly between the 1500 and 3000 m isobaths and the deep floats between the 3500 and 4000 m isobaths. The location of the float launch sites within the hydrographic and velocity structure of the DWBC is discussed in BH00. In general, the recently ventilated water masses that are flowing equatorward along the continental slope in the DWBC were successfully tagged with floats. In the following analysis, we focus on 18 floats that drifted equatorward to the crossover region, 6 shallow and 12 deep.

## 3. Results

### *a. The shallow floats*

#### 1) Upper Labrador Sea Water pathways in the crossover region

Figure 1 depicts the tracks of six shallow floats just in the crossover region, defined as the area 34°–40°N, 76°–66°W. Two floats were launched right in the crossover region (numbers 270 and 276), while the others entered the region along the continental slope in the northeastern corner. Their daily positions are shown by colored dots, where the color indicates temperature along the float track (blue: coldest, red: warmest). Mean pressures of the floats are indicated in parentheses next to the float number. Four floats remained near the targeted density surface (Figs. 1a–d), but two sank to about 1500 dbar (Figs. 1e,f). This is near the transition between ULSW and classical Labrador Sea Water. At these pressures, the floats behave like isobaric floats.

All the shallow floats initially drifted southwestward parallel to the topography, then abruptly turned eastward and northeastward, accelerated, and in some cases observed increasing temperature. These features of the float tracks indicate that they were entrained into the Gulf Stream, as has been described previously by Bower and Rossby (1989) for floats in the main pycnocline of the Gulf Stream. The location along each float track where the abrupt change in flow direction occurred is indicated by a star, and it corresponds well with where the float track crossed the synoptic surface thermal front at the northern edge of the Gulf Stream (''north wall,'' solid red line in panels of Fig. 1). In this and subsequent figures, the surface location of the Gulf Stream was obtained from Advanced Very High Resolution Radiometer (AVHRR) observations of sea surface temperature, and digitized at the U.S. Naval Oceanographic Office. The mean Gulf Stream path (dashed red line) was obtained from eight years of AVHRR observations (Lee 1994).

The longitude of float entrainment apparently depended mostly on cross-slope position: floats 270, 275, and 276 (Figs. 1a,b,e) were over or inshore of the 2500-m isobath north of the stream and were entrained at or west of about 74°W, while floats 277, 266, and 267 (Figs. 1c,d,f), over or offshore of the 3000-m isobath north of the stream, were entrained farther east, at or east of 72°W. Float 275 surfaced in the crossover region shortly after being entrained, while the other shallow floats departed the crossover region toward the east, some making cyclonic loops along the way.

Figure 2 illustrates the entrainment process in more detail for one representative shallow float, number 270. Between launch in November 1994 and entrainment into the Gulf Stream in late February 1995, this float drifted southwestward (Fig. 2a), with speed increasing from less than 5 cm $s^{-1}$ to about 15 cm $s^{-1}$ (Fig. 2d). At the end of February, the float turned offshore and temperature and pressure increased slightly (Figs. 2b,c). This indicates that the float was entrained and subducted downward along sloping isopycnals at the northern edge of the stream (Bower and Rossby 1989). If the float had had exactly the same compressibility as seawater, it would have followed the isopycnal more closely, temperature would have remained more constant along the float track, and pressure fluctuations would have been larger. But, since the float was less compressible than its surroundings, it could not exactly follow the vertical component of fluid parcel motion and, therefore it cut across isopycnals (and isotherms) as the surrounding fluid parcels were subducted along the isopycnals.

After the float was entrained, it drifted northeastward for about one month, with maximum speeds of about 25 cm $s^{-1}$. Starting in mid-April 1995 and continuing until the float left the crossover region near the beginning of June, temperature fluctuated between 4° and 6°C, and pressure covaried, ranging between 900 and 1100 dbar. The temperature and pressure fluctuations are highly correlated with the cyclonic loops in the float track that occurred in April–May 1995, indicating that the float was crossing in and out of the stream along its northern edge (Bower and Rossby 1989). After leaving the crossover region, float 270 drifted rapidly eastward in the Gulf Stream to about 55°W and returned to the crossover region via the northern recirculation gyre in June 1996, about one year after it had initially departed (see Fig. 7b in BH00 for the full trajectory).

#### 2) Cross-stream transport of ULSW properties

None of the shallow floats crossed under the Gulf Stream in the crossover region to continue southward along the western boundary. So how do the tracer sig-

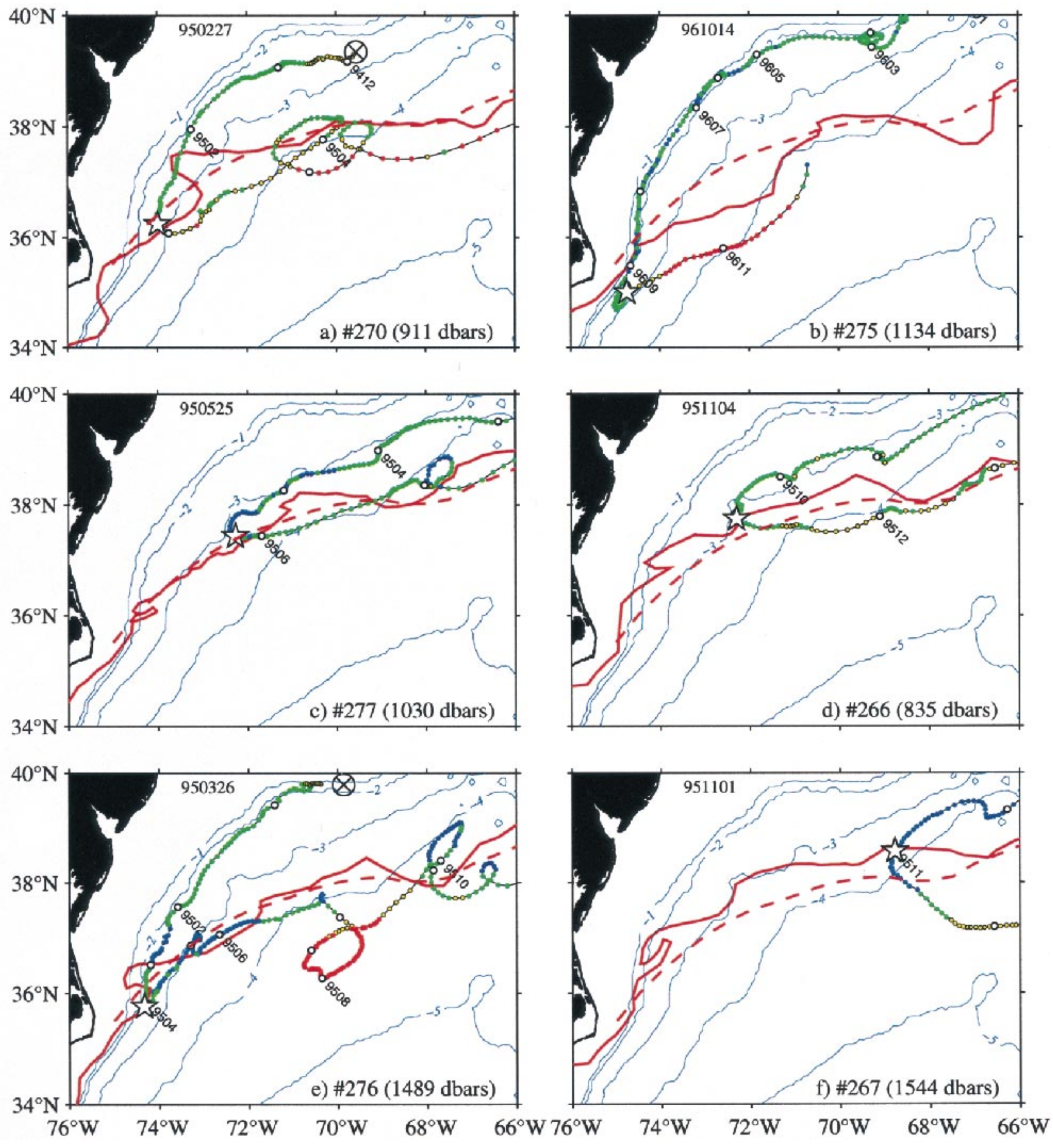


FIG. 1. Tracks of six RAFOS floats launched in the upper DWBC, just during the time they were transiting the DWBC–Gulf Stream crossover region. Mean pressure of float is indicated in parentheses next to float number in lower right of each panel. Circled ×'s denote float launch sites. Daily float positions are shown by colored dots, where the color indicates float temperature. (a–d) Blue: $T \leq 4.0$, green: $4.0 < T \leq 4.5$, yellow: $4.5 < T \leq 5.0$, red: $T > 5.0$°C. For deeper floats in (e,f) blue: $T \leq 3.75$, green: $3.75 < T \leq 4.00$, yellow: $4.00 < T \leq 4.25$, red: $T > 4.25$°C. Open circles are plotted along float track at the first of each month, and labeled every other month (yymm). These floats drifted southwestward along the continental slope in the upper DWBC until entrained into the Gulf Stream, evidenced in all cases by an abrupt change in direction toward the east or northeast, and sometimes by a rapid increase in temperature. The approximate entrainment location along each float track is indicated by a star, and the location of the Gulf Stream north wall at the sea surface on the day of entrainment (from satellite infrared imagery) is shown by the solid red line (date listed in upper-left corner of each panel, yymmdd). The dashed red line shows the long-term mean path of the Gulf Stream. Bathymetric contours are shown every 1 km.

