Evidence of Cross-Frontal Exchange Processes in the Gulf Stream Based on Isopycnal RAFOS Float Data

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ABSTRACT

A unique set of Lagrangian observations has recently been collected in the Gulf Stream using the newly developed isopycnal RAFOS float. Between January, 1984 and October, 1985, thirty-seven of these drifters were launched in the main thermocline of the current off Cape Hatteras and tracked acoustically downstream for 30 or 45 days. Temperature and pressure were also recorded along each float trajectory. The isopycnal capability of this drifter allows it to follow fluid parcel pathways quite accurately along the sloping density surfaces of the Gulf Stream.

The RAFOS drifters revealed a striking pattern of vertical and cross-stream motion in Gulf Stream meanders. Floats were consistently observed to upwell (downwell) and move onshore (offshore) as they approached anticyclonic (cyclonic) meander crests (troughs). The rms vertical velocity in the center of the stream was observed to be 0.08 cm s^{-1} on the 12°C surface. No mean vertical motion was detected in the main thermocline of the Gulf Stream between 70° and 55°W. Using a model of the mean cross-stream thermal structure of the current, rms cross-stream velocities were estimated to be 8–10 cm s^{-1}.

This meander-induced circulation represents an important mechanism for cross-frontal exchange. When the Gulf Stream is meandering, fluid parcels from the center of the current are brought to the edges and often escape completely. In fact, 60% of the floats launched at Cape Hatteras escaped from the Gulf Stream at least once before reaching 65°W. These losses were not evenly distributed in the vertical; retention was greater in the upper thermocline (11–16°C) than in the lower thermocline (7°–11°C). Comparison of float trajectories with infrared satellite imagery shows that the meander-induced cross-frontal fluid exchange is enhanced by ring—current interaction and time evolution of the Gulf Stream path.

1. Introduction

The Gulf Stream is probably the most intensely studied ocean current. Over the past 50 years, many hydrographic sections have been taken across the stream between the Florida Straits and the Grand Banks (e.g., Iselin 1936; Worthington 1976; Fuglister 1963; Clarke et al. 1980). These sections always reveal strong property gradients aligned with the current, indicating that the stream is a boundary between cold, fresher slope and shelf waters and warm, more saline central waters (Bower et al. 1985). Biologists have also recognized the role of the Gulf Stream as a boundary between two environments, each with its own unique set of flora and fauna (e.g., Wishner and Allison 1986).

The velocity structure of the Gulf Stream has also been observed to be quite similar at many locations along its 3000 km path (Richardson et al. 1969; Halkin and Rossby 1984; Leaman et al. 1989). Velocity observations always reveal large lateral and vertical shears, whether the measurements are made indirectly from the density field, or directly using absolute velocity profilers such as PEGASUS or moored current meters (e.g., Hall 1986).

All these observations have led to the present concept of the Gulf Stream as a single, connected, well-defined jet extending over several thousand kilometers. But these studies tell us very little about fluid pathways through the current. For instance, where do fluid parcels in the stream go? If exchange does take place between the stream and the surrounding fluid, where and how does it occur? What conditions of the flow field enhance or prevent exchange? How is the strength of the property fronts along the stream path (or lack thereof) related to the fluid exchange between the two adjacent water masses?

A preliminary examination of these questions was undertaken by Shaw and Rossby (1984) based on the trajectories of 17 quasi-Lagrangian SOFAR floats launched in the Gulf Stream region. In this work, Shaw and Rossby introduced the concept of a *Lagrangian* stream to describe the upper layers where fluid parcels are retained for long downstream distances. At depth, they claimed, the stream does not exist as a Lagrangian

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current since SOFAR floats seem to cross in and out so freely.

Some floats at 700 m were observed to escape from the current after an extended period in the stream. From simple kinematic considerations, Shaw and Rossby inferred that it was fluid motion along sloping isopycnals, which has both a lateral (cross-stream) and vertical component, that caused these floats to cross out of the current. Since these excursions were observed to occur when the path was disturbed by meanders, ring formation and shingles, Shaw and Rossby concluded that vertical motion must be present during these events.

The importance of vertical motion in the Gulf Stream had been inferred by Newton (1978) by analogy with the atmospheric jet stream, where vertical motion plays a cirtical role in the development of midlatitude synoptic systems. In addition, several investigators have made indirect observations of vertical velocity in Gulf Stream meanders from moored current meter arrays and divergence of float clusters (e.g., Johns and Watts 1985; Hall 1986; Osgood et al. 1987; Chew 1974). A review of these measurements is given by Osgood et al.

The desire to track fluid parcels more accurately and to measure vertical velocity directly led to the design and development of isopycnal, or constant-density, drifters. By adding a simple spring-backed piston, a float can be made to have nearly the same compressibility as seawater, and can then follow the vertical motion of fluid parcels along density surfaces quite accurately (Rossby et al. 1985).

Levine et al. (1986) were the first to use this new instrument in the Gulf Stream. They tracked an isopycnal Swallow float for three days from a ship just upstream of Cape Hatteras, while the float telemetered its temperature and pressure at regular intervals. With these measurements, Levine et al. confirmed that significant vertical $O(0.1 \text{ cm s}^{-1})$ and lateral $O(10 \text{ cm s}^{-1})$ velocity components are present in the Gulf Stream. From comparison with satellite infrared imagery, they also found that these motions were correlated with the meanders of the Gulf Stream path, as had been suggested by Shaw and Rossby.

In order to analyze the role of vertical motion in cross-frontal exchange processes more quantitatively, a unique Lagrangian dataset has been collected using the newly developed isopycnal RAFOS float. Thirty-seven RAFOS floats were successfully launched in the main thermocline of the Gulf Stream off Cape Hatteras and tracked downstream for distances up to 2000 km. They revealed a striking feature of Gulf Stream flow, specifically a systematic pattern of vertical motion which is closely linked to the meandering of the Gulf Stream path. In addition, cross-frontal exchange was observed to take place as a result of this meander-induced circulation, indicating an important mechanism for stirring and mixing of the adjacent water masses in this region.

The dynamical processes governing the motion of the floats are examined in a companion paper by Bower (1989). In the following sections, a detailed description of fluid pathways in the Gulf Stream is given based on the RAFOS trajectories. The RAFOS field program is described in section 2, and the results from one RAFOS float are examined at length in section 3 to illustrate the basic pattern of fluid motion in the stream. The mean structure of the vertical, cross-stream and downstream components of velocity in the current is presented in section 4. In section 5, we discuss where and how fluid is exchanged between the Gulf Stream and the neighboring water masses. The work concludes with a comparison of the RAFOS results with previous hydrographic and Lagrangian studies of cross-frontal exchange.

2. The experiment

a. The RAFOS float

The RAFOS float used in this experiment is a small subsurface Lagrangian drifter developed at the University of Rhode Island to follow the pathways of water parcels in the ocean. A thorough description of the RAFOS float and its navigation is given by Rossby et al. (1986), but a brief summary of the system as it was employed in the Gulf Stream pilot experiment will be presented here for the reader's convenience.

The RAFOS float consists of a 2 m glass pipe enclosing batteries, microprocessor, antenna and other electronics, sealed with an aluminum endplate. Sensors mounted on the endplate measure temperature, pressure and acoustic signals from moored sound sources. Measurements are repeated every eight hours during the float's mission (15, 30 or 45 days), after which it pops to the surface and begins transmitting the stored data to ARGOS, a satellite-based platform location system.

The float package is rendered isopycnal by the addition of a spring-backed piston which gives the RAFOS float nearly the same compressibility as seawater. This device allows the float to change its volume, and thus make (nearly) the same vertical excursions as the fluid parcel.

