Particle Pathways in the Gulf Stream

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Abstract

An experiment is under way to study the kinematics, dynamics, and path evolution of the Gulf Stream front between Cape Hatteras and 60°W. The Rafos float, which can track the true motion of water parcels along density surfaces which slope steeply across the Gulf Stream, has recently been developed for this study. These instruments are launched in the center of the Gulf Stream every 5–15 days for a 30-day mission. Each float provides a trajectory and a continuous record of temperature and pressure along the trajectory. Our results so far show that: a) cross-stream motion has a significant vertical component (ranging to some 0.1 cm · s^{-1}) compared to vertical velocities in midocean; b) floats systematically shoal (upwell) as they approach anticyclonic meanders and deepen (downwell) as they approach cyclonic meanders; c) more than half of the floats launched so far remained trapped in the Gulf Stream for distances on the order of 1000 km; d) when floats do escape from the stream, it is more likely they will do so to the south; and e) both internal processes, such as the rapid growth of meanders, and external features, such as nearby rings or eddies, can expel or extract floats from the stream. These observations are also being used in numerical simulations of the Gulf Stream to develop predictive skills for the path of the current.

1. Introduction

Due to its proximity to the U.S. east coast, the Gulf Stream is one of the best-studied ocean currents. We know of nearly 200 hydrographic sections that have been taken across it since the 1930s. From these and other observations, mostly of the surface currents, it is generally agreed that the Gulf Stream is a narrow, simply connected current which flows along the coast from its origin in the Gulf of Mexico, through the Florida Straits, and north to Cape Hatteras where it turns eastward away from the coast. Eventually, the current appears to break up in several directions south and east of the Grand Banks. It is remarkable that regardless of location along this 4000 km path, one can always intercept the current by simply steaming seaward from the coast. The surface currents have typical maximum speeds of about 200 cm · s^{-1} (4 knots). Except in summer, the current is conspicuously warmer at the surface than the surrounding waters, and at depth it is always characterized by rapid deepening of the density surfaces as one proceeds seaward. Figure 1 shows the mean velocity and temperature field of the current off Cape Hatteras. This figure is a composite of fourteen sections obtained over a three-year period using the free-fall velocity profiler "Pegasus" (Halkin and Rossby, 1985).

East of Cape Hatteras, the Gulf Stream front separates two water masses: Sargasso Sea water to the south and the cold slope waters to its north. The sharpness of the water mass boundary along the current's cyclonic edge and its coincidence with the stream suggests that the front is impermeable to cross-stream exchange of water. (It should be noted that this distinction of separate water masses loses validity below the midthermocline, where increasing uniformity of water properties suggests greater cross-stream exchange.) The Gulf Stream is not so isolated from the Sargasso Sea, however. Between the Florida Straits and Cape Hatteras the transport of water more than doubles, with nearly all the new water coming from the Sargasso Sea. East of Cape Hatteras, there is only a modest further increase in warm water transport out to the New England Seamounts, beyond which the transport decreases (Fofonoff and Hall, 1983). Thus, the very sharp and discrete character of the current, the strong and in some sense stable dynamic balance over great distance, and its transport of mass and heat all contribute to the perception of the current as a giant conduit wiggling about in the ocean, but otherwise in only weak contact with the surrounding waters.

In recent years, deployments of neutrally buoyant Sofar floats in the Western North Atlantic have provided a wealth of information on quasi-Lagrangian (isobaric) motion in the Gulf Stream from Cape Hatteras to the Grand Banks south of Newfoundland (Rossby, 1982; Owens, 1984). Analysis of trajectories in the stream suggests that water parcels in the main thermocline (700 m) should remain in the current over long distances and that the stream is a well-defined jet at these depths (Shaw and Rossby, 1984). The Sofar float, however, is not designed to track vertical motion of water parcels. In the open ocean, where vertical displacements are small, this is not a problem (Riser, 1982), but in the Gulf Stream, where isopycnal (σ_θ) surfaces dip nearly 600 m across 100 km, cross-stream isopycnal motion has a substantial vertical component. Thus an isobaric Sofar float and a fluid parcel, initially together, may rapidly diverge from each other.

Over the last several years we have developed a new type of Lagrangian drifter which is able to approximate isopycnal motion quite well (Rossby *et al.*, 1985). These floats, which consist of a 1.7-meter-long borosilicate Pyrex glass pipe, are constructed to drift along an isopycnal (σ_θ) surface by the addition of a compressible element (spring and piston system) which eliminates any buoyancy or ballast induced by changes in pressure. Some floats track the density surface quite well; others underestimate the depth changes due to variations in stiffness of the glass pipe and spring.