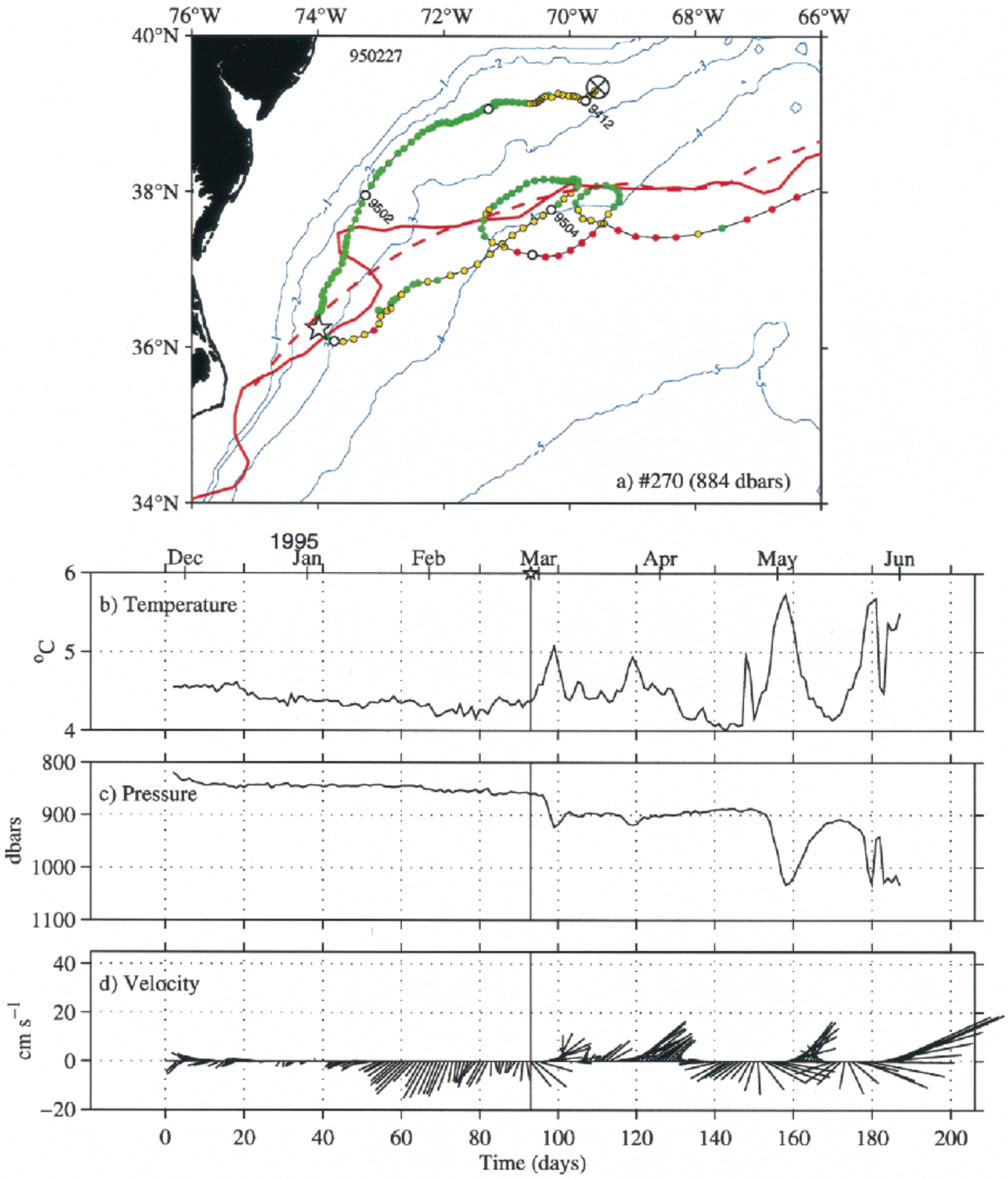


FIG. 2. (a) Track of a representative shallow float, 270, with records of (b) temperature, (c) pressure, and (d) velocity (northward velocities are upward) along the float track. Colored circles along track indicate float temperature as in Fig. 1, and open circles are plotted monthly. The approximate location where the float was entrained into the stream is indicated by a star in (a) and corresponds to the vertical lines in (b–d). The location of the Gulf Stream surface front when the float was being entrained (27 Feb 1995) is shown by the solid red line, and the mean path by the dashed red line. The temperature fluctuations from Mar to May 1995 indicate that the float was crossing in and out of the Gulf Stream along its northern edge, as also indicated by the cyclonic loops in the float track.

nals associated with ULSW reach the subtropical gyre where they have been observed along the western boundary (see, e.g., Fine and Molinari 1988; Johns et al. 1997)? Smethie (1993) suggested that cold core ring formation probably contributes to the cross-stream flux of ULSW properties, and in fact one shallow float crossed the Gulf Stream in a cold core ring formation event east of the crossover region (BH00). However,

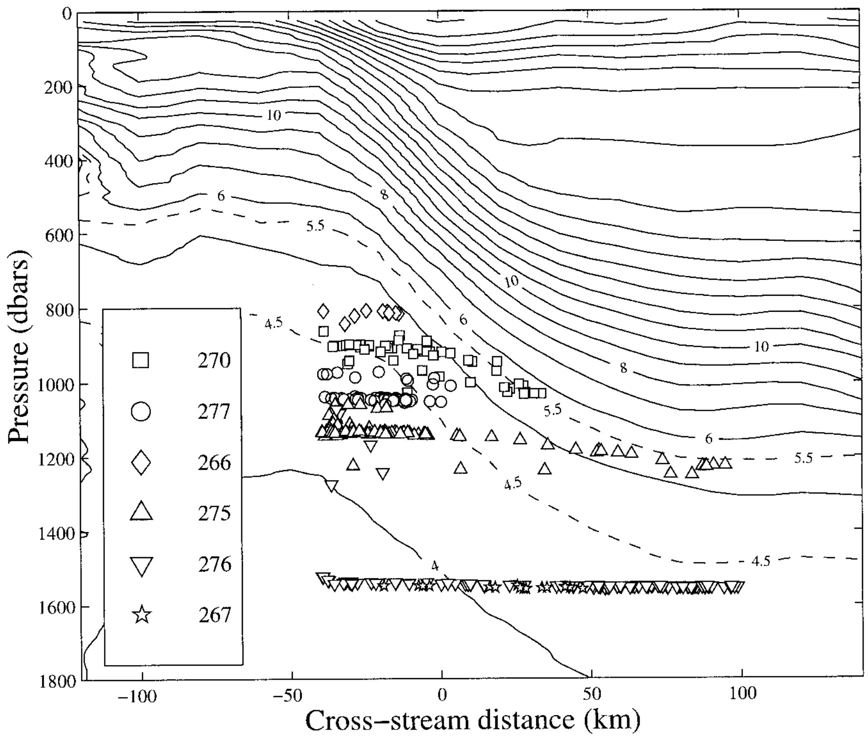


FIG. 3. Mean temperature section across the Gulf Stream at 73°W in ''stream'' coordinates from Halkin and Rossby (1985) with the cross-stream positions of each shallow float superimposed. Two floats, 275 and 276 (upright and inverted triangles), completely crossed the baroclinic jet in the crossover region, while the other floats were confined along the northern edge of the stream.

Bower et al. (1985) concluded that the contribution of rings may be relatively small, at least at the main pycnocline level, and that some other mechanism is responsible for the cross-stream flux of water properties.

Several investigators have demonstrated how cross-stream motion of fluid parcels and mixing can result from time-dependent meandering of the Gulf Stream using relatively simple kinematic models of a meandering jet (Bower 1991; Samelson 1992; Duan and Wiggins 1996). The same basic mechanism has also been explored in the context of more realistic, dynamical models of a meandering jet (Lozier et al. 1997; Rogerson et al. 1999). Some of the shallow floats made large excursions across the Gulf Stream, and this behavior appears to be related to meandering of the stream. To demonstrate this, we have first used the float temperature and pressure observations along with a mean ''stream coordinate'' temperature section across the Gulf Stream to determine how far across the current's baroclinic structure each float penetrated (Fig. 3). The mean temperature section was constructed from 16 repeat sections across the Gulf Stream at 73°W made over a 3.5-yr period, where the sections were transformed into a streamwise coordinate system before averaging (Halkin and Rossby 1985). This mean section thus represents the mean *synoptic* temperature structure across the Gulf Stream, which has been shown to vary little in time or with downstream distance (Halkin and Rossby 1985; Johns et al. 1995). Note that the float temperature and pressure observations could be used to determine cross-stream position only where temperature increases monotonically across the stream, between −40 and 100 km.

It is apparent from Fig. 3 that four of the shallow floats remained mostly on the northern side of the Gulf Stream and two completely crossed the baroclinic part of the stream in the crossover region, floats 275 and 276 (upright and inverted triangles). Their trajectories are illustrated in Figs. 1b and 1e, respectively. By comparing the float tracks to the changing position of the Gulf Stream, we have found that the large cross-stream excursions of the floats occurred when a *cyclonic* meander trough was present in the crossover region. Smaller cross-stream displacements were observed when the Gulf Stream path was closer to its mean position, which has *anticyclonic* curvature. For example, Fig. 4 shows the location of floats 275 and the Gulf Stream's north wall at two-week intervals starting on 15 October 1996. Temperature along the float track increased rapidly (indicating subduction and offshore cross-stream displacement) when the float was *upstream* of a cyclonic meander trough (Figs. 4a,b). *Downstream* of the trough axis, the float observed decreasing temperatures, indicating it was moving back to the northern side of the stream (Fig. 4c). This behavior is consistent with the

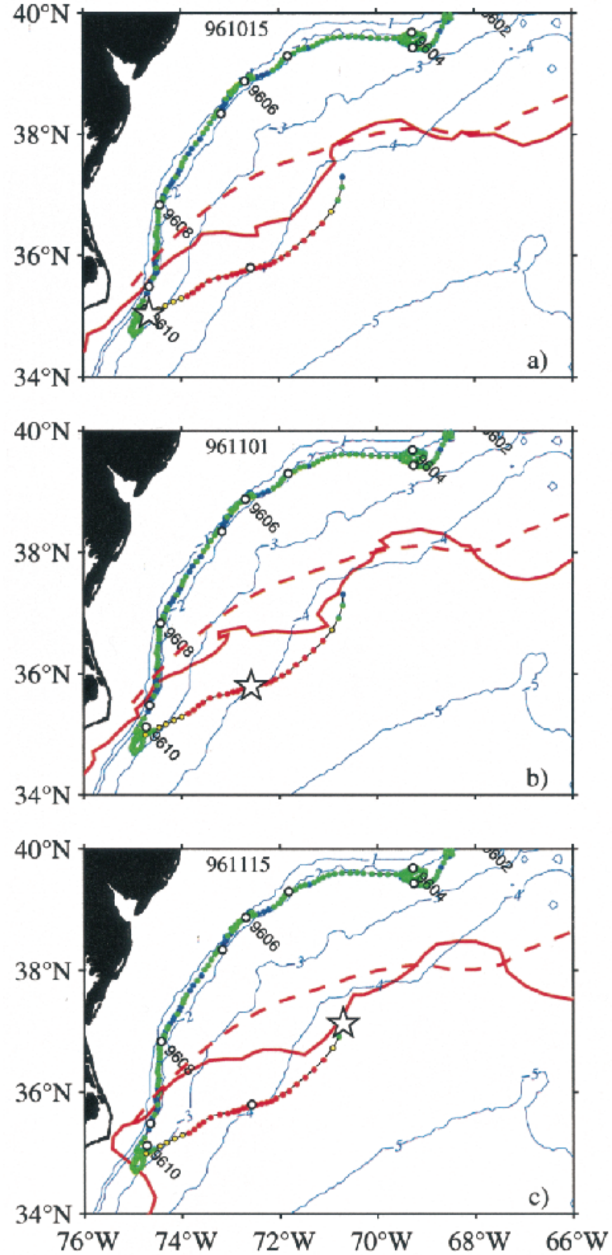


FIG. 4. Gulf Stream north wall positions (solid red lines) and positions of float 275 (stars) at 15-day intervals beginning on 15 Oct 1996. During this time, there was a meander trough northeast of the float entrainment point, and the float was displaced to the southern edge of the stream as it drifted downstream, indicated by the increase in float temperature. Color coding along float track is same as for Fig. 1.