Most of the floats in this experiment were very good isopycnal followers, with deviations, usually less than ±1°C (±0.1 sigma units) and with compressibilities between 80% and 90% that of seawater (Rossby et al. 1986). Since the float compressibilities are slightly less than the value for seawater, vertical motions of water parcels are underestimated by 10%–20%. In the main thermocline of the Gulf Stream, where the vertical temperature gradient is about 2.5°C/100 m, a 1°C deviation corresponds to a 40 m vertical separation between the fluid parcel and the float. Given typical vertical shears of (0.5–2.0) × 10^{-3} s^{-1} for the main thermocline (Fig. 2), the float speed may differ from that of the fluid parcel initially tagged by 2–8 cm s^{-1}.

b. The Gulf Stream field program

RAFOS floats were launched sequentially in the current off Cape Hatteras, North Carolina between January, 1984 and October, 1985 (Fig. 1). In 1984, floats were launched in the vicinity of 34°30′N, 75°W (L84) under contract with a commercial fishing vessel. Due to the difficulty of reaching the Gulf Stream in a small boat in heavy weather, the launch program was continued in 1985 from a container ship making weekly trips between Norfolk, Virginia and Bermuda. Floats were launched from the freighter about 200 km downstream of Cape Hatteras, in the vicinity of 36°N, 74°W (L85). Finally, nine floats were released during the Joint Norwegian–American Gulf Stream frontal study in October 1985 at various locations between 35° and 38°N, 75° and 70°W. Three of these were not launched directly in the Gulf Stream but in the Slope Water adjacent to the current. A total of 37 trajectories were obtained for the main thermocline of the Gulf Stream with associated temperature and pressure records. A summary of their launch schedule is given in Table 1.

The seeding of the current was fairly simple due to the well-defined thermal structure. XBTs were dropped as the vessel crossed the Gulf Stream until the point where the 12°C isotherm reached 500 m depth, at which point a float was launched. The portion of the stream seeded with floats via this process is illustrated in Fig. 2 on the mean cross-sections of temperature and velocity in "natural" coordinates from the PEGASUS study at 73°W (Halkin and Rossby 1985). The 27.0σ_t density surface (T = 12°C, s = 35 psu in Gulf Stream waters) was chosen as the level at which to seed the current with floats in order to maximize retention of the floats in the stream but at the same time minimize vertical distance from the sound channel axis.

One can see from Fig. 2 that a number of floats came to neutral buoyancy on temperature surfaces below 12°C. These floats were ballasted before the importance of removing dissolved minerals from the ballasting water was realized. The mean initial temperature of all the floats was 10.2°C.

c. Treatment of the data and uncertainties

The raw data files from each float were processed using a software package developed at the University of Rhode Island (see the technical report by Bower et al. 1986, for details). The resultant temperature, pressure and position records have measurement uncertainties of 0.1°C, 0.5% and 5 km. Horizontal and vertical velocities were estimated along each trajectory from the time rate of change of position and pressure over 16 hours using a simple centered difference scheme. The result was exceptionally smooth velocity

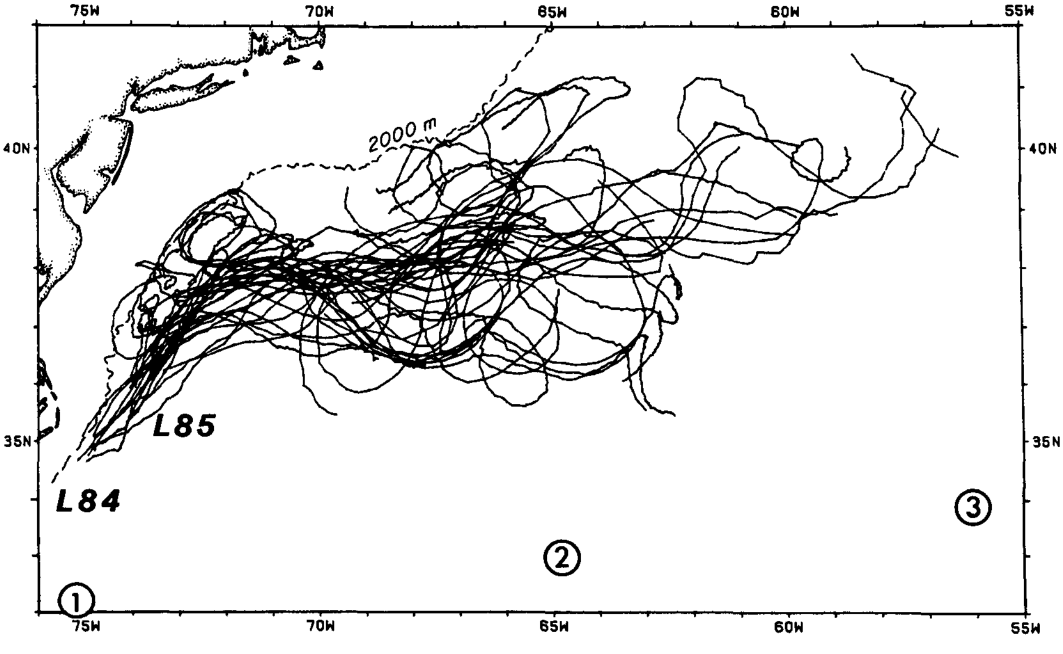

FIG. 1. Trajectories of 37 RAFOS floats launched during the Gulf Stream pilot experiment. L84 and L85 refer to the approximate launch sites in 1984 and 1985, and circled numbers indicate locations of the three sound sources.

TABLE 1. Summary of RAFOS float launchings, 1984–85. Launch date is (yearday/year). Comments: 1—no tracking west of 70°W due to sound source failure; 2—some tracking missing due to acoustic propagation problems; 3—no temperature record.

Float	Launch date	Launch position Lat (°N)	Launch position Long (°W)	Mission length (days)	Mean temperature (°C)	Comment
004	17/84	36.030	73.559	15	15.8	ok
008	128/84	34.408	75.194	30	8.2	ok
010	91/85	36.110	73.853	30	11.0	1
011	81/85	36.116	73.849	30	11.6	1
012	86/85	35.616	74.220	30	12.1	1
014	110/85	35.250	73.407	30	9.4	1
015	102/85	36.047	73.696	30	8.5	1
016	192/84	34.579	75.244	30	14.2	ok
017	202/84	34.576	75.099	30	12.1	ok
018	211/84	34.618	75.128	30	12.6	ok
020	225/84	34.584	75.152	30	12.2	ok
021	268/84	34.442	75.011	30	11.5	ok
022	279/84	34.446	75.289	30	10.2	ok
023	292/84	34.454	75.184	30	11.0	ok
024	331/84	34.431	75.313	30	12.8	ok
025	32/85	35.686	74.280	45	10.3	ok
026	46/85	35.641	74.180	45	9.1	ok
027	19/85	35.667	74.242	45	8.5	ok
028	6/85	35.624	74.109	45	7.3	ok
029	60/85	35.683	74.182	45	9.5	ok
030	74/85	35.608	74.266	45	8.7	ok
031	114/85	35.840	73.254	45	8.6	1
032	136/85	36.024	73.689	45	7.2	ok
033	138/85	35.457	74.149	45	7.0	ok
034	142/85	36.023	73.808	45	8.2	ok
035	152/85	35.640	74.185	45	11.4	ok
036	156/85	36.134	73.875	45	8.9	ok
037	173/85	35.626	74.177	45	9.3	ok
043	286/85	38.015	73.456	45	12.7	2
047	277/85	35.193	74.578	45	—	2, 3
050	285/85	37.815	73.198	45	11.1	2
052	280/85	37.443	72.750	45	11.7	ok
053	277/85	35.281	74.269	45	12.0	ok
054	278/85	36.532	73.657	45	14.4	2
058	277/85	35.515	74.418	45	12.9	ok
061	285/85	37.403	73.021	45	11.6	2
063	280/85	37.277	72.612	45	12.1	ok

records which required no further filtering for the purposes of this study. Assuming the uncertainties in successive position fixes are uncorrelated, the uncertainty in the estimate of the horizontal component of velocity is about ±12 cm s^{-1}. This is most likely an overestimate since successive positions have some common timing uncertainties. The uncertainty in the estimate of vertical velocity is ±0.006 cm s^{-1}.

In order to monitor the cross-stream position of floats in the Gulf Stream, an analytical model of the thermal structure of the current was developed to fit the PEGASUS mean temperature section in natural coordinates (Fig. 2, Appendix A). The model parameters were adjusted subjectively until the model reproduced the PEGASUS mean section within ±2 km. Hall (1986a) and Hendry (1988) have used similar analytical forms to model the thermal structure of the Gulf Stream.