We call these instruments "Rafos" floats. Rafos is the acronym Sofar (sound fixing and ranging) spelled backwards, which refers to the use of the deep-sound or Sofar channel as an acoustic waveguide for underwater navigation (Bowditch, 1962). The floats are programmed to listen (rather than talk, thus the reversed spelling) to acoustic transmissions from

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three moored sound sources: one south of Cape Hatteras, one north of Bermuda and one south of the Gulf Stream near 57°W. The useful operating area for a Rafos system is a function of the float's depth relative to the sound channel axis, sound source power, and ambient noise conditions. The fact that we are working at shallow depths in a noisy region (heavy shipping) limits the acoustic range in this study to about 1000 km. The floats are designed for up to 12 months' operation. In this study, they are programmed for 30 days' submergence after which they drop ballast, return to the surface and telemeter the acoustic tracking, pressure, and temperature measurements to "Systeme Argos," a French satellite-based location and data-collection system. A detailed description of the Rafos system is given in Rossby *et al.* (1985).

This is a preliminary report on our efforts to use these floats to study the Lagrangian properties of fluid motion in the Gulf Stream. We hope this work will be of interest to those concerned with the kinematics and dynamics of frontal systems.

2. The experiment

The starting point in the design of this experiment is our premise that the Gulf Stream is a well-defined baroclinic front along which there is a high likelihood of fluid remaining trapped. Thus by repeatedly seeding the current with floats we can look at a) the space-time evolution of the path of the stream; b) the isopycnal dispersion of water from the center of the current; and c) the mechanisms by which dispersion from the stream takes place: are they endemic to the stream or are they triggered by external factors.

Since July 1984 we have been launching floats in the center of the Gulf Stream off Cape Hatteras. Although weather and high seas have made this a more difficult task than anticipated, over ten 30-day trajectories have been obtained to date (in addition to others at different depths). The floats are ballasted for $\sigma_t = 27.0$ ($T = 12.5$, $S = 35.6\%$) which at launch is at about 500 m.

3. Results and discussion

As an example of the type of results we have obtained, consider the track of float #22, shown by the curved black line on the front cover. Launched off Cape Hatteras, the float is carried along by the meandering current to the east. The three panels show the surface thermal fields at a time when the float is in the area (float position shown by the crosses). They clearly demonstrate that the float is in the current at all times. This is also evident from the float speed, which ranges between approximately 40 and 100 cm · s^{-1} with an average of 66 cm · s^{-1}. In addition, we know from the records of pressure and temperature that the float in fact stayed well within the current throughout its journey. Referring to Fig. 1, we see that the depth of the density surface at which the float was neutrally buoyant (corresponding to T = 10°C) ranges between 250 and 850 m from the slope waters to the Sargasso Sea. Yet the float remains at 500 m ± 200 m (not shown), which in terms of the slope of the density surfaces corresponds to lateral displacements of about ±20 km. Furthermore, the depth fluctuations that do occur are not stochastic but are highly correlated with the curvature of the current. As we will show, floats shoal in anticyclonic and deepen in cyclonic turns of the current.

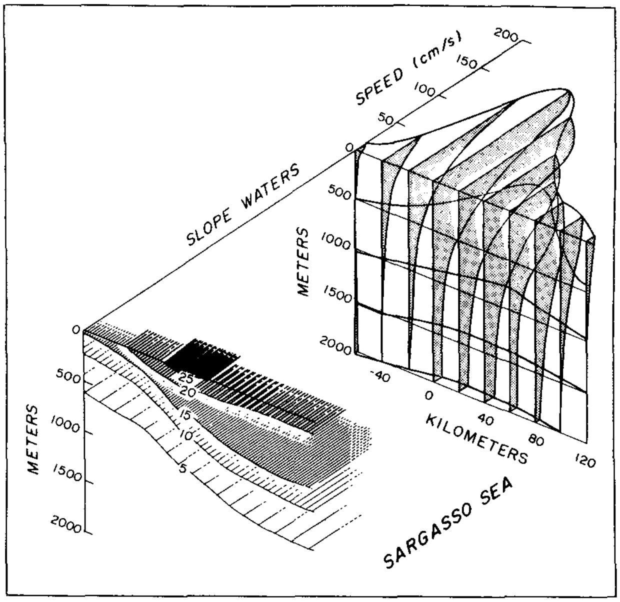

FIG. 1. Pictorial representation of the structure of the Gulf Stream off Cape Hatteras. This is constructed from 14 sections over three years. At right, the velocity field, and at left, the temperature field (Rossby, 1984; based on data from Halkin and Rossby, 1985).