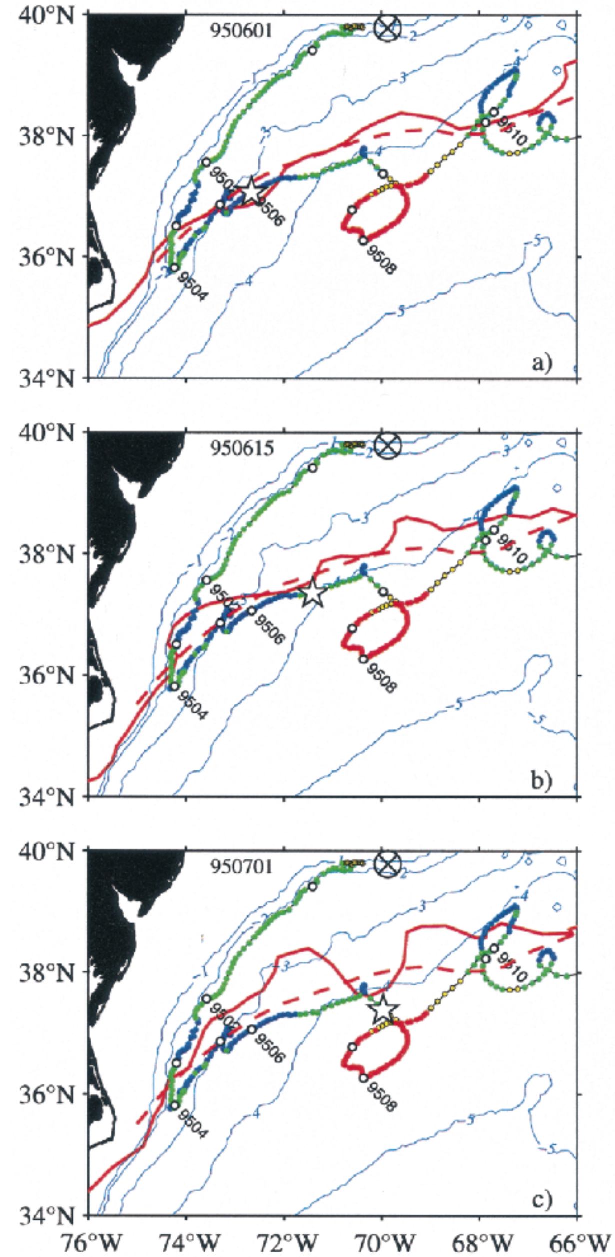


FIG. 5. As in Fig. 4 but for float 276, beginning on 1 Jun 1996. See text for explanation.

observations of Bower and Rossby (1989) and with the kinematic model results of Bower (1991), which showed offshore fluid parcel displacements between meander crests and troughs and onshore motion between troughs and crests.

Figure 5 shows a similar sequence for the other float that completely crossed the Gulf Stream, float 276. When this float was entrained, the Gulf Stream was close to its mean position, and the float initially skirted along the northern edge of the stream. This is indicated by the relatively cool temperatures and slow speeds during April–June 1995 (Fig. 5a). In mid-June, a short meander began to steepen near 69°W (Fig. 5b), and at the beginning of July 1995, when the meander had amplified further, the float suddenly crossed to the south side of the Gulf Stream. This occurred just upstream of the meander trough axis. The float then made a slow anticyclonic loop, indicating that it had been completely

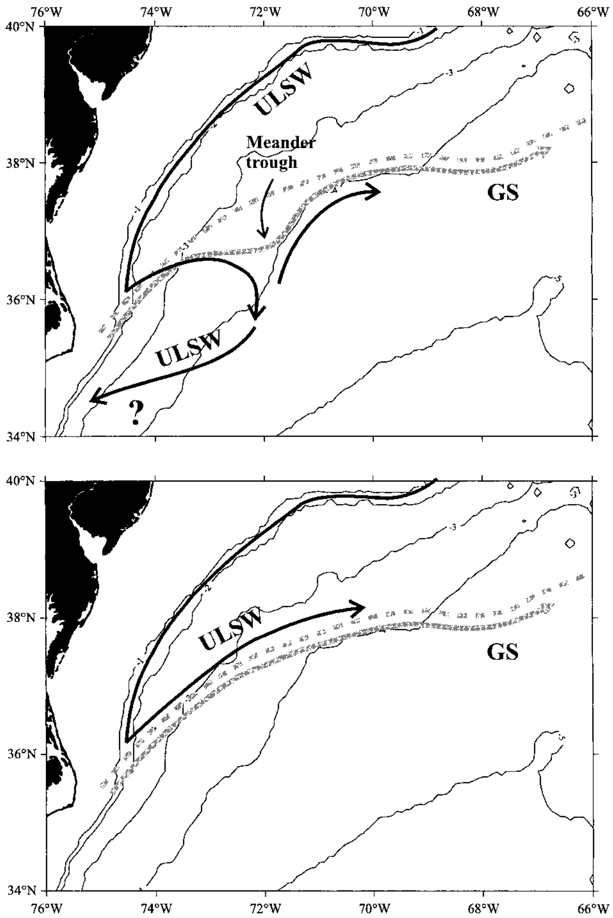


FIG. 6. Schematic diagram illustrating ULSW fluid parcel trajectories for two different Gulf Stream configurations. (a) The stream is curving cyclonically due to the presence of a meander trough, and fluid parcels make large cross-stream excursions, which can result in the fluid parcels being expelled on the southern side. A return path from south of the Gulf Stream back to the DWBC was not observed, although one float temporarily drifted southwestward on the south side of the stream. (b) The stream is closer to its mean path, which curves anticyclonically through the crossover region. In this case, ULSW fluid parcels skirt along the northern edge of the stream after being entrained.

expelled from the northeastward flowing Gulf Stream, *at least temporarily*. About two months later, it was reentrained into the stream, observed rapidly *decreasing* temperature, and eventually made a cyclonic loop, indicating that it crossed out of the stream on the northern side. Comparison of the synoptic Gulf Stream path with the other four shallow floats, which remained just along the northern edge of the stream, shows that the stream was close to its mean position when these floats were transiting the crossover region.

Although none of the six shallow floats ''permanently'' crossed the stream in the crossover region, they reveal that time-dependent meandering of the Gulf Stream causes large cross-stream fluid parcel displacements, that could result in transport of ULSW properties southward. Figure 6 illustrates this mechanism schematically. When there is a meander trough in the crossover, fluid parcels will be entrained into the stream, strongly subducted, and potentially expelled on the southern side (Fig. 6a). The temporary, two-month southwestward drift of float 276 south of the stream (Fig. 5) suggests that expelled fluid parcels may return to the DWBC south of the crossover, indicated by the question mark in Fig. 6a. On the other hand, if the Gulf Stream is flowing more directly northeastward, closer to its mean position, fluid parcels will be entrained along the northern edge of the stream, but will not cross the stream completely (Fig. 6b). This mechanism is not restricted to the crossover region. Fluid parcels at this level that encounter a steep meander *east* of the crossover region may also be expelled to the southern side of the stream, as observed at the pycnocline level by Bower and Rossby (1989).

### *b. The deep floats*

#### 1) OVERFLOW WATER PATHWAYS IN THE CROSSOVER REGION

Figure 7 shows the trajectories of 12 deep floats just in the crossover region. North of the Gulf Stream, all of them tended to drift southwestward along the continental slope, where they observed relatively cool temperatures. When they reached the Gulf Stream, indicated by an abrupt increase in temperature (see below), they split into two branches. Floats that crossed the Gulf Stream west of about 70°W (Figs. 7a–f) were more likely to cross smoothly and directly under the stream near the western boundary and continue equatorward, although only two actually exited the domain across the southern boundary. The floats that intersected the stream east of 70°W (Figs. 7g–l) tended to exhibit more eddy motion in the crossover region and, with the exception of one float, followed a path eastward in the deep Gulf Stream. The longitude where each float crossed the stream depended to a large extent on its cross-slope position: floats farther inshore tended to intersect the stream farther west, although the synoptic position of the stream also influenced where the crossing occurred.

To illustrate in more detail how the deep floats crossed under the Gulf Stream, an expanded version of the trajectory of one deep float, 280, is shown in Fig. 8, with records of temperature, bottom depth, and velocity along the float track. This float entered the crossover region in the northeastern corner and generally drifted southwestward in the DWBC along the 3500–3700-m isobaths (Figs. 8a,c), at speed as high as ~30 cm s$^{-1}$, from August through October 1995 (Fig. 8d). Temperature along this segment fluctuated between 2.25° and 2.50°C (Fig. 8b). In mid-November 1995, temperature increased abruptly to about 2.8°C where the float track intersected the surface thermal front at the northern edge of the Gulf Stream (Figs. 8a,b). The float took about 10 days to cross under the Gulf Stream. From December

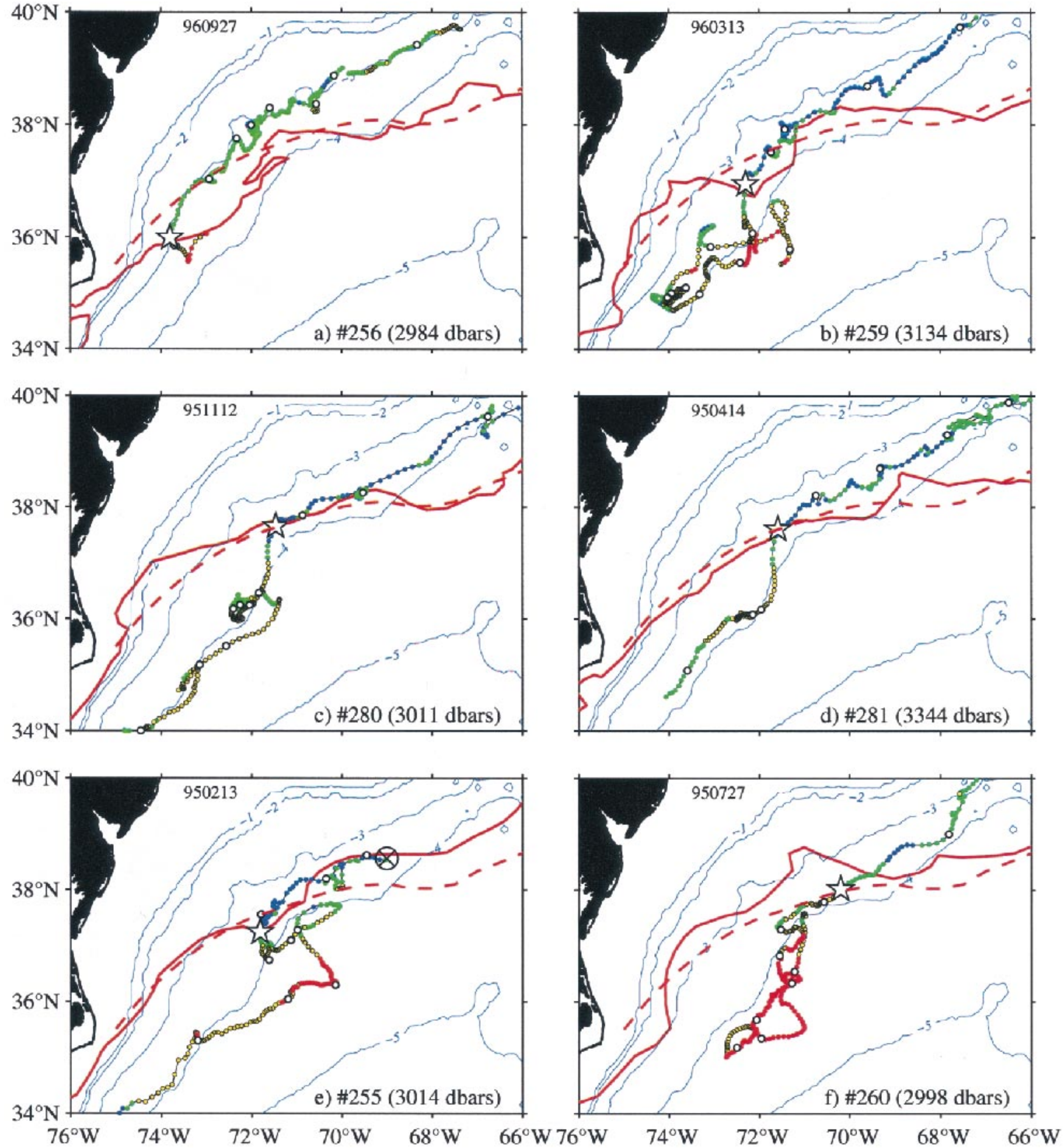


FIG. 7. As in Fig. 1 but showing trajectories of 12 deep RAFOS floats. For all but floats 281 and 262 blue: $T \le 2.50$, green: $2.50 < T \le 2.75$, yellow: $2.75 < T \le 3.00$, red: $T > 3.00$°C. For 281 and 262 (d,j) temperature limits are 0.25°C lower.