This model clearly does not take into account variations in the thermal structure which may be functions of stream path curvature. Although we expect that the thermal structure alters somewhat in sharp meanders, there are insufficient observations available in these sections of the current to develop a functional relationship between path curvature and thermal structure.

The curvature of the float trajectories was estimated by first smoothing the trajectories with a Gaussian low-pass filter (half-power point = 14 hours, 11 weights total). A third-order polynomial was fit to two-day segments of the smoothed trajectories (7 points), and the curvature was evaluated analytically for the central point of each segment according to the expression:

$$\kappa = \frac{(\dot{x}\ddot{y} - \ddot{x}\dot{y})}{(\dot{x}^2 + \dot{y}^2)^{3/2}}$$

where dots represent derivatives with respect to time (Thomas 1972). By sliding this fitting procedure along the trajectory, curvature was estimated at eight-hour intervals. For uncorrelated uncertainties in position,

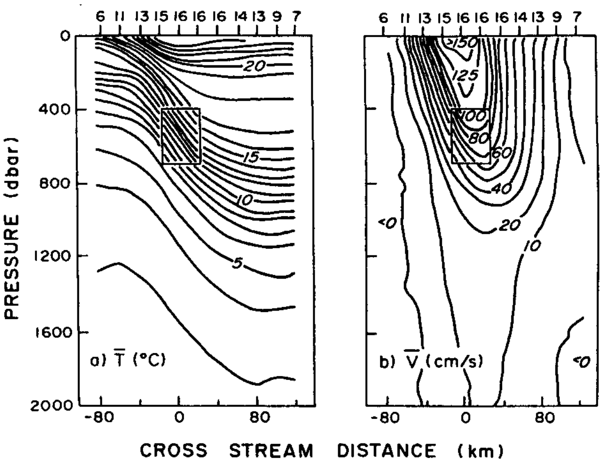

FIG. 2. Mean (a) temperature and (b) velocity sections in natural coordinates from the PEGASUS study at 73°W. The boxed areas indicate the part of the Gulf Stream seeded with floats. Number of velocity profiles used to construct this figure at each cross-stream location is indicated on the top axis.

the estimated uncertainty in curvature is about ±20%, again probably an overestimate.

3. An example from the data—RAFOS 022

Figure 3a–c shows the 30-day trajectory of RAFOS 022 with the temperature and pressure records along the float path. From the temperature record, it can be seen that the float was approximately on the 10°C surface (σ_t = 27.2). The largest changes in temperature are highly correlated with the pressure record due to the fact that the float is not perfectly isopycnal. After launch at Cape Hatteras, the float is observed to travel along the Gulf Stream, flowing alternately through meander troughs and crests. The average speed along the trajectory was 67 cm s^{-1}.

The most striking feature of the entire dataset is dramatically illustrated in the pressure record for this float, Figure 3c. Comparing this record with the trajectory, one sees that on yearday 286, the curvature of the trajectory was anticyclonic and the float was at 500 db on the 10°C surface. As the float approached the first meander trough, it downwelled to about 800 db on yearday 292 at the maximum of cyclonic curvature. The float then upwelled to 400 db in the next meander crest, with maximum anticyclonic curvature on yearday 298. The pattern is repeated in the next wavelength, until the end of the float's mission on yearday 309.

A schematic view of this three-dimensional motion is illustrated in Fig. 4. Due to the slope of isopycnals across the stream, the observed upwelling (downwelling) as the float approaches a meander crest (trough) implies an onshore (offshore) component to the flow as well. Thus the fluid parcel tagged by RAFOS 022 apparently did not remain in the same cross-stream position as it went downstream, but traveled systematically back and forth across the current along the 10°C surface in response to changing curvature of the stream path. The correlation between pressure and curvature is quite high statistically as well as visually, with a correlation coefficient (r) of 0.82 for a linear least squares fit.

The vertical velocities in the stream were of course much larger than observed in midocean. RAFOS 022 had a maximum upward speed of 0.18 cm s^{-1} on yearday 293 (Fig. 3d) and a maximum downward speed of 0.11 cm s^{-1} on yearday 298. These values are typical

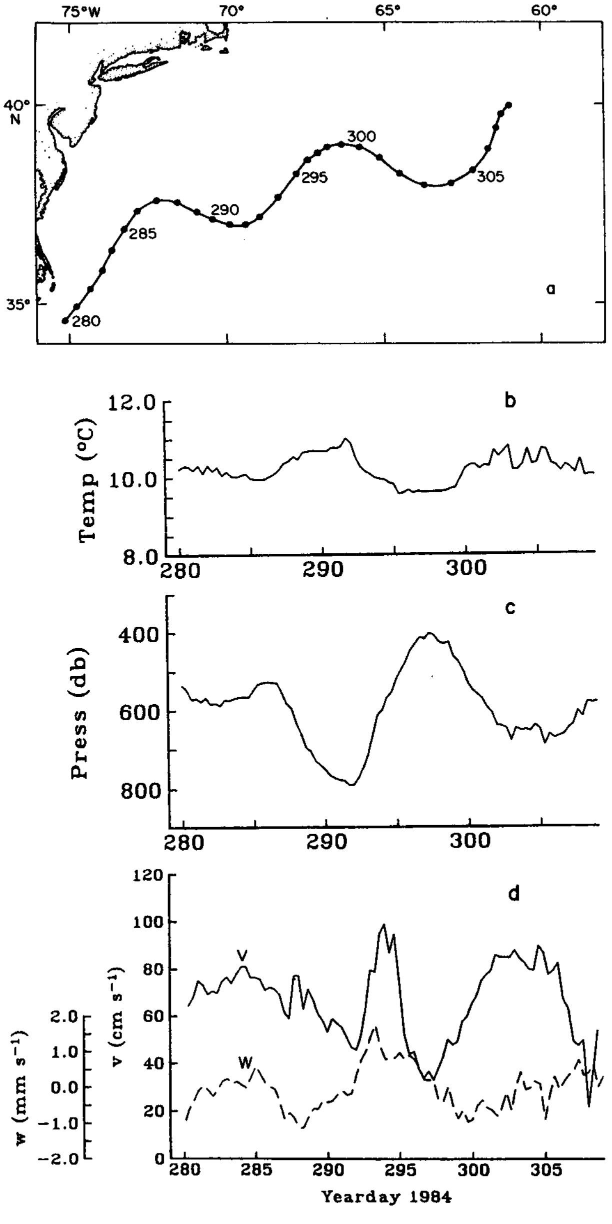

FIG. 3. (a) Trajectory, (b) temperature, (c) pressure, and (d) horizontal (solid line) and vertical (dashed line) speed records for RAFOS 022. Dots on trajectory are 0000 UTC fixes and dates are yeardays in 1984.

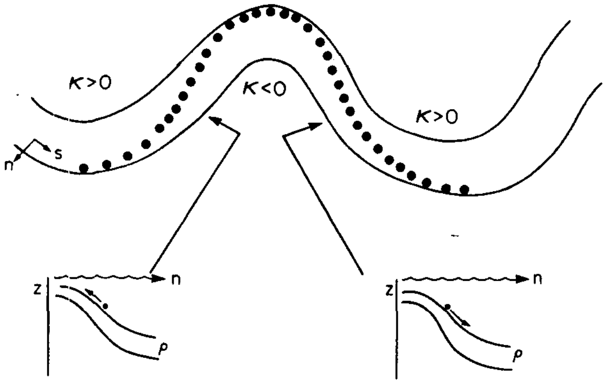

FIG. 4. Schematic view of three-dimensional motion of RAFOS floats. Dots indicate trajectory of a float through a Gulf Stream meander.

of those observed with other floats; vertical velocity usually reaches a maximum midway between troughs and crests and changes sign in meander extrema.

Figure 3d also shows the magnitude of the horizontal velocity vector as a function of time along the float's trajectory. The large variations in speed, from as high as 95 cm s^{-1} to as low as 25 cm s^{-1}, are due to the motion of the float back and forth across the stream. The largest velocities occurred when the float was in the center of the current.

The properties observed with RAFOS 022 are representative of those of other floats. The correspondence between up- and downward motion and changes in curvature is especially evident in all the trajectories, another example of which is shown in Fig. 5 ($r = 0.72$).