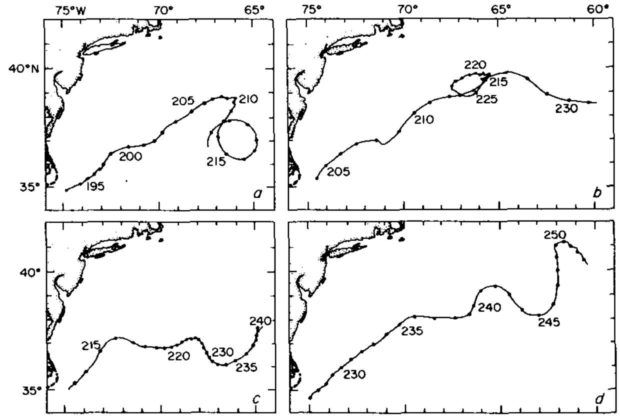

FIG. 2. Trajectories for four Rafos floats launched sequentially in July and August, 1984: (a) #16; (b) #17; (c) #18; and (d) #20. They are 30 days long and the dates are given in yeardays. The heavy dots are shown daily; their separation gives a measure of the float's speed (1° latitude = 111 km).

In July–August we were able to obtain four float tracks separated by 10 days. Shown in Fig. 2a–d, they exhibit quite a range of behavior. The first one in this mini-series, #16 in Fig. 2a, moves along smoothly until 66°W where it slows down and enters into a circular orbit to the south on day 210. Inspection of satellite imagery shows that a meander broke off into a cold core ring on day 211 or 212. Ten days later, float #17 in Fig. 2b follows a generally parallel path about 50 km to the north of #16. Close to where the ring was formed the

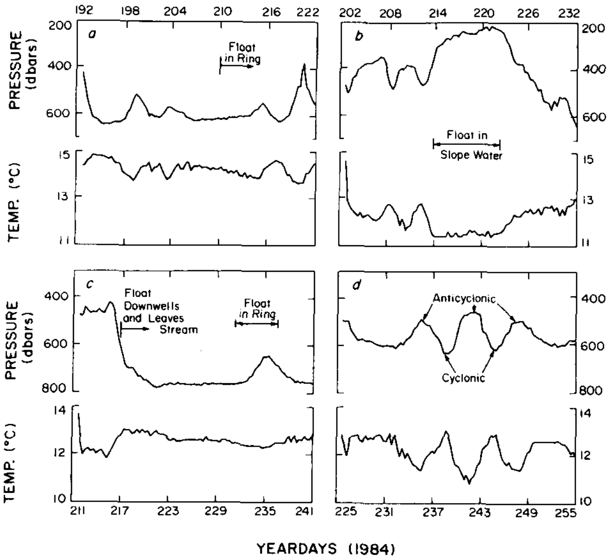

FIG. 3. The pressure and temperature data as a function of yearday for the same four floats: (a) #16; (b) #17; (c) #18; and (d) #20. Note that a perfectly isopycnal float imbedded in a single water mass will measure constant temperature.

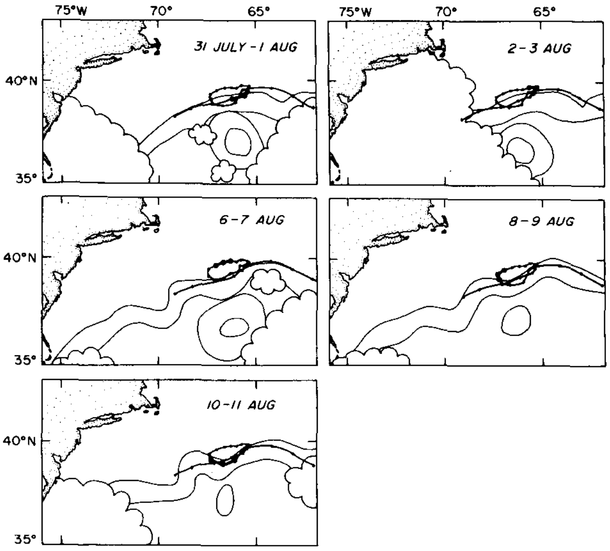

FIG. 5. As for Fig. 4 except for float #17. The escape of this float on the trailing edge of a meander crest and its reentrainment at the leading edge of the next one is clearly depicted.