1995 through February 1996, southward speed decreased, the float drifted slowly upslope, and temperature gradually decreased to about 2.50°C (with shorter period fluctuations superimposed). Starting in March, the float accelerated and continued drifting southwestward at speeds as high as ~25 cm $s^{-1}$. It left the crossover region in the DWBC to the south along the continental slope.

### 2) The crossing process

A common characteristic of all the deep float tracks was the offshore motion of the floats (crossing isobaths into deeper water) when they crossed under the Gulf Stream. This phenomenon can be seen clearly in Fig. 8 for the representative deep float, number 280. Bottom depth along the float track (Fig. 8c) was estimated by

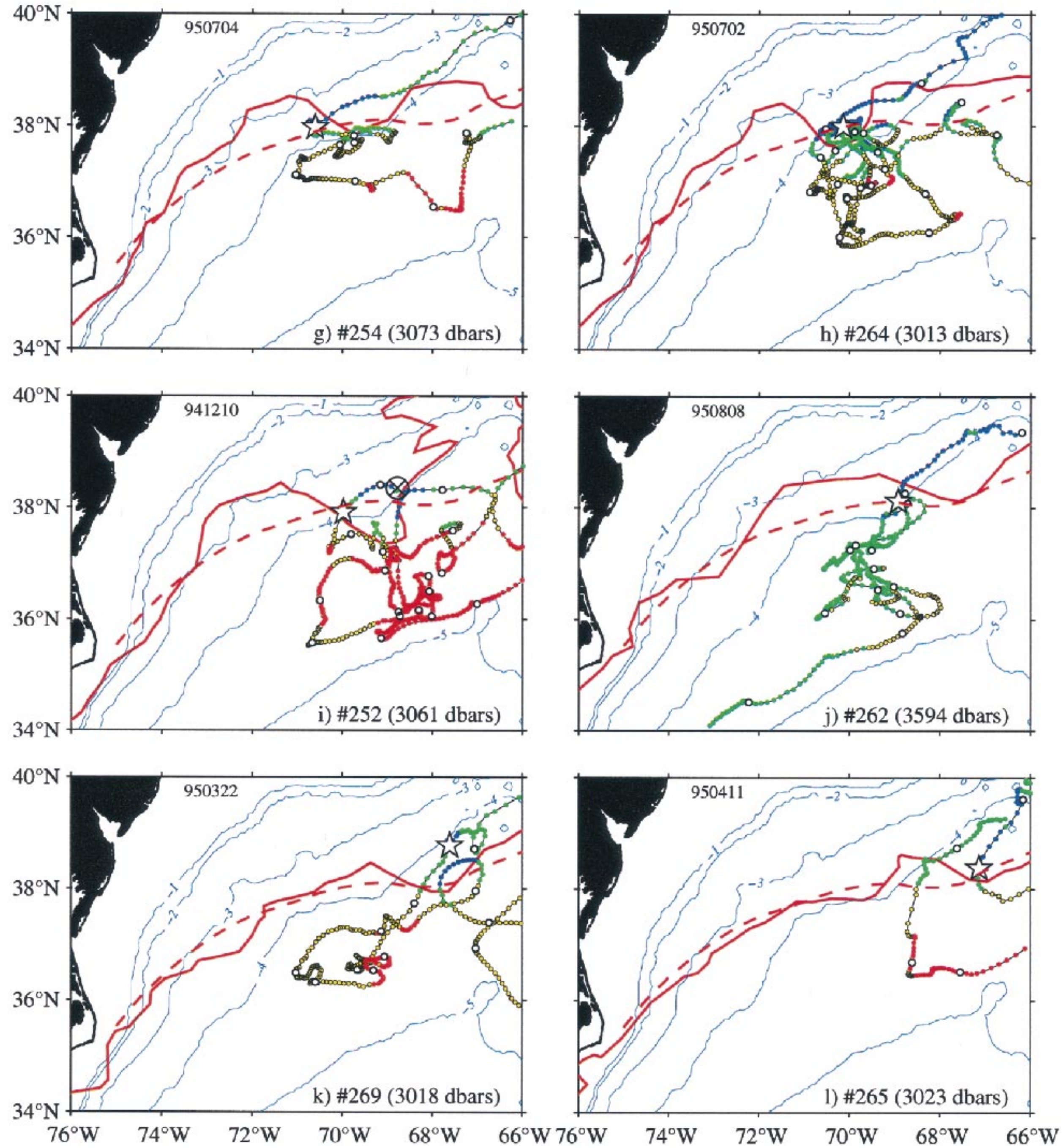


FIG. 7. *(Continued)*

first smoothing the ETOPO5 bathymetric data with a 100-km-square box car filter, then interpolating the smoothed bathymetry along the float track. The filter width was chosen based on an estimate of the internal Rossby radius for the water column below the pycnocline. Comparing Figs. 8b and 8c, the float crossed from the 3500 m to the 4000 m isobath at the same time that temperature increased from about 2.25° to 2.85°C in mid-November 1995. Over the next several months, the float slowly drifted back upslope to the 3750-m isobath, as the temperature decreased. In February and March 1996, the float drifted back downslope, this time to the 4200-m isobath, and temperature simultaneously increased to its highest value along this track, nearly 3.0°C.

This correlation between bottom depth along the float track and float temperature was observed in all the deep floats as they crossed under the Gulf Stream. It is most

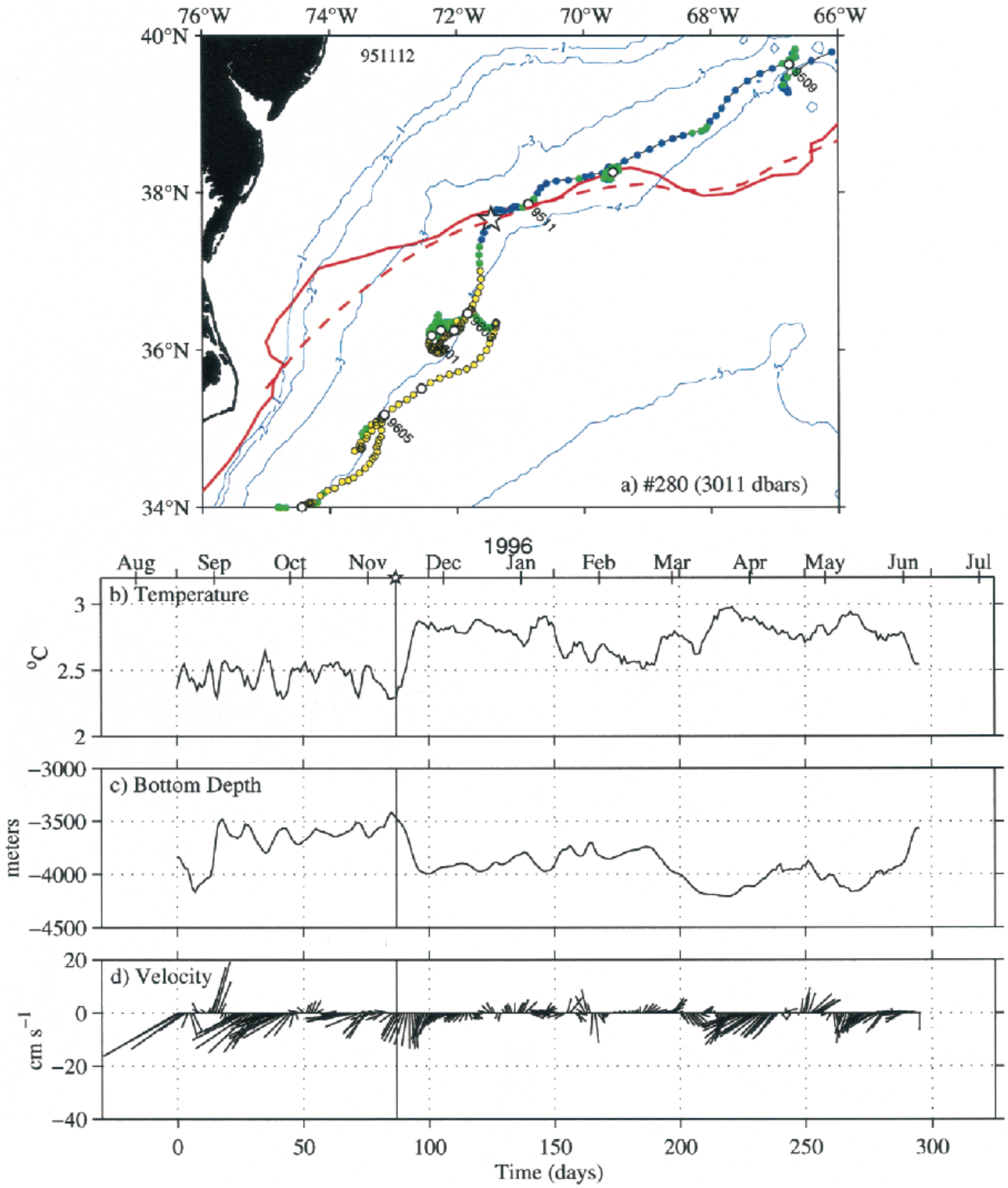


FIG. 8. (a) Track of representative deep float, 280, with simultaneous records of (b) temperature, (c) bottom depth, and (d) velocity along the float track. Color coding of temperature along float track is same as in Fig. 7. The location where the float began to cross under the Gulf Stream (on 12 Nov 1995) is indicated by a star in (a), and corresponds to the vertical lines in (b–d).

easily seen in the relatively simple first six float tracks (Figs. 7a–f) by noting the coincidence of cross-slope displacements with increasing temperature where the float tracks intersected the Gulf Stream's north wall. These observations are consistent with the two-layer steady model of the crossover introduced by Hogg and Stommel (1985), in which the DWBC crosses the isobaths into deep water when it encounters the downward sloping pycnocline of the Gulf Stream in order to conserve planetary potential vorticity (PPV), $f/H$, where $H$ is the layer thickness between the pycnocline and the seafloor. This is illustrated schematically in Fig. 9. The

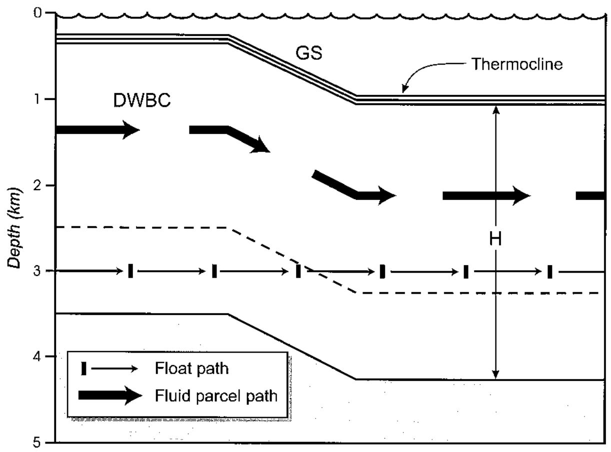


FIG. 9. Schematic diagram illustrating how fluid parcels (bold arrow) and isobaric floats (thin arrows) in the DWBC cross under the Gulf Stream, according to the two-layer model of Hogg and Stommel (1985) and the float observations.

lower-layer flow (DWBC, bold arrows) follows the bathymetry until it hits the downward sloping thermocline associated with the Gulf Stream. To conserve PPV, the fluid parcels flow downslope as they cross under the Gulf Stream. Since the isobaric RAFOS floats are constrained to a pressure surface, they can only follow the horizontal component of fluid parcel motion (thin arrows in Fig. 9). The deep isotherms slope downward parallel to the pycnocline (see below), so the float observes increasing temperature as the lower-layer fluid parcels cross under the Gulf Stream. Once south of the Gulf Stream, both the float and fluid parcels in the lower layer follow a different, deeper isobath. According to the model, in the absence of mixing, and over the short meridional distances of the crossover, the new isobath will be deeper by the same amount that the thermocline deepens across the Gulf Stream. The total increase in bottom depth along the track of float 280 between mid-November 1995 and March 1996 was ~700 m. This is about the same as the typical increase in depth of the main pycnocline across the Gulf Stream (see, e.g., Joyce et al. 1986), consistent with the model. As can be seen in Fig. 7, the other deep floats exhibited similar behavior, drifting into water 500–1000 m deeper as they crossed under the Gulf Stream.