4. Structure of three-dimensional velocity in the Gulf Stream

a. *Vertical velocity*

As the floats moved back and forth across the stream, vertical velocities were measured at various cross-stream locations. Combining all the float data, the cross-stream structure of vertical velocity along temperature surfaces can be examined. The data were first divided by temperature surface and then further separated into cross-stream bins according to pressure. The mean ($\langle w \rangle$), rms (w') and standard error of the mean (w_{se}), for each bin were then calculated. Finally, each temperature/pressure bin was mapped onto a cross-stream distance coordinate derived from the model of the mean thermal structure discussed earlier.

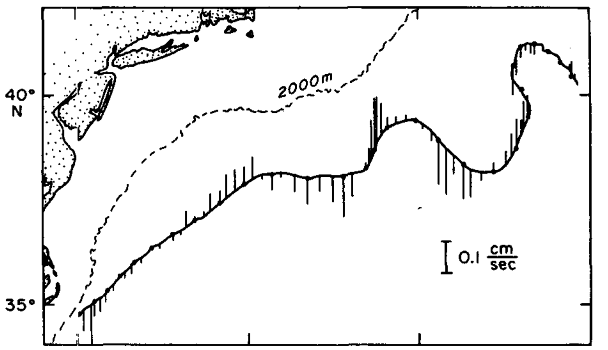

FIG. 5. RAFOS 20 (1984, 12°C) with bars indicating vertical velocity. Bars point northward for $w > 0$ and southward for $w < 0$.

The results for the 12°C surface are listed in Table 2. Except for the deepest bin, the standard error is greater than the mean, indicating that the means on this temperature surface are not significantly different from zero (see further discussion in section 5a). The rms amplitude is a maximum in the center of the stream and falls off to either side. This result is plausible since the cross-stream slope of isopycnals is greatest in the center of the current. This peak in w' occurs in the center of the current throughout the main thermocline, Fig. 6a. The structure appears to scale quite well with the slope of these temperature surfaces, Fig. 6b, estimated from the mean PEGASUS section (Fig. 2). These estimates of w' compare well to the indirect estimates by Hall (1986a) ($w' \approx 0.084$ cm s^{-1}) and Osgood et al. (1987) ($w' \approx 0.074$ cm s^{-1}) for the main thermocline.

b. *Cross-stream velocity*

We can infer the cross-stream structure of u' from the pattern of w' and the isotherm slopes from the PEGASUS mean temperature section according to

$$u' = w'\left(\frac{\Delta z}{\Delta x}\right)_T^{-1}.$$

This cross-frontal component of motion is shown in Fig. 6c as a function of cross-stream distance. As expected from the similar shape of Fig. 6a and 6b, u' has a fairly uniform value of 8–10 cm s^{-1} across the center of the jet. It should be noted that these lateral velocities represent cross-stream motion *relative* to the stream's thermal and velocity structure.

c. *Downstream velocity*

The structure of the horizontal velocity field in and around the Gulf Stream can be investigated using the

TABLE 2. Mean and rms vertical velocity on the 12°C surface.

	Pressure bin (db)				
	250–350	350–450	450–550	550–650	650–750
x (km)	−26	−13	0	14	35
$\langle w \rangle$ (cm s^{-1})	.005	.006	−.005	−.003	−.012
w'	.047	.078	.074	.054	.035
w_{se}	.005	.010	.010	.005	.004
n	85	66	69	110	68

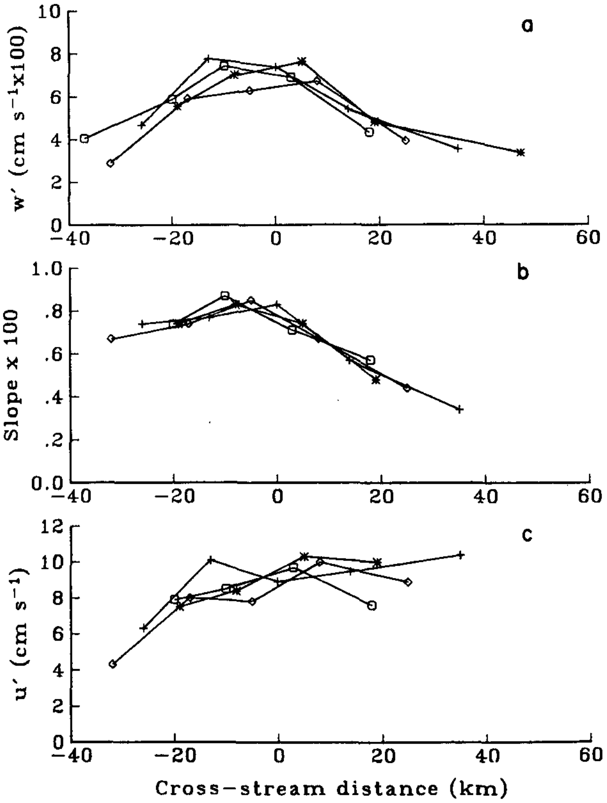

FIG. 6. (a) Rms vertical velocity as a function of cross-stream distance on four temperature surfaces in the main thermocline from the RAFOS observations (asterisk: 13°C, plus: 12°C, diamond: 11°C, square: 10°C); (b) cross-stream slope of isotherms as function of cross-stream distance from PEGASUS mean temperature section; (c) Rms cross-stream velocity (inferred).

RAFOS floats as roving current meters. The mean of all speed measurements in the stream are shown in Fig. 7a and 7b for the 12° and 10°C surfaces, respectively. The mean was constructed in the same manner as for vertical velocity and here, the "downstream" speed has been approximated by the total horizontal velocity vector since the cross-stream component is usually a small fraction of the total vector. The number of observations in each bin is comparable to those in Table 2 for vertical velocity, except for the two offshore bins on the 10°C surface which each have less than 20 observations. Mean downstream speed at 73°W from the PEGASUS study in natural coordinates along the two temperature surfaces is also shown for comparison.

The peak in the mean speed on the 12°C surface is 100 cm s^{-1} and on the 10°C surface is 80 cm s^{-1}. The characteristic asymmetry in the widths of the cyclonic and anticyclonic shear zones is evident. Peak cyclonic shear (along temperature surfaces) is on the order of 2.6×10^{-5} and 1.9×10^{-5} on the 12° and 10°C surfaces, respectively. Anticyclonic shear is about 50% less, -1.1×10^{-5} and $-0.9 \times 10^{-5}\ \mathrm{s}^{-1}$.

Even though the RAFOS observations of mean speed have been mapped from a pressure–temperature coordinate to a cross-stream distance coordinate using the model of the mean thermal structure, the agreement with the PEGASUS mean speed observations is remarkable, especially considering that the RAFOS measurements were made at various downstream locations out to 60°W. This unformity is borne out clearly by plotting the RAFOS float speed data from the center of the Stream only for the 12°C surface (Fig. 8). We see that the peak instantaneous speed in the main thermocline is quite constant between Cape Hatteras and 60°W. This was observed by Shaw and Rossby (1984) using SOFAR floats. Their floats at 700 db showed peak speeds on the order of 75 cm s^{-1} between 75° and 57°W (based on 11 float crossings). Thus, both the SOFAR and RAFOS studies indicate no significant weakening of peak speeds in the main thermocline out to about 60°W.