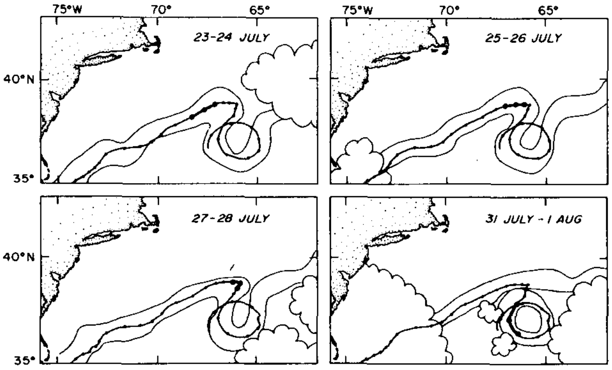

FIG. 4. A sequence of four cartoons (each a composite of all satellite images taken during the two-day period noted) depicting a meander-ring break off. The plain solid lines show the northern and southern edges of the stream, and the track of float #16 during the time of the imagery is indicated by the thick line. Curly lines indicate cloud cover.

float escapes northward into the slope water on day 215 where it slowly drifts westward until, a week later, it is reentrained by a rapidly propagating (and growing) meander and swept downstream at great speed. On day 230, two days before it surfaced, the float was beginning to leave the stream to the south. The third float, Fig. 2c, crosses the stream rapidly after a sharp anticyclonic turn, and downwells from 450 to 700 m between days 216 and 218, escaping to the south shortly thereafter. It slowly drifts eastward and encounters the previously formed cold core ring on day 233 where it briefly accelerates and rides up on its southeast slope. This behavior is suggestive of the streaming motion around closed eddies discussed by Flierl (1981). The last float, Fig. 2d, like float #22 on the cover, remained in the center of the current for the entire period.

The pressure records provide important information on the vertical component of lateral movement in the stream. Close inspection of these, Fig. 3a–d, shows that upwelling and downwelling nearly always occur in anticyclonic and cyclonic turns, respectively, although the amount of vertical motion varies considerably. If the lateral displacement is too large the float will leave the stream. Indeed, the escapes of #17 and #18 to the south and #17 to the north (temporarily) took place in sharp bends of the current. This is much more evident in satellite imagery which reveals the meanders the floats did not negotiate.

Loss of floats to a ring, such as that of float #16, must happen within a rather narrow time window (approximately one week in this case) while the float is looping around the meander. Figure 4 shows a cartoon of the meander-ring transformation (as inferred from IR imagery) and the float's position during this process. Had the float arrived just a little later it would have streamed by instead of getting caught in the ring. We can estimate the likelihood of losing floats to rings. If 10 rings (both warm and cold) form per year (Lai and Richardson, 1977), then 10/52 (assuming a one-week window), or 20%, of the floats launched upstream might get trapped in rings. Clearly, the probability of float escapes increases with increasing float depth.

The loss of float #17 into the slope waters appears to be related to the rapid propagation of the anticyclonic meander through which it was passing. After leaving the current it was picked up a week later by the next, rapidly steepening meander (see Fig. 5). The almost perfect symmetry between the loss and reentrainment of the float between the two meanders is reminiscent of the induced circulation shown by Robinson and Niiler (1967; their Fig. 10) and by Saltzman and Tang (1975; their Fig. 5). The significance of this point is that meander-induced up- and downwelling can give rise to cross-stream exchange which is not necessarily irreversible. The slight change in temperature measured by the float as it moved into the slope water region is due to a small deviation from the original isopycnal surface, and does not indicate that the float was mixing with the nearby slope waters. Since the float was clearly imbedded in Gulf Stream water at all times, it would appear that the water mass boundary separating the Gulf Stream and the slope waters can become temporarily separated from the dynamical front during such periods of meander-induced circulation.

There is some evidence that the more sudden escapes such as that of #18 to the south may be connected with the presence of rings or eddies nearby which upset the downstream uniformity of the density field. This question of external factors upsetting the two-dimensionality of the Gulf Stream is one that will be explored in some detail in the near future, particularly with the help of satellite IR imagery.