### 3) POTENTIAL VORTICITY ALONG FLOAT TRACKS

In this section, we present a method for estimating PPV along the float tracks in order to examine the hypothesis of Hogg and Stommel (1985) more quantitatively and to examine the long-term changes in PPV along fluid parcel trajectories. We begin by noting that the Ertel potential vorticity of the deep flow can be approximated by the layer potential vorticity (LPV),

$$\frac{f + \zeta}{\rho_0}\frac{\partial \rho}{\partial z} \approx \frac{f + \zeta}{H} \equiv \mathrm{LPV},$$

where $f$ is the Coriolis parameter, $\zeta = \partial v/\partial x - \partial u/\partial y$ is the vertical component of relative vorticity, $\rho_0$ is the reference density, $\partial \rho/\partial z$ is the vertical density gradient, and $H$ is the thickness of the deep layer bounded by the main pycnocline above and the seafloor below. This approximation is justified based on the observation that the flow below the pycnocline is relatively barotropic: vertical shear in the deep layer is about $1 \times 10^{-4}$ s$^{-1}$ or less, which is about an order of magnitude smaller than the shear across the pycnocline (see, e.g., Joyce et al. 1986).

In the deep ocean, relative vorticity is generally much less than planetary vorticity, and LPV can be approximated by the PPV, $f/H$. However, in the crossover region, relative vorticity can be a significant fraction of $f$ due to the presence of energetic topographic Rossby waves along the continental slope (Pickart and Watts 1990). For example, for waves with an amplitude of $V = 20$ cm s$^{-1}$ and a wavelength of $L = 100$ km (Pickart and Watts 1990), relative vorticity would be $(2V)/(L/2) = 0.8 \times 10^{-5}$ s$^{-1}$, which is about 9% of $f$ at this latitude. We therefore anticipate that, for timescales near the dominant period of topographic waves in this region (~40 days; Pickart and Watts 1990), there could be fluctuations in PPV on the order of 10% that are compensated by changes in relative vorticity such that LPV is conserved. Such fluctuations in PPV would be larger than the uncertainty in PPV due to the uncertainty in the estimate of pycnocline depth, which is 113 dbar/3200 dbar, or about 4%.

PPV was estimated along the float tracks as follows. Bottom depth was easily obtained from digital bathymetric data, as described above. Pycnocline depth along the float tracks could also be estimated because there is a strong correlation between temperature at 3000 dbar (float depth) and the depth of the main pycnocline. This is illustrated qualitatively in Fig. 10, which shows the mean pressure of the $27.2\sigma_0$ density surface (found in the middle of the main pycnocline, and corresponding approximately to the 10°C isotherm) and mean temperature at 3000 dbar from the HydroBase climatology of the North Atlantic (Lozier et al. 1995; Curry 1996). Downstream of where the mean Gulf Stream path separates from the western boundary (near 36°N), the relatively steep cross-stream slope of the $27.2\sigma_0$ surface coincides with the strongest temperature gradient at 3000 dbar. This reflects the fact that the isopycnals slope across the Gulf Stream throughout the water column. Shoreward and seaward of the stream, the isopycnal slopes and deep temperature gradients are relatively weak.

To estimate the depth of the pycnocline along the float tracks, we took advantage of the fact that much of the spatial and temporal variability of temperature in the crossover region can be represented by vertical displacement of a "standard" temperature profile (at least below the level of seasonal influence) (Hogg 1991). Once the standard profile has been determined, the tem-

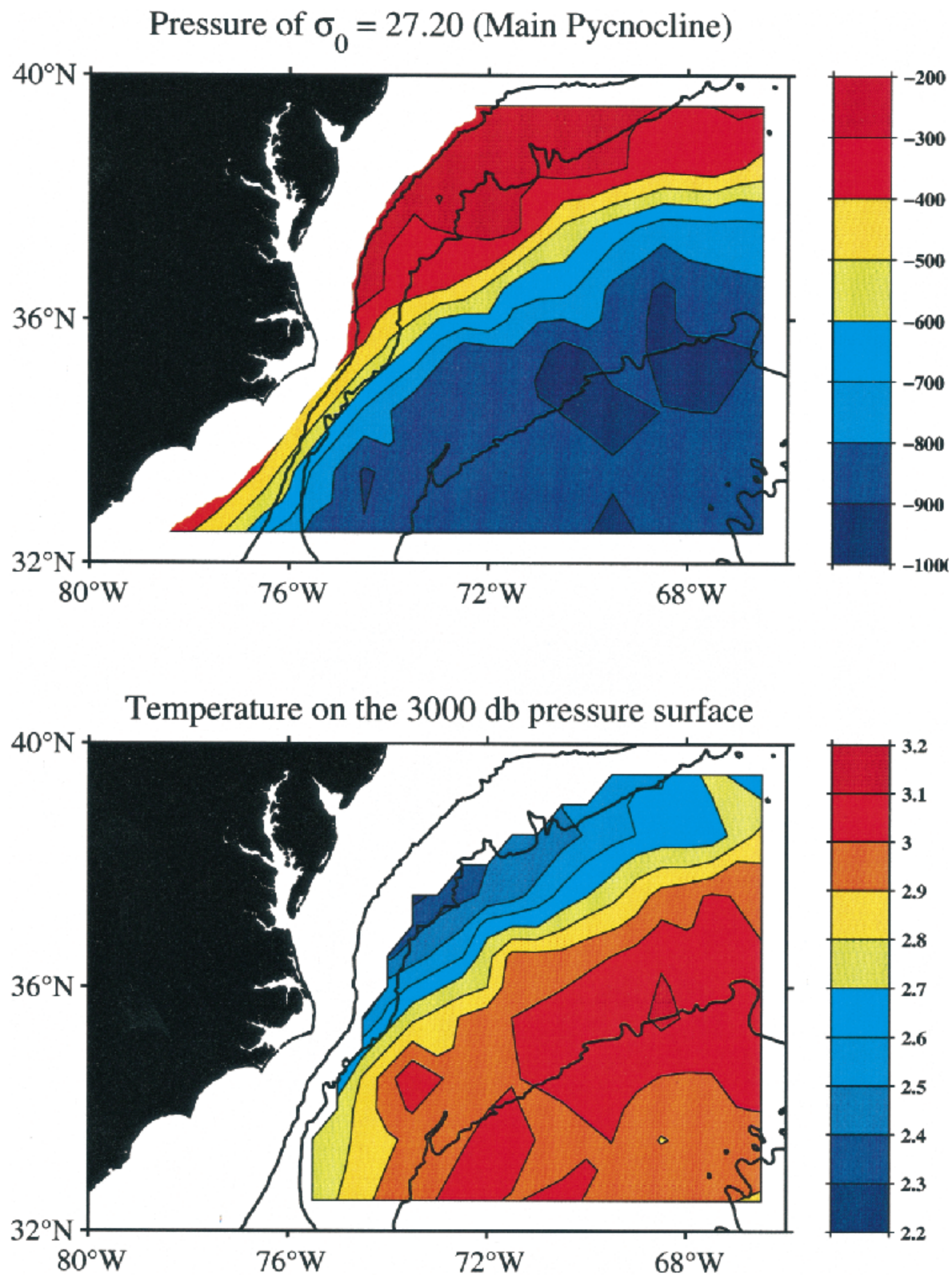


FIG. 10. (a) Mean pressure of the density surface $\sigma_0 = 27.2$ in the crossover region from the HydroBase climatology. Observations were averaged in 1° lat. by 1° long. boxes. Bathymetric contours are shown at 1000, 3000, and 5000 m. (b) Mean temperature at 3000 dbar from the same database.

perature at any pressure (or equivalently, the pressure of any isotherm or isopycnal) can be determined by knowing the temperature at any other pressure, which the floats provide. For the present purpose, the standard profile was obtained using the observations in the HydroBase climatology. Figure 11a shows the 543 temperature profiles in the crossover region that were in water deeper than 3000 m and that reached to at least 2800 dbar. The pressure of the main pycnocline ($P_{ref}$) for each of these profiles was estimated by fitting a line to the corresponding density profile between $\sigma_0 = 26.8$ and 27.6 and finding the pressure of the $27.2\sigma_0$ surface from the resulting coefficients. This density range spans the middle section of the main pycnocline, where the stratification is approximately linear, and minimizes intrapycnocline perturbations that are not necessarily representative of a depth change of the whole pycnocline. Only profiles for which there were at least three obser-

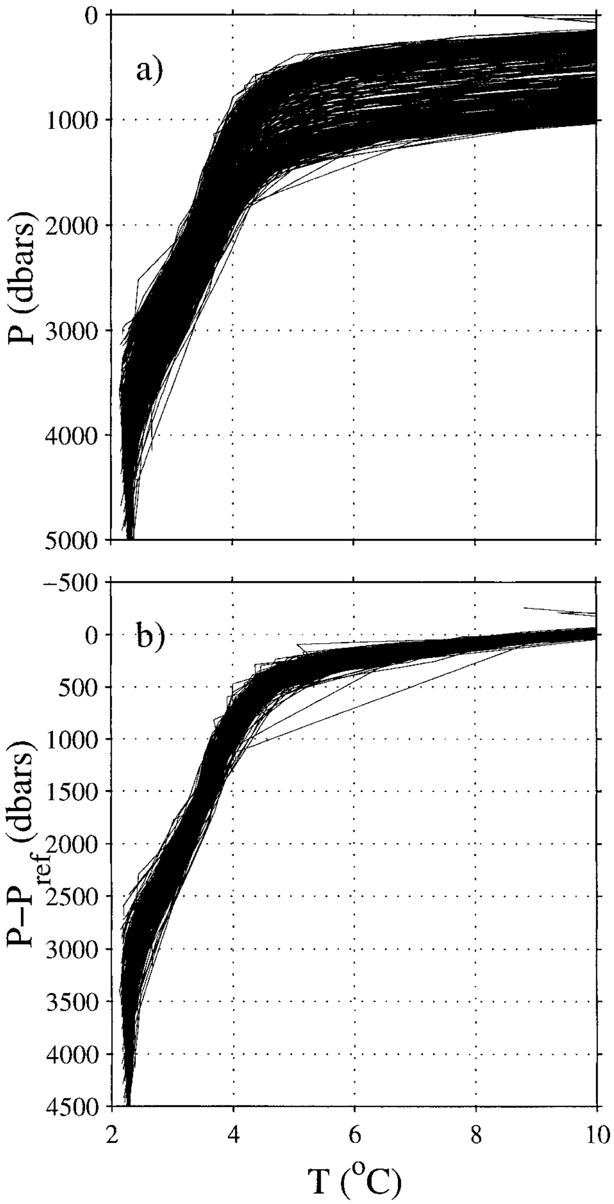


FIG. 11. (a) Composite of 534 temperature profiles from HydroBase that were made in the crossover in water depth greater than 3000 m, and which extended to at least 2800 dbar. (b) Same temperature profiles as in (a) but in a coordinate system with its origin at the pressure of the 27.2 $\sigma_0$ surface (about 10°C).