The low speeds observed at 74°W are from RAFOS 021 which escaped very soon after being launched compared to other floats in its temperature range (see Fig. 11a). Its rapid deceleration may have been an important factor in its early expulsion from the current. At 71°W, RAFOS 050 was approaching a region where

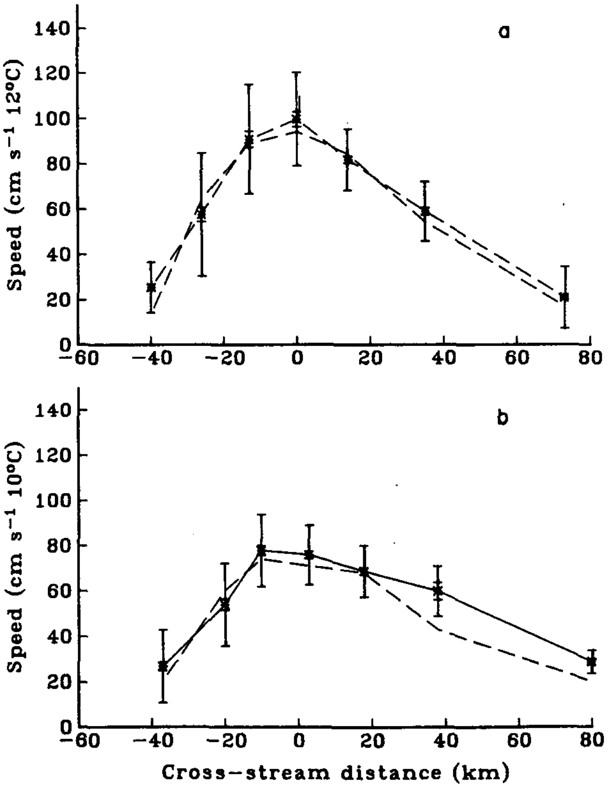

FIG. 7. Mean horizontal speed in the Gulf Stream as a function of cross-stream distance on (a) 12°C surface (11.5 < T < 12.5°C) and (b) 10°C surface (9.5 < T < 10.5°C). Bars indicate standard deviation (large) and standard error (small) of each estimate of the mean. Dashed line represents mean from PEGASUS study.

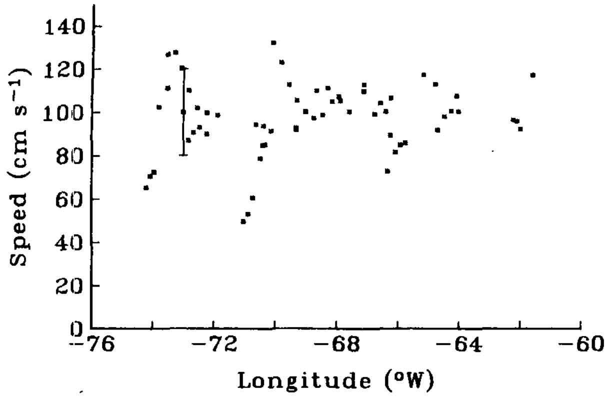

FIG. 8. RAFOS float speed observations from the center of the Gulf Stream as a function of longitude on the 12°C surface (400 < P < 600 db defines center). Data point with bars indicates PEGASUS mean and standard deviation in the center of the stream.

the stream was interacting with a cold core ring (see Fig. 17f) when it decelerated to unusually slow speeds for the center of the current, which may itself be shifting position rapidly.

A significant number of speed estimates were collected outside the stream by floats which escaped from the current. Those floats which escaped to the north and were not entrained into warm core rings, showed persistent flow to the southwest at 10–15 cm s^{-1}, consistent with the concept of a meander-induced counterflow present in some models of the Gulf Stream (Robinson and Niiler 1967; Saltzman and Tang 1985). South of the stream, the speeds were comparable to those observed to the north, but there was no preferred direction to the float movement. In particular, there was no evidence of a westward recirculation south of the stream in this region.

5. Cross-frontal exchange processes

In this section, we examine how the meander-induced circulation can lead to cross-frontal exchange, whereby fluid parcels from the center of the stream are brought close to the edges and are often lost to the surroundings.

a. Where are fluid parcels exchanged?

The trajectories of all 37 RAFOS floats are shown in Fig. 1. No indication of speed is given here, only the float pathways after launch at Cape Hatteras. In general, the floats follow the stream in a northeast direction until 72°–70°W, where the current turns to a more eastward heading, flowing off the continental slope into deep water ($z > 4000$ m). Beyond this point, large amplitude meanders are apparent from the trajectories. The circular motion of some floats east of 70°W results from entrainment into warm and cold core rings.

Most of the floats in this experiment did not remain in the stream for their entire mission. The spaghetti diagram (Fig. 1) has been summarized schematically in Fig. 9 to show the regions where fluid escaped from the stream. Of the 34 floats launched in the current, only 8 (24%) stayed in the current for their entire mission. The other 26 (76%) all escaped at least once (some were reabsorbed and escaped again) before 30 days at various downstream locations. Nine (26%) escaped before reaching 70°W, eight to the north and one to the south. The floats that left the stream to the north were all on temperature surfaces colder than 11°C and all reentered the stream (some made several trips in and out of the current in this region). The only float lost to the south in the region west of 70°W was warmer than 11°C. The 11°C surface has been chosen as the boundary between the "warm" and "cold" floats because the T–S relationships, which identify slope and Gulf Stream waters above 11°C, become indistinguishable below that level (e.g., see Bower et al. 1985).

East of 70°W, 17 (50%) of the floats escaped before the end of their mission, but the losses to both sides of the stream were more equal. Ten floats (8 warm, 2 cold) escaped to the north, nine of which remained in the Slope Water region drifting westward for the rest of their mission (>1 month for some). Seven floats (4 warm, 3 cold) were lost to the south with only one making it back into the stream. The others drifted rather aimlessly in the Sargasso without being reabsorbed or were entrained into cold core rings.

These results suggest that between Cape Hatteras and 70°W, fluid loss from the stream occurs primarily in the deeper layers below 11°C, and the loss appears to take place almost exclusively to the north. This seems to indicate a mean upward motion in the lower half of the main thermocline in the region where the Gulf Stream is flowing over the continental slope. East of 70°W, fluid exchange takes place both above and below 11°C and losses are comparable to both sides of the stream. This observation is consistent with the result (stated in section 4a) that there is no significant mean vertical motion in the main thermocline of the Gulf Stream in this region. The mean residence time for a

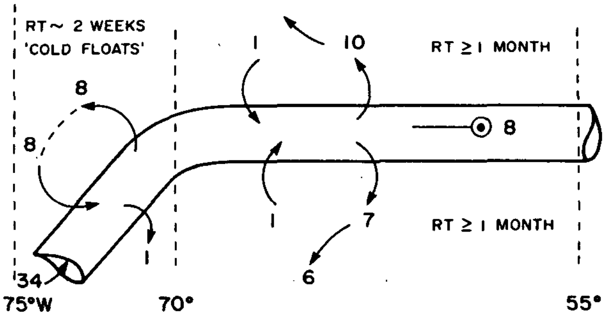

FIG. 9. Schematic diagram showing numbers of floats escaping from the stream between 75° and 55°W. RT: residence time.

fluid parcel in the main thermocline of the Gulf Stream is about three weeks (before first escape) based on these trajectories.

In order to examine the effect of meanders on cross-stream motion and escape, we have superimposed some trajectories on the NOAA/NESDIS charts of sea surface temperature which show the shape of the Gulf Stream path when floats escape. Figure 10 shows the pattern of the Gulf Stream on two occasions when floats were escaping to the north. In Fig. 10a, RAFOS 010 decelerated rapidly and upwelled (from pressure record, not shown) out of the stream. The float was approaching a very sharp anticyclonic turn in the path of the current. In Fig. 10b, RAFOS 052 also decelerated and upwelled out of the stream along the 12°C surface as it approached another sharp crest. These examples are representative of most of the floats which left the stream to the north.

The downwelling and lateral motion toward the Sargasso Sea in troughs can lead to a loss of water to the south. Two examples are given in Fig. 11. RAFOS 021 (Fig. 11a) downwelled rapidly and decelerated as it left the stream to the south on approach to a cyclonic bend in the path of the current. At the same time, a cold filament was being drawn into the current at the northern edge. In Fig. 11b, the location of the surface fronts of the stream is partially obscured by clouds, but the downwelling and deceleration of RAFOS 035 as it crossed the estimated position of the southern edge is consistent with the overall pattern.

Shingles were sometimes observed to occur at the surface when a float was escaping from the stream to the north at depth, Fig. 10b. This suggests a common mechanism for shingle formation and float escapes; in fact, previous investigators have emphasized the importance of vertical motion in the formation of shingles (e.g., Chew et al. 1985).