A composite of all trajectories, a "spaghetti" diagram, is shown in Fig. 6. All tracks start in the center of the stream off Cape Hatteras, where the meander envelope is relatively small. Of the eight floats shown, five continue to approximately 60° W. Although several of the floats leave the stream there, it is evident from this set of tracks that a significant fraction of the floats stayed trapped in the current for distances on the order of 1000 km, or an order of magnitude greater than the stream width, approximately 100 km. We expect that only a small number of floats will escape from the stream, and there is little doubt that these float escapes are more likely to occur to the south. Three of the eight floats launched so far escaped from the stream, all to the south (#17 escaped only temporarily to the north). Richardson (1981) also observed this with surface drifters. This is consistent with a recent isopycnal water-mass analysis of the Gulf Stream system (Bower *et al.*, 1985) where a much greater similarity of water masses between the Gulf Stream and the Sargasso Sea is shown than with the slope waters at the density surface corresponding to these floats.

The meander-induced lateral (and subsequent vertical) displacements in the stream can be understood in two ways. In an anticyclonic turn the centrifugal force is in the same direction as the pressure gradient, which thus must be reduced if the water parcel speed does not change. To accomplish this, the sloping density surfaces must flatten slightly, resulting in a broader stream and horizontally divergent motion. These ideas were put forth by Newton (1978) in his steady-state model of the Gulf Stream. The observed upwelling of floats could be in response to this adjustment of the density field. Alternatively we know that the fluid parcels must be conserving potential vorticity along their path: as they approach an anticyclonic curve, the curvature vorticity decreases, and so too must the height of the individual water parcels (other vorticity terms remaining constant). Thus, water parcels must upwell along the density surfaces toward the cyclonic side of the stream where the vertical density gradient is larger. Note how this upwelling (and downwelling in cyclonic meanders) causes the trajectory to exaggerate the amplitude of the meandering.

Superimposed on these large-amplitude lateral oscillations associated with the meanders is a slow drift of floats toward the anticyclonic side of the stream. We have observed a downwelling speed on the order of 100 meters in 30 days or approximately 0.003 $\mathrm{cm \cdot s^{-1}}$, which implies a Sargasso Sea-ward drift for an isopycnal float on a sloping density surface. This can be for two reasons. As we have seen in the examples above, floats may disperse more readily to the south due to the presence of an energetic eddy field there. Freeland *et al.* (1975) have pointed out how Sofar floats during the Mid-Ocean Dynamics Experiment (MODE) tended to migrate towards areas of greater eddy kinetic energy, but it is not yet obvious to us how to employ this argument to the meandering Gulf Stream. The other possibility is that the Gulf Stream transport is decreasing. From the isopycnal analysis of Bower *et al.* (1985), one can estimate that the mass transport loss to the south is equivalent to a southward velocity of about 1 $\mathrm{cm \cdot s^{-1}}$ (dynamic height at southern edge of the stream decreases from 0.9 dyn m at 68.5° W to 0.8 dyn m at 60° W). This translates into a downwelling velocity of between 0.005 $\mathrm{cm \cdot s^{-1}}$ and 0.01 $\mathrm{cm \cdot s^{-1}}$, which is of the same order as that observed with the floats. It is premature to put too much weight on these numbers, but they indicate to us which possibilities should be explored.

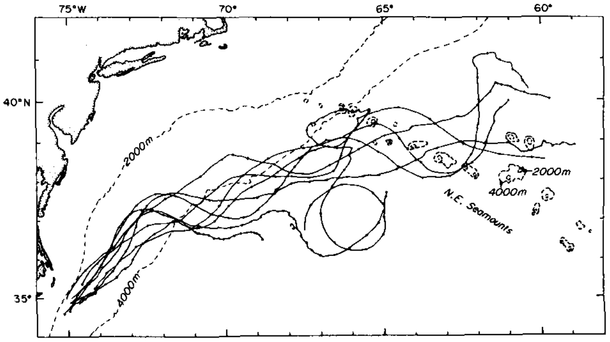

FIG. 6. Spaghetti diagram of eight Rafos trajectories since July 1984. Dots show daily positions. The 2000- and 4000-m bathymetric contours and the New England Seamounts are shown.

The smoothness of the trajectories is somewhat deceptive for there are in fact considerable variations in float speed. Part of this is due to cross-stream motion in a region of high lateral shear, but there is also considerable variability at a given cross-stream position in the stream. This can be seen in Fig. 7 which shows the means and the standard deviations of downstream speed across the current on the 12.5°C surface. This was obtained from 14 sections of the velocity field near 73° W (Halkin and Rossby, 1985). In the center of the current the downstream velocities are about 100 $\mathrm{cm \cdot s^{-1}}$. As a float shifts laterally, the downstream speeds will change. In addition, there are local speed variations ranging to approximately 20 $\mathrm{cm \cdot s^{-1}}$ for any cross-stream location. Still, except close to the edges, these fluctuations should be less than the mean flow at that location in the stream. If we define the width of the current on this density surface as that region where the mean flow exceeds the local RMS fluctuations (which include all time scales) we find it is approximately 150 km. This illustrates vividly how slender the Gulf Stream is compared to the long downstream excursions made by the floats.