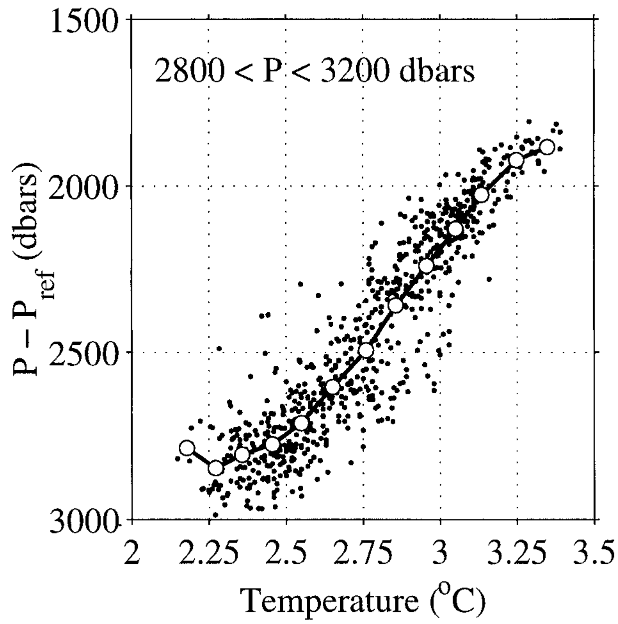


FIG. 12. Same as Fig. 11b but showing only observations in the pressure range 2800–3200 dbar. Observations were averaged in 0.1°C temperature bins (open circles) to obtain standard profile (solid line).

vations in this density range were used. Each temperature profile was then displaced vertically by an amount equal to the pressure of the 27.2$\sigma_0$ surface and replotted in Fig. 11b. This coordinate transformation reduced the variability in temperature at the level of the deep floats by more than half, from about 0.27°C (standard deviation at $P$ = 3000 dbar, Fig. 11a) to 0.12°C (standard deviation at $P - P_{ref}$ = 2400 dbar, Fig. 11b). The remaining variability in temperature at a given $P - P_{ref}$ reflects any spatial or temporal variability in the standard profile.

Before averaging the profiles in Fig. 11b to obtain the standard profile, the data were subsampled to include only observations near the pressures of the floats. Figure 12 shows only data in the pressure range 2800–3200 dbar. The data were averaged in temperature bins and a cubic spline was fit to the points to obtain the standard profile. Then, for each daily observation of float temperature, $P - P_{ref}$ was estimated using the standard profile, and this was subtracted from float pressure, $P$, to obtain $P_{ref}$. The rms difference between the estimate of $P - P_{ref}$ from the curve fit and the actual observations was about 113 dbar.

Figure 13 shows pycnocline depth, bottom depth, and PPV along the track of the representative deep float, 280 (see Fig. 8). Both the daily (thin lines) and low-pass filtered (thick lines) values are shown. There are three basic features to note: First, there is evidence of topographic wave activity, reflected in the large oscillation in unfiltered bottom depth during the first 30 days (Fig. 13b) that was not reflected in pycnocline depth (Fig. 13a). This resulted in a corresponding oscillation in PPV (Fig. 13c). Referring to the beginning of the float track (Fig. 8a), there is a wavelike perturbation in float position corresponding to this event. Assuming LPV was conserved through this event, the deviation in PPV indicates wave velocities of about $\Delta(f/H)(\overline{H})(L/4) = (0.25 \times 10^{-8}\ \mathrm{m}^{-1}\ \mathrm{s}^{-1}) \times (3200\ \mathrm{m}) \times (25\ \mathrm{km}) = 10\ \mathrm{cm\ s}^{-1}$, where $L$ (100 km) is a typical wavelength. This estimate of the wave velocity is similar to the speeds observed by the float (Fig. 8d).

The second feature to note is that although bottom depth and pycnocline depth increased significantly as

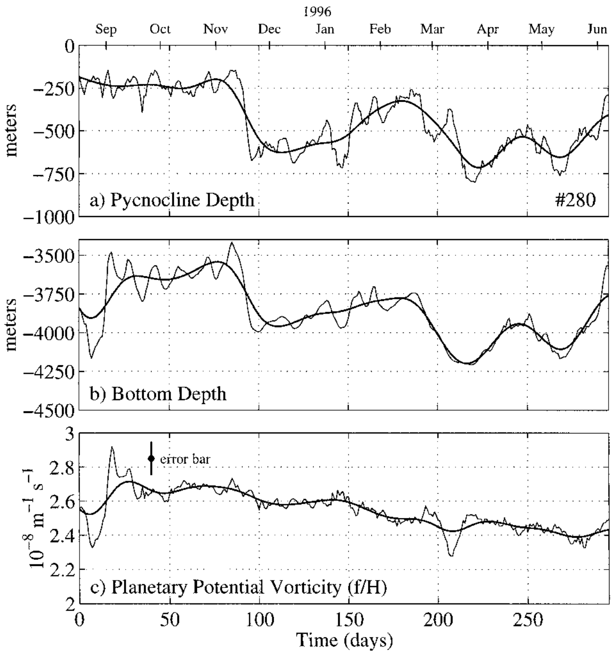


FIG. 13. (a) Pycnocline depth, (b) bottom depth, and (c) planetary potential vorticity ($f/H$) along 10-month track of float 280 as it transited the crossover region. Track is shown in Fig. 8a. Daily and low-pass filtered values (obtained with Butterworth filter with 40-day cutoff period) are shown.

the float crossed under the Gulf Stream, PPV was conserved within the uncertainty. In mid-November 1995, both the unfiltered pycnocline depth and bottom depth increased by about 500 m over 10 days such that $H$ only changed by about 95 m. PPV thus remained constant within the uncertainty (113 m, Fig. 12). Similarly, between February and March 1996, pycnocline depth and bottom depth again increased by about the same amount, and $H$ only changed by 36 m. In this case, PPV was conserved within less than 1% from the beginning to the end of the crossing, although there was an uncompensated oscillation in pycnocline depth during mid-March that resulted in an oscillation in PPV.

Interestingly, the path of this deep float (and others) was not unidirectional as it crossed under the stream, but oscillated back and forth (up- and downslope) on both long (multimonth) and short (weekly) timescales. PPV is apparently conserved through these events (Fig. 13c). This oscillatory motion may be due to the response of the deep flow to propagating meanders of the Gulf Stream, which will cause cross-slope displacements of the sloping pycnocline. For example, from December 1995 through late February 1996, float 280's equatorward velocity decreased (Fig. 8d) and the float drifted slowly upslope as it also executed several higher-frequency fluctuations in bottom depth and pycnocline depth (Figs. 13a,b). Figure 14 shows the track of float 280 superimposed on the Gulf Stream north wall positions in monthly intervals from November to March. In November (when the float crossed under the Gulf Stream) and December, the Gulf Stream was generally north of its mean position, but from January to March, it shifted south of its mean path (closer to the float), and there is evidence of significant meandering. The fluctuations in float temperature (and pycnocline depth) probably indicate the movement of the stream toward and away from the float.

The third notable feature in Fig. 13 is the gradual decrease in PPV along the 10-month track (Fig. 13c). The total change in filtered PPV between day 30 and 270 is about $-0.3 \times 10^{-8}$ m$^{-1}$ s$^{-1}$, which is about 12% of the average PPV. Since this change is considerably more than the rms uncertainty in PPV ($\sim 0.1 \times 10^{-8}$ m$^{-1}$ s$^{-1}$) and since relative vorticity is not significant on these long timescales, we interpret this decrease to be the signature of eddy mixing. Scaling analysis of the conservation equation for PPV,

$$\frac{D(\mathrm{PPV})}{Dt} = \kappa_H \nabla^2(\mathrm{PPV}),$$

where $D/Dt$ is the material derivative, and $\kappa_H$ is the horizontal eddy diffusivity, gives the order of magnitude of the timescale,

$$T = O(L^2/\kappa_H),$$

where $L$ is the typical length scale of the distribution of PPV. From the mean PPV field for the deep layer in the crossover region (see Fig. 17), PPV decreases by about 10% ($0.25 \times 10^{-8}$ m$^{-1}$ s$^{-1}$) over a $\sim$50-km cross-slope distance above the 3500-m isobath (typical location of the DWBC core). Using $L = 50$ km, and an often quoted value for $\kappa_H$ of 100 m$^2$ s$^{-1}$ (see, e.g., Pickart and Hogg 1989), the timescale for a 10% change in PPV along a fluid particle trajectory would be $T = O(300$ days). This is of the same order as the timescale inferred from the record of PPV along the track of float 280 (Fig. 13c), in which PPV changed by 10% over about 200 days. Thus the long-term decrease in PPV observed by float 280 is consistent with what might be expected from eddy mixing.

The tendency for PPV to be conserved over the relatively short timescale associated with the float crossing under the Gulf Stream, and for PPV to decrease over longer timescales, was observed in all the deep float tracks, including those that exhibited more eddy motion in the crossover region and exited toward the east along the Gulf Stream path. Figure 15 shows the track of one of these floats, number 264, plotted in two-month segments to make the track easier to follow. The records of pycnocline depth, bottom depth, and PPV along this float track are shown in Fig. 16. Like float 280, this float was drifting southwestward along the slope between the 3500 and 3700 m isobaths until it encountered the Gulf Stream near 70°W (Figs. 15a,b and 16b). It crossed under the stream during July 1995, indicated by the abrupt increase in pycnocline and bottom depth (Figs. 15b and 16a,b). As was the case for float 280,