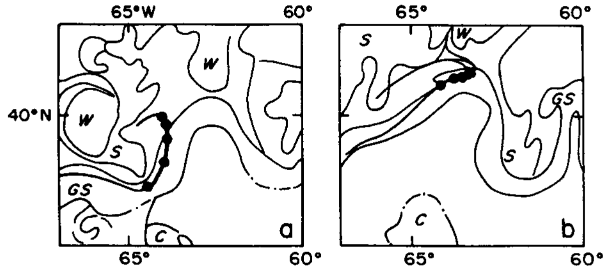

FIG. 10. Two examples of RAFOS floats crossing out of the Gulf Stream to the north superimposed on sea surface temperature (SST) field (redrawn from NOAA/NESDIS cartoons). GS: Gulf Stream, W: warm core ring, C: cold core ring. Dotted and dashed lines in SST field indicate position of front is uncertain due to cloud cover. Dots on trajectories are 0000 UTC fixes and leading two dots indicate position of the float when the SST satellite image was obtained. Note that the trajectories shown can span as many as 45 days, during which time the configuration of the stream path can change considerably. (a) RAFOS 010 (114/85, 12°C); (B) RAFOS 052 (298/85, 12°C).

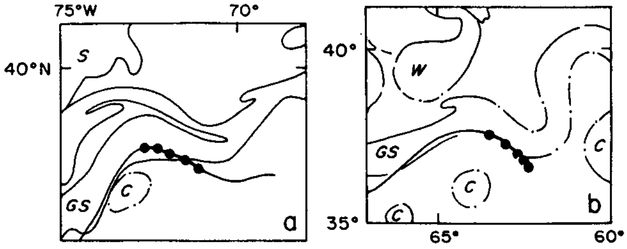

FIG. 11. As in Fig. 10 but showing floats crossing out of the stream to the south. (a) RAFOS 021 (279/84, 12°C); (b) RAFOS 035 (189/85, 11°C).

In addition to observations of fluid loss from the stream, there were numerous examples of entrainment as well. Figure 12a illustrates one example, RAFOS 017, which was drawn into the stream at the leading edge of a meander crest. RAFOS 027 (Fig. 12b) was also reabsorbed in front of a crest. Entrainment was also observed near Cape Hatteras where the southwestward flowing Slope Waters are forced into the Gulf Stream. Halkin and Rossby (1985) consistently observed inflow at 73°W due to this convergence in the circulation pattern.

From these observations of fluid loss and entrainment, a conceptual model has been constructed which illustrates the primary regions of fluid exchange (Fig. 13). The RAFOS trajectories show that this exchange is strongly linked to the meandering of the Gulf Stream path. Fluid parcels in the main thermocline escape to the north (south) as they approach an anticyclonic (cyclonic) meander. Likewise, entrainment was observed at the leading edge of meander crests. The pattern does not appear to be completely symmetric, since no floats were absorbed from the south at the leading edge of meander troughs. Exchange was not observed as often when the path of the current was relatively straight (except in the confluence region near Cape Hatteras).

b. Factors and processes affecting cross-frontal exchange

1) SHARPNESS OF CURVATURE

Comparisons between float trajectories and stream path shape such as those presented in the last subsection suggest that the *magnitude* of the change in flow curvature along the path of the Gulf Stream may determine if a fluid parcel is lost or retained. Very sharp changes in stream path curvature along fluid parcel trajectories seem to induce larger vertical and lateral motions in the current, which in turn can lead to the loss of a parcel from the stream. This is tested quantitatively by breaking the trajectories into segments between meander extrema and measuring the lateral (cross-stream) displacement of the float and the change in curvature experienced by the float. Segments where

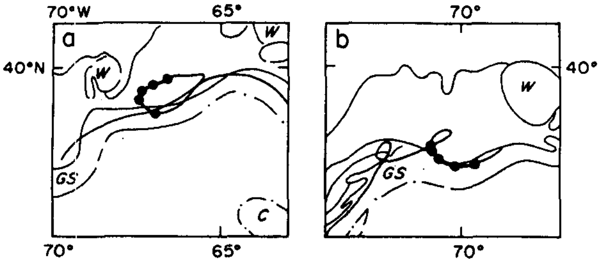

FIG. 12. As in Fig. 10 but showing float reentrainment. (a) RAFOS 017 (223/84, 13°C); (b) RAFOS 027 (60/85, 9°C).

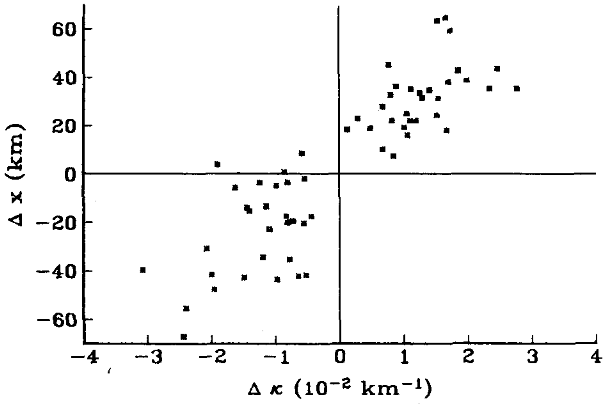

FIG. 14. Cross-stream displacement of RAFOS floats in meanders as function of change in trajectory curvature.

floats escaped were not used since the cross-stream position of the float cannot be measured outside the baroclinic portion of the current.

The results of this analysis are presented in Fig. 14. A least squares linear regression gives a slope of 20 km/0.01 km^{-1} and a correlation coefficient of 0.81. This implies that a typical fluid parcel in the main thermocline flowing from meander crest to trough, each of which has a radius of curvature of 100 km, will be displaced toward the Sargasso Sea by about 40 km. Since the current is approximately 100 km wide, the initial position of the float will determine if it will escape, but it is clear from this figure that larger changes in curvature of the stream path lead to greater lateral displacements and more likely escape of fluid parcels in the high-velocity core.

2) THE INFLUENCE OF RINGS

Warm and cold core rings were observed to affect cross-frontal exchange in two ways. The first and most prevalent mechanism occurred when fluid parcels from the center were brought to the edges of the current and then drawn out completely by a nearby ring, which was impinging on the edge of the stream. The second mechanism is related to ring formation, which affects large segments of the stream path.

Of the 37 floats in this experiment, 18 showed some ring involvement. Two examples are shown in Fig. 15. Figure 15a shows clearly how RAFOS 011 was influenced by the warm core ring adjacent to the stream. Many floats in the stream were lost to the surroundings via this mechanism.

Only one float was caught in the detachment of a new ring (RAFOS 016, Fig. 15b). The detachment of the cold core ring is complicated by the reattachment of a warm core ring upstream, but the open loop which will become a new *cold* core ring is visible. The subsequent motion of RAFOS 016 around a new cyclonic ring is clearly evident.

3) TEMPERATURE DEPENDENCE

It was pointed out in Section 5a that fluid parcels deeper in the main thermocline seemed to escape from the stream and be reabsorbed much more rapidly than floats at shallower levels. This difference becomes very apparent when the floats are divided into warm ($T > 11°\mathrm{C}$) and cold ($T < 11°\mathrm{C}$) groups (Fig. 16). Here the trajectories of the floats are shown only up to the point of first escape. In the warm group, all but one of the floats remain in the stream until 70°W, and half are still in the stream past 65°W. Comparing this to the trajectories of the floats in the cold group, half of these do not stay in the stream past 70°W and three-quarters are lost by 65°W. These figures illustrate quite

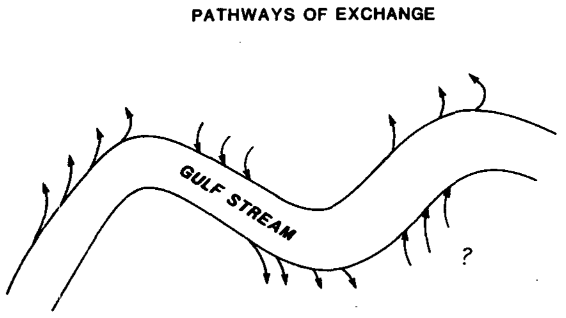

FIG. 13. Schematic view of Gulf Stream meander showing relationship between wave pattern and fluid exchange.