This research will also attempt to answer questions about the evolution of the stream path. Planetary vorticity obviously exerts strong control over the local path of the current. This is evident from the fact that northward-protruding meanders always curve anticyclonically and vice versa. The most striking examples of this are probably the sharp clockwise curvatures (approximately 100 km radius) of the float tracks about 300 km northeast of Cape Hatteras where the current turns northeast (see Fig. 6).

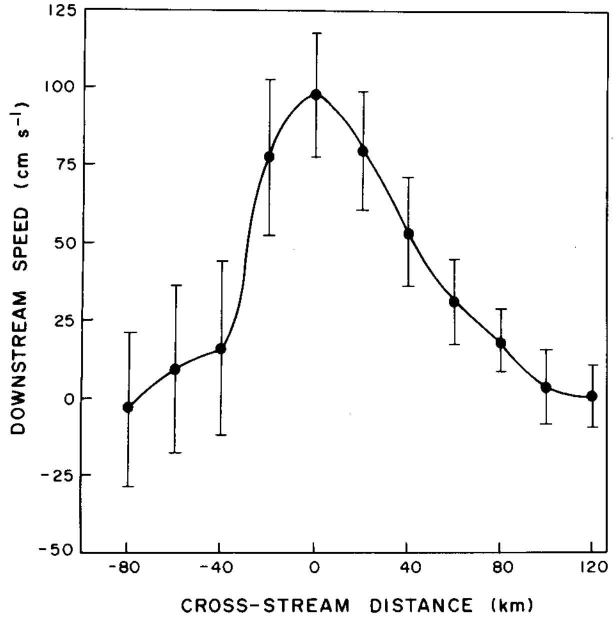

FIG. 7. Means (solid circles) and standard deviations (fiducial marks) of downstream speed on the 12.5°C surface at eleven locations across the Gulf Stream. This is based on 14 sections of velocity measurements over a three-year period (Halkin and Rossby, 1985).

On the other hand, increasing bottom depth in both the downstream and cross-stream directions also has a significant effect on the path of the stream (Warren, 1963; Robinson and Niiler, 1967). Levine *et al.* (1985) have studied the kinematics and local dynamics of an isopycnal Swallow float trajectory in the Gulf Stream as it leaves the Blake Plateau just south of Cape Hatteras. They see a distinct correlation between path curvature and bottom depth. The water depth at the launch site of the present experiment is about 2800 m and increases to 4000 m about 300 km farther downstream. Thereafter, the depth changes are gradual until the stream encounters the New England Seamounts. There is also a strong bathymetric slope perpendicular to the current such that the ocean is always deeper to the right looking downstream. The lateral bottom slope is particularly large right off Cape Hatteras. We will be in an excellent position to further examine how these factors influence the path of the Gulf Stream. Efforts are under way to use these observations in conjunction with numerical studies of the Gulf Stream. In particular, we are cooperating with A. R. Robinson's numerical modeling group at Harvard University, which is seeking to develop a predictive capability for the path of the Gulf Stream. These data can be used to help calibrate and optimize the forecasting skills of the models.

4. Summary

Pathways of fluid motion in the Gulf Stream are now being studied with a new class of passively controlled isopycnal floats. Although they have yet to be used with such frequency that the space-time structure can be resolved in detail, the results so far show there is a high likelihood of floats remaining trapped in the current over substantial distances, and that this trapping is a characteristic of the Gulf Stream. Not surprisingly, when floats do leave the current, it appears to be the result of dynamical disturbances of the basic two-dimensionality of the current caused by intensifying (unstable) meanders or the proximity of rings and eddies to the current.

Water mass and potential vorticity analyses (Bower *et al.*, 1985) indicate that the Rafos floats are dynamically constrained only to remain south of the slope water–Gulf Stream front. Thus we expect a certain amount of scattering to the south of the stream. It is also true, however, that the transport decreases east of the New England Seamounts and that such divergent flow should be seen as a mass flux to the south. We hope that as the program unfolds and the database grows we will be able to examine these many aspects in greater detail.

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