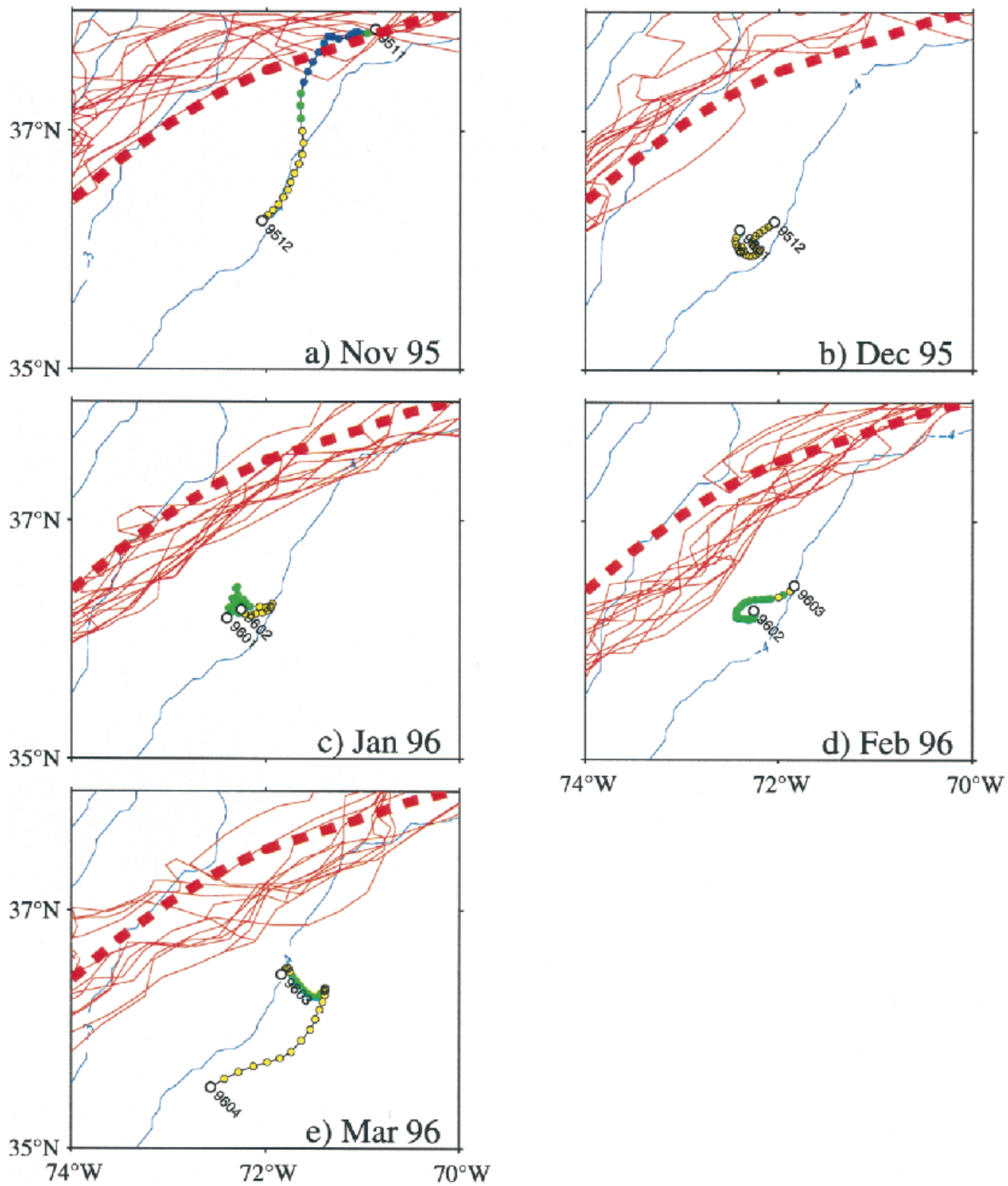


FIG. 14. Sequence of Gulf Stream north wall positions in monthly intervals beginning in November 1995, superimposed on one-month track segments of float 280 as it crossed under the Gulf Stream. Mean Gulf Stream path is indicated by dashed red line. Other annotations are as in Fig. 8a.

PPV was conserved (within the uncertainty) during the crossing event.

From then on, float 264 behaved quite differently from float 280: it slowly meandered around in the crossover region for almost a year and a half before drifting east out of the crossover region (Figs. 15c–j). During that time period, it moved up and down the slope, and these motions were highly correlated with changes in pycnocline depth, on timescales of a few weeks to a few months (Figs. 16a,b). PPV was conserved during many of these events, but showed a gradual decrease over the length of the record. The rate of change of PPV over the entire record was $-0.58 \times 10^{-8}$ m$^{-1}$ s$^{-1}$ (from day 30 to day 580), which is about 25% of the mean PPV. This corresponds to a 9% change for every 200 days, similar to the 10% observed over 200 days along the track of float 280.

One particularly striking feature of these observations is the strong visual correlation between pycnocline depth and bottom depth during the short-period fluctuations (Figs. 16a,b) such that PPV is nearly conserved. ''Bursts'' of higher-frequency cross-slope float motion

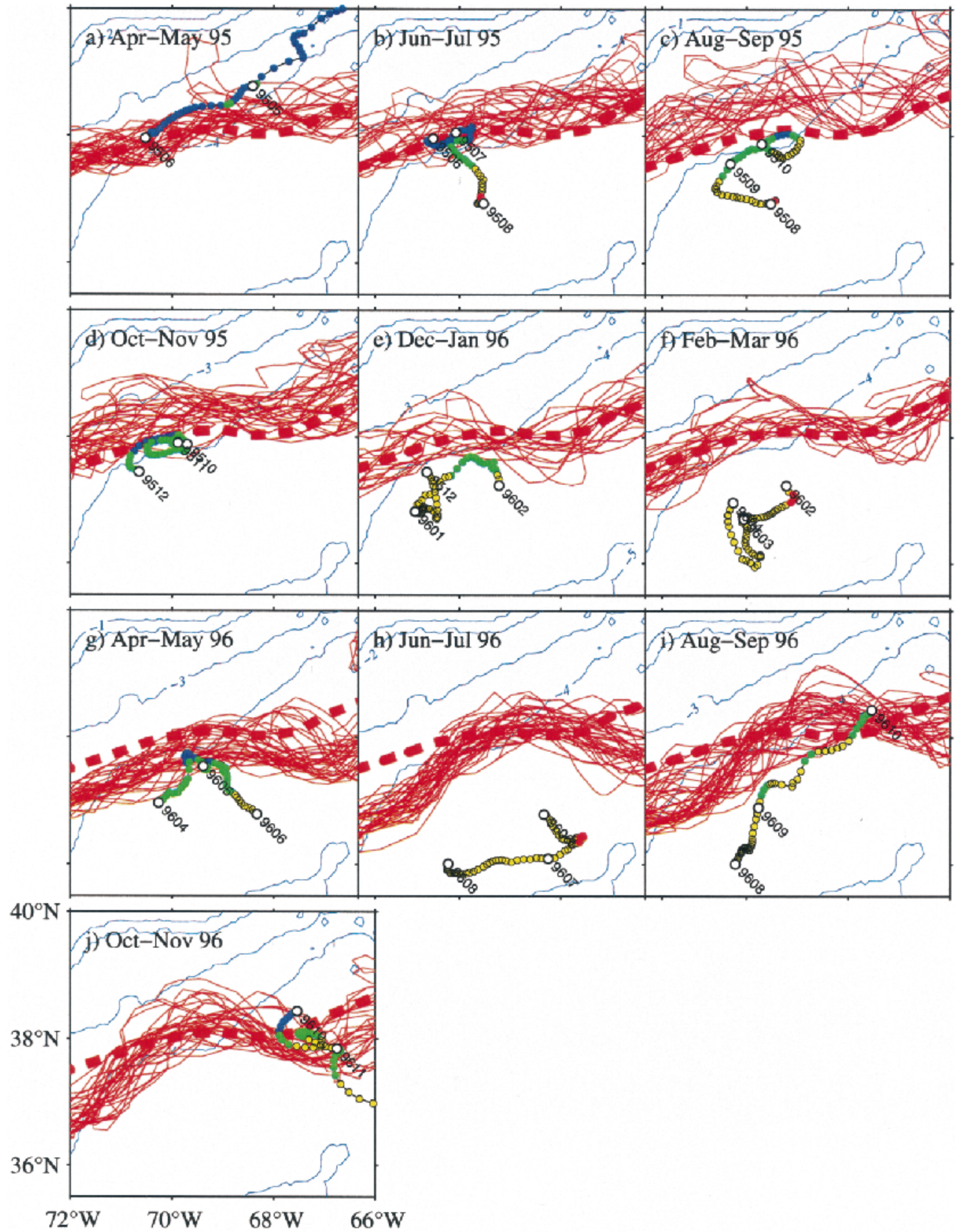


FIG. 15. Gulf Stream north wall positions in two-month intervals beginning in Apr–May 1995, with track segments of float 264 for same time periods. Thick dashed line is mean Gulf Stream position.

occurred in September–October 1995, April–May 1996, and September–November 1996. These are times when the float was near the north wall of the Gulf Stream, as can be seen in Figs. 15c,d; 15g; and 15i,j. The fluctuations in pycnocline depth are probably related to the passage of Gulf Stream meanders, and the deep flow apparently responds by moving up- and downslope in order to conserve potential vorticity.

## 4. Discussion

### *a. The upper Labrador Sea Water*

Based on the shallow float tracks described above, it is clear that ULSW flowing equatorward in the DWBC is diverted offshore and into the ocean interior at the site where the upper DWBC collides with the separating Gulf Stream. PS93 came to the same conclusion based

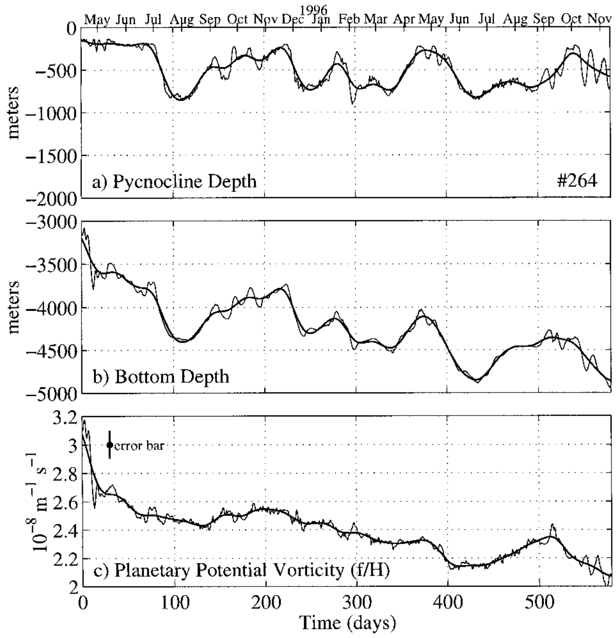


FIG. 16. As in Fig. 13 but for 20-month track segment of float 264 in the crossover region. Time period as in Fig. 15.

on tracer distributions and inferred fluid parcel trajectories from their synoptic survey of the crossover region. The *directly* observed fluid parcel trajectories have further revealed that ULSW fluid parcel pathways are sensitive to the *synoptic* position of the Gulf Stream in the crossover region: large cross-stream displacements of fluid parcels entrained from the upper DWBC occur when a strong meander trough is present in the crossover region.

PS93 also found that there was a very narrow band of ULSW right against the slope that crossed directly under the stream in the crossover region. According to their Fig. 7b, this band was inshore of the 2000-m isobath and concentrated in the lower density classes of ULSW. This feature was not observed in the float tracks, possibly because all the floats but one approached the crossover offshore of the 2000-m isobath. Interestingly, the one float that was inshore of the 2000-m isobath, float 275 (Fig. 1b), followed the western boundary farthest to the south before being entrained in the stream.

Regarding the dynamics of the flow field in the crossover region at the ULSW level, PS93 concluded that the mean flow of the upper DWBC crossed mean potential vorticity contours in the crossover region, implying that there must be a divergence of the eddy potential vorticity flux there. This conclusion was based on the assumption that their inferred fluid parcel trajectories, and the synoptic potential vorticity distribution, were representative of the mean. BH00 showed that on a large scale, the shallow floats tended to remain north of a mean potential vorticity gradient aligned with the Gulf Stream, but we do not have enough trajectories to determine the mean flow field or to make any quantitative assessment regarding PS93's conclusions. The floats do however highlight the importance of time-dependence in the Gulf Stream path on fluid parcel pathways at the ULSW level. This emphasizes the need for more long-term observations in the crossover region to sort out the dynamical balances.

The most important result from the shallow float observations in the crossover region is that fluid parcels at the ULSW level can cross the Gulf Stream as a result of time-dependent meandering of the stream. This is consistent with the results from kinematic models of the Gulf Stream, such as that described by Bower (1991). In that work it was found that in the subsurface Gulf Stream, a relatively small fraction of fluid parcels is actually trapped in the jet, flowing continuously downstream, and that most of the parcels are circulating in and out of the jet in adjacent ''recirculating cells'' due to meander propagation. Bower (1991) found that for a meander with a wavelength of 400 km, amplitude of 50 km, phase speed of 10 km $d^{-1}$, and peak jet speed of 50 km $d^{-1}$, 60% of the fluid parcels are circulating in and out of the jet. Extrapolating Fig. 10b in Bower (1991) to peak jet speed of 25 km $d^{-1}$, typical of what is observed in the Gulf Stream at the ULSW level (1000 m) (Halkin and Rossby 1985), it is apparent that *most* (>90%) of the fluid parcels are circulating in and out of the jet, and only a small fraction are trapped in the jet itself. This points out how sensitive fluid parcels at the ULSW level are to meandering of the Gulf Stream.