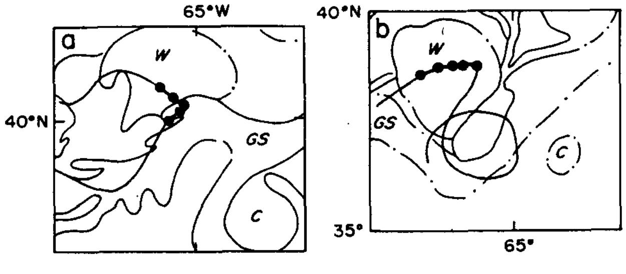

FIG. 15. As in Fig. 10 except showing interaction of RAFOS with warm and cold core rings. (a) RAFOS 011 (95/85, 12°C); (b) RAFOS 016 (209/84, 14°C).

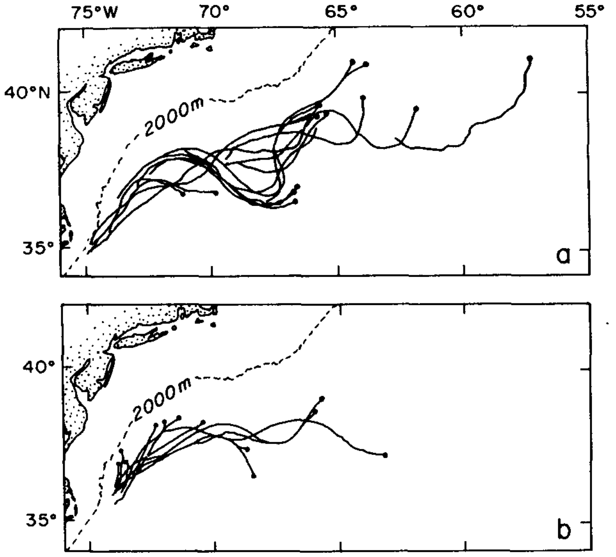

FIG. 16. (a) Trajectories of RAFOS floats on temperature surfaces between 11 and 16°C up to the point of first escape; (b) as for (a) but for floats on temperature surfaces between 7° and 11°C.

convincingly that fluid parcels in the upper main thermocline are retained in the stream for considerably greater distances than those in the lower half of the thermocline.

Why this difference exists over such a limited vertical range is not completely clear. The meander-induced vertical and lateral motions appear to be rather depth-independent through the main thermocline (see Fig. 6), but their effect on the deeper floats may be greater due to the slower downstream speeds at these levels. In contrast, the faster moving floats in the upper main thermocline have less time to respond to the vertical and lateral motional fields.

4) TIME EVOLUTION OF THE STREAM PATH

We suspect that the vertical and lateral motions observed with the RAFOS floats are also related to the propagation and growth of meanders. This is certainly the case for waves in the upper-tropospheric jet stream (e.g., see Holton 1979). However, it is difficult to quantify the effects of time evolution on cross-frontal exchange in the Gulf Stream with the present dataset due to several factors, including the limited number of floats passing through a given feature during its evolution (usually only one float), gaps in the IR imagery time series due to cloud cover and insufficient knowledge of the evolution of the subsurface structure of the jet. Nonetheless, some initial understanding of the importance of time dependence can be gained by viewing a time series of stream positions from satellite and float trajectories which illlustrates both meander evolution and ring interaction.

Such a sequence is shown in Fig. 17 for a group of eight floats launched close together in time (within 10 days), including three launched in the Slope Water adjacent to the stream. During the nearly 2-month period spanned by these images, the stream path was dramatically altered, primarily by the attachment and detachment of rings. In the first sequence of panels (282-301/85), the five floats launched in the stream flowed through the first meander crest and into a very deep trough. At this point, two floats continued downstream, but the other three, which came along one or two days later, were lost to the south and eventually wrapped around a new cold core ring. The two in the stream did not remain there, but were expelled into the Slope Water when a meander crest grew rapidly to the north.

The second sequence (301-329/85) involves the floats launched outside the stream, two of which entered into the center of the current near Cape Hatteras. These floats followed the stream through the first crest, which had grown sharper since the other floats traveled through. At the next trough, the floats entered a ring which had apparently reattached to the meander trough, but the completion of one full revolution by the floats seems to indicate that the ring was now *not* attached to the trough. But after another half revolution, the floats continued downstream in the current as the ring joined once again. This example in particular illustrates how one must be cautious when using surface imagery to infer flow at depth.

6. Discussion and conclusions

The first experiment with RAFOS floats in the Gulf Stream has added a new dimension of information about the current's velocity field. These isopycnal drifters exhibited a bold pattern of vertical motion induced by changes in flow curvature along the meandering path of the stream. Fluid parcels tagged with floats were consistently observed to upwell (downwell) and move onshore (offshore) along sloping density surfaces as they approached anticyclonic (cyclonic) bends in the current, and the lateral displacement of fluid parcels were found to be directly proportional to the changes in flow curvature. Vertical velocities measured with the RAFOS floats were on the order of 0.10 cm s^{-1} (rms), two or more orders of magnitude larger than values estimated for midocean. The associated cross-stream component of motion was about 10 cm s^{-1} (rms). In spite of these regular oscillations of fluid parcels back and forth across the stream, the drifters also showed that the structure of downstream velocity is quite constant in the alongstream direction out to about 60°W, with no substantial weakening of peak speeds.

The up- and downwelling induced by the meandering of the current is an important mechanism for fluid exchange between the core waters of the Gulf Stream and the surrounding fluid. The RAFOS trajectories

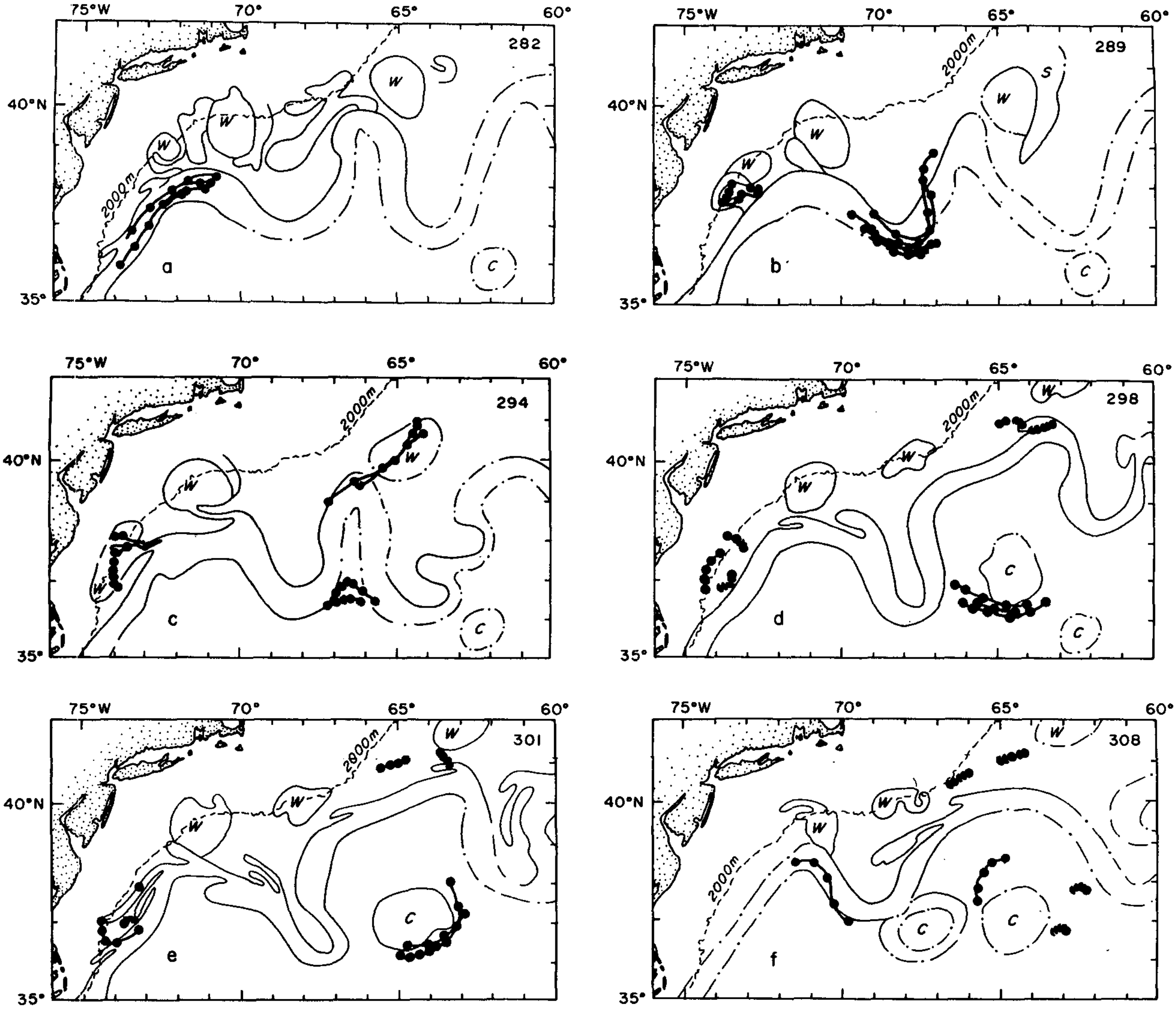

FIG. 17. Time series of eight RAFOS float trajectories (043, 047, 050, 052, 053, 058, 061, 063) from yearday 282 to 322, 1985 (9 October–22 November). Four-day segments of each float are shown but only that portion of trajectory between leading two dots corresponds to the time of the satellite image.