## *b. The overflow water*

The deep float tracks clearly illustrated a bifurcation in fluid parcel pathways of OW in the crossover region. This bifurcation is consistent with the deep layer potential vorticity ($f/H$) distribution in the crossover region (Fig. 17). This map was produced by assuming that the water column below the pycnocline is well represented by a homogeneous layer with thickness $H$, which is bounded by the main pycnocline and the seafloor (BH00). The depth of the pycnocline has been modeled here to be flat north and south of the mean position of the Gulf Stream (dashed line) and slope downward by 750 m over 100 km in the stream (see, e.g., Joyce et al. 1986). This gives a view of the *average* synoptic distribution, which is the closest approximation to the *actual* synoptic distribution that we have available. This is the field that is most appropriate to compare with the individual float tracks. A similar figure was shown in BH00 and in Hogg and Stommel (1985), but for the entire western North Atlantic. Here we focus just on the crossover region. The tracks of four representative deep floats are superimposed on the potential vorticity field.

The sloping pycnocline associated with the Gulf Stream causes the potential vorticity contours to deviate offshore from the bathymetric contours in the immediate vicinity of the crossover and a ridge of high potential

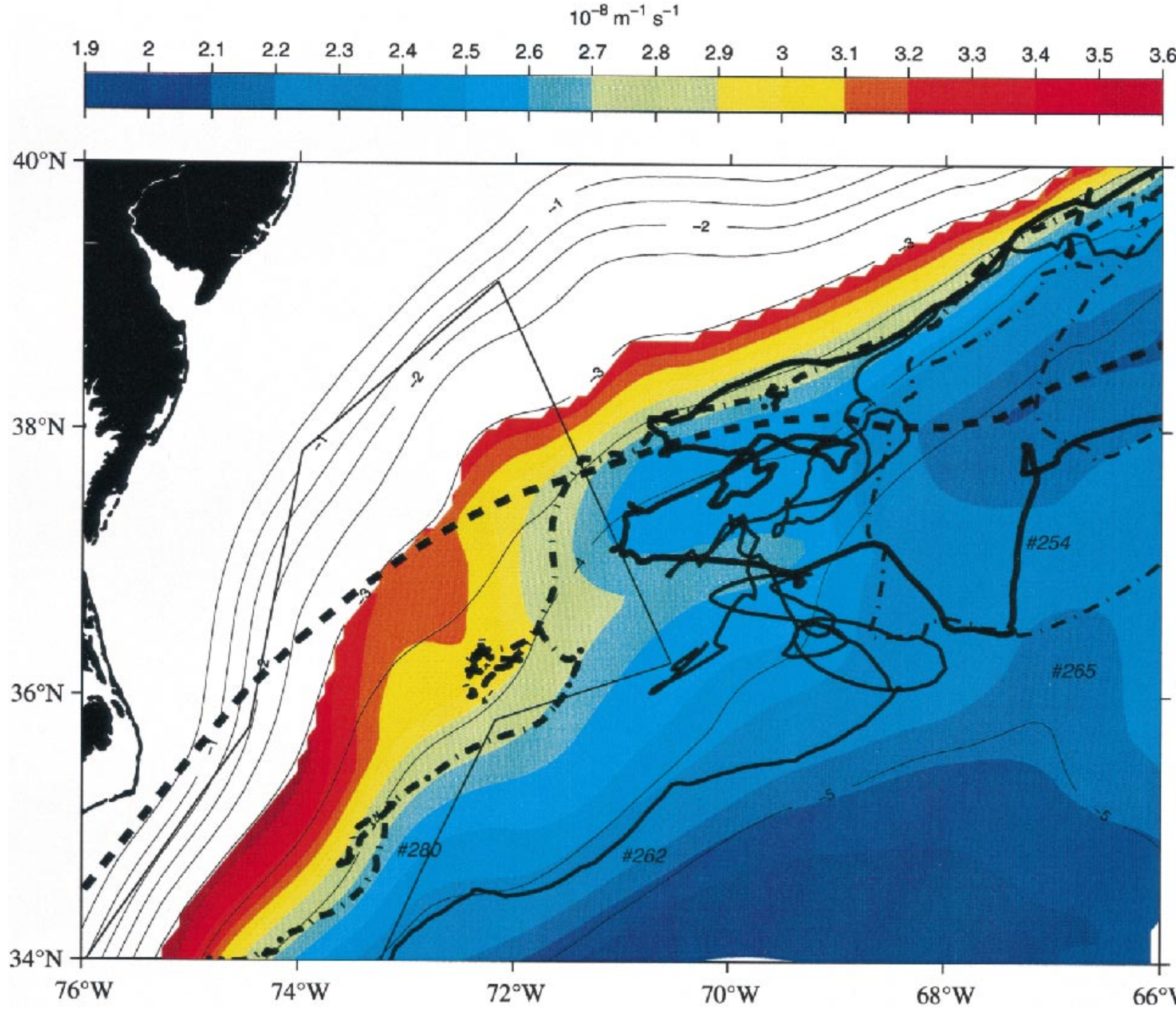


FIG. 17. Distribution of planetary potential vorticity ($f/H$) for the layer bounded by the main pycnocline and the seafloor (color shading). Units are $10^{-8}$ m$^{-1}$ s$^{-1}$. See text for description of the spatial structure of pycnocline depth used to estimate layer thickness. Tracks of four deep floats are superimposed, dot–dash, and solid black lines. The mean path of the Gulf Stream at the surface is indicated by the thick dashed line. Contour interval for smoothed bathymetry (thin solid lines) is 0.5 km. Polygon in the west is region of PS93 study.

vorticity to extend eastward from the western boundary. The float tracks tend to bifurcate at that ridge, as also pointed out in BH00. There are several other features that are worth noting in this close-up view. First, north and south of the Gulf Stream along the continental slope, the float tracks are relatively simple, oriented more or less along the potential vorticity contours. But in the region where the potential vorticity contours diverge from the bathymetric contours, two of the floats exhibit significant eddy motion (254 and 262). One ends up returning to the western boundary and exiting to the south (262), and the other follows the ridge of higher potential vorticity toward the east (254). After emerging from this relatively ''turbulent'' region, both of these floats were in regions of lower potential vorticity than before they entered, suggesting that this may be a region of strong mixing.

Second, offshore of the 4000-m isobath, there are potential vorticity contours that curve back toward the east in the northeastern corner. This is the western extension of the closed potential vorticity contours north of the Gulf Stream that Hogg and Stommel (1985) associated with the northern recirculation gyre. Fluid parcels that enter the crossover region at the base of the continental slope will tend to circulate back toward the east, as illustrated by float 265 in Fig. 17.

The pathways revealed by the deep floats are consistent with the conclusion of PS93 that the inshore part of OW crosses more directly under the Gulf Stream compared to ULSW, generally conserving its potential vorticity. PS93 also found that the offshoremost edge of the OW in their survey area (shown by polygon in Fig. 17) was diverted offshore along the path of the Gulf Stream. The float observations extend the PS93 observations and reveal two new features of the crossover region. First, fluid parcels in the DWBC at the OW level can be diverted offshore into the ocean interior all along the slope from 72° to 68°W. Where recirculation takes place depends on cross-slope position and the synoptic location of the Gulf Stream (fluid parcels tend to be recirculated farther east if they are more offshore and/or if the Gulf Stream is north of its mean position). Second, fluid parcels that intersect the Gulf Stream in the eastern half of the crossover region can still return to the western boundary (e.g., float 262 in Fig. 17).

The deep float observations are consistent with the two-layer model of Hogg and Stommel (1985) and suggest that the deep flow ''feels'' both the sloping pycnocline and bottom slope in the crossover region. Fluid parcels are apparently displaced offshore where the DWBC encounters the downward sloping pycnocline associated with the Gulf Stream, and the increase in bottom depth along the tracks is the same as the increase in pycnocline depth across the Gulf Stream. This is in contrast to the results obtained by Spall (1996a) in a three-layer regional primitive equation model of the crossover. In his lowest layer, which represented OW, the mean flow crossed almost directly under the stream without being diverted significantly into the interior. As pointed out by Spall (1996a), and discussed in more detail in BH00, this is apparently due to the presence of an intermediate layer in the model, which substantially reduces the effect of the sloping interface between the upper two layers on the deep flow. The mean pathways in the intermediate layer of the model actually resembled the deep float pathways more than those in the deep layer, most likely because the intermediate layer is strongly influenced by the sloping upper interface.

## 5. Summary and conclusions

In this study, we have used the tracks of 18 RAFOS floats deployed in the DWBC to describe some aspects of the kinematics and dynamics of the circulation in the Gulf Stream–DWBC crossover region. Floats launched at the level of ULSW (~800 dbar) indicate that this water mass is entrained into the Gulf Stream and carried into the ocean interior, consistent with previous hydrographic observations. The pathways of this water mass in the crossover region were found to be sensitive to the time-dependent meandering of the Gulf Stream. When the stream was near its mean position, fluid parcels entrained from the upper DWBC skirted along the northern edge of the stream, in contrast to times when the stream was perturbed due to the presence of a cyclonic meander trough. In this case, entrained fluid parcels made large excursions across the Gulf Stream, and in one case were expelled on the south side of the stream. This mechanism could lead to the flux of ULSW properties across the stream in the crossover region, as well as farther east. None of the floats at this level passed directly under the stream against the slope, as had been shown in tracer distributions and inferred fluid parcel trajectories by PS93. This may be because the floats were too far offshore. However, the float that was drifting southward farthest inshore went the farthest south before being entrained into the Gulf Stream, suggestive of an inshore pathway for ULSW under the stream.

The deep float tracks revealed a bifurcation in the pathway of fluid parcels in the deep DWBC at the crossover. Floats that intersected the Gulf Stream farther west tended to cross more directly under the stream and continue equatorward near the western boundary, and floats that hit the stream farther east in the crossover region entered the ocean interior along the Gulf Stream path. This observed pattern is consistent with the potential vorticity distribution for the layer below the pycnocline. Enhanced eddy variability was observed in the crossover region compared to north and south of that area.

The deep float behavior in the crossover region is consistent with the two-layer model of Hogg and Stommel (1985), in which the lower-layer flow slides down the topography in order to conserve potential vorticity. The offshore displacement of the floats was found to be exactly what would be required based on the change in depth of the pycnocline across the Gulf Stream. This suggests that the flow at 3000 m is influenced by both the sloping pycnocline and the bottom slope, and that a two-layer representation is valid. Comparison of the float tracks and Gulf Stream position shows a remarkable correlation between the passage of Gulf Stream meanders and cross-slope motion of the floats. Estimates of potential vorticity along the deep float tracks indicate that potential vorticity is conserved on the short timescales of the crossing events (up to one month), but changes over longer timescales by an amount consistent with what would be expected from eddy mixing.

Several questions remain to be explored regarding fluid parcel pathways in the DWBC, specifically in the crossover region. For example, how are the DWBC pathways affected by low-frequency variability in the Gulf Stream path? Thompson and Schmitz (1989) found that the separation latitude of the Gulf Stream was affected by DWBC transport variability. Spall (1996b) showed how the DWBC path could switch from one that generally follows the western boundary to one that enters the ocean interior on decadal timescales depending on the energy state of the Gulf Stream and its adjacent recirculation gyres. In future work, we will attempt to associate the variability in float pathways to low-frequency changes in Gulf Stream position. Such interactions, if they exist, could have a significant impact on the basin-scale circulation.

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