clearly show that the systematic pattern of vertical motion leads to fluid *loss* from the stream to the surroundings at the trailing edges of meander extrema while fluid is *entrained* from the surroundings at the leading edges. Fluid exchange of Gulf Stream core waters was not observed along straight sections of the current.

This meander-induced mechanism for cross-frontal fluid exchange has not previously been documented. Earlier studies of stirring and mixing at the Gulf Stream front have examined other processes such as forced entrainment at Cape Hatteras (Ford et al. 1952), small-scale interleaving (Lambert 1982; Schmitt and Georgi 1982; Mork and Rossby 1986), and ring formation (Bower et al. 1985). The relative importance of each of these mechanisms is difficult to determine, although Bower et al. (1985) showed the contribution of ring shedding to be much less than eddy diffusive fluxes across the front (fluxes which would include the meander-induced exchange), a conclusion borne out by this study as well.

Similarly, the relative contribution of the exchange processes observed with the RAFOS floats cannot be determined quantitatively, but the large number of floats exiting from the stream due to this meandering effect suggests at least qualitatively that it is an important mechanism for fluid exchange across the front. Sixty percent of the floats launched at Cape Hatteras managed to cross out of the current at least once before reaching 65°W, primarily due to the curvature effect. This implies that at the level of the main thermocline, 60% of the core Gulf Stream waters is lost and replaced

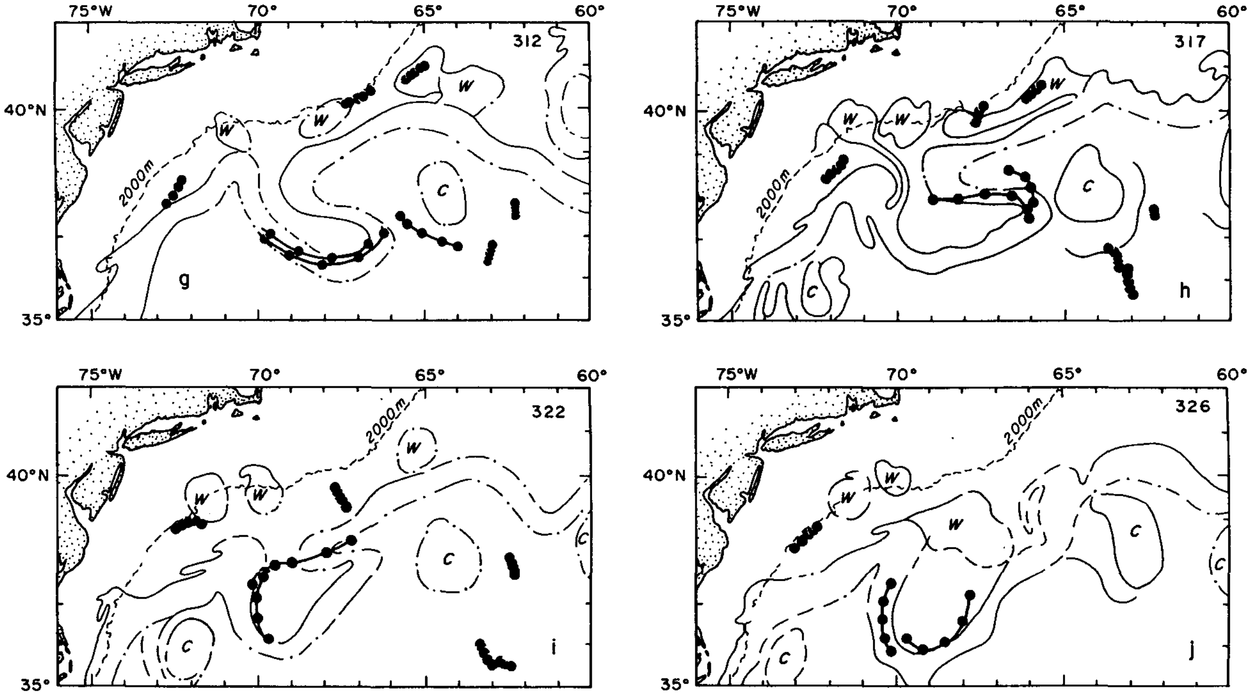

FIG. 17. (*Continued*)

by fluid from outside the stream between 75° and 65°W, with more replacement in the lower half than in the upper half of the thermocline.

This increase in exchange with depth is consistent with Bower et al.'s (1985) study of the GS '60 hydrographic sections. They showed that above the main thermocline, water property and potential vorticity gradients along density surfaces are strong, indicating little water mass exchange that would tend to blur these water mass differences. The water property contrast weakens with depth, however, such that below the $27.1\sigma_\theta$ surface (11°C in the Gulf Stream) there is virtually no property or potential vorticity front at all, suggesting more vigorous cross-stream exchange.

Shaw and Rossby (1984) and Owens (1984) also pointed out this difference between the upper and lower layers of the Gulf Stream with SOFAR floats. Shaw and Rossby, as mentioned earlier, introduced the term *Lagrangian* Gulf Stream to characterize the retention of fluid parcels for long distances in the upper layers. Since this is not the case at 2000 m, Shaw and Rossby suggested that the Gulf Stream does not exist as a Lagrangian current at these depths. The RAFOS trajectories show the thermocline to be a transition layer between these two extremes, where some fluid is lost and entrained, and where exchange increases with depth. It is probable that had RAFOS floats been launched in the stream above the main thermocline, they would on average have been retained in the current for considerably greater distances than was the case in this experiment.

This pilot study with RAFOS floats has illustrated the value of making Lagrangian observations in the Gulf Stream. The new isopycnal feature of the RAFOS drifter has allowed us to examine the actual pathways of fluid parcels in the Gulf Stream for the first time, and thereby identify and study in detail meander-induced vertical and lateral motion and cross-frontal exchange processes.

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APPENDIX A

Model of Cross-stream Thermal Structure

In order to determine the position of a RAFOS float in the cross-stream plane, an analytical function was developed to model the mean thermal structure of the Gulf Stream. The parameters in this function were set so that the model would reproduce the mean temperature section (thermocline only) in natural coordinates from the 3-year PEGASUS study at 73°W (Halkin and Rossby 1985). In addition, the deepening of the thermocline with increasing distance downstream along the southern edge of the stream was modeled using data from a study of historical hydrographic sections by Rossby and Rago (1984). The algorithm gives the pressure (or depth) of an isotherm as a function of cross-stream distance, x:

$$P = \frac{\mathrm{P2}e^{(x-5)/\mathrm{L2}} + \mathrm{P1}e^{-(x-5)/\mathrm{L1}}}{e^{(x-5)/\mathrm{L2}} + e^{-(x-5)/\mathrm{L1}}}$$

where

P1 = $280 - (T - 10) \times 39$ (limiting depth of isotherms on north side of stream)
P2 = $(910 - (T - 10) * 49) + 4 \times (\mathrm{long} - 73)$ (limiting depth on south side with correction for longitude)
L1 = 30 km (scale width of cyclonic side)
L2 = 52 km (scale width of anticyclonic side);

P1 and P2 are calculated given the float's temperature and longitude. An initial guess is then given for x, and P is computed iteratively until it is within 1 db of the float's pressure.

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