The Influence of Propagating Waves on Cross-Stream Excursions

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ABSTRACT

A kinematic model is developed to examine the relationship between meander propagation and Lagrangian pressure change within a meandering jet. Basically, the model equates changes in pressure along the path of a water parcel with the cross-stream motion of a parcel in a reference frame moving with the meander. The model is tested by combining isopycnal float data from the Gulf Stream with contemporaneous meander phase speed observations from satellite infrared images. Time series of pressure changes along individual float trajectories show a qualitative trend for the amplitude of pressure changes to generally increase in response to large phase speeds. However, the model suggests that the pressure change following a fluid parcel is related to the *vector difference* between the velocity and phase speed vectors, not just the magnitude of the phase speed. This is confirmed by the data analysis, which shows that Lagrangian pressure changes are more highly correlated with cross-stream flow when both the zonal and meridional components of the meander propagation are included in the kinematic model. Approximately 90% of the variability associated with the floats' pressure changes can be accounted for by cross-stream flow using this kinematic formulation.

1. Introduction

Studies of float trajectories during the past decade have done much to dispel the notion that the Gulf Stream transports fluid particles continuously along it path from its separation point near Cape Hatteras to the Grand Banks. Instead, trajectories of SOFAR and RAFOS floats indicate that fluid particles make significant excursions across the Gulf Stream as they move downstream, leading in some cases to detrainment and entrainment of fluid particles near the edges (Owens 1984; Bower and Rossby 1989; Song et al. 1995). Bower and Rossby (1989) and Song et al. (1995) have characterized the cross-stream motions of the isopycnal-following RAFOS floats as upward and onshore from trough to crest and downward and offshore from crest to trough, as illustrated in Fig. 1. (Note: In this paper "trough" and "crest" refer to the extrema of a propagating meander.) Such a pattern is consistent with a potential vorticity balance where the anticyclonic vorticity that a parcel gains as it approaches a crest is offset by a decrease in upper layer thickness, which is accomplished via upwelling. For the Gulf Stream, with its steeply sloping isopycnals, upwelling is associated with the along-isopycnal ascent of the particle to the onshore side of the jet. Conversely, when a parcel approaches a trough, downwelling and offshore motion balance the increase in cyclonic vorticity. However, in an analysis of the potential vorticity terms along the path of subsurface floats released as part of the Pilot RAFOS Program, Bower (1989) did not find such a simple balance to hold. Curvature vorticity and stretching vorticity were not simply inversely proportional because of the sizeable contribution of shear vorticity to the overall potential vorticity balance.

In a further investigation of cross-stream motion for flow along isopycnals, Bower (1991) used a kinematic model to show that cross-stream motion in a meandering zonal jet is strongly related to the downstream phase propagation of the meanders. Basically, this model illustrates how a fluid parcel gains a cross-stream velocity component in the presence of a zonally propagating meander, shifting its position relative to the streamfunction field that defines the current, as shown in Fig. 2. Thus, for a parcel transiting from trough to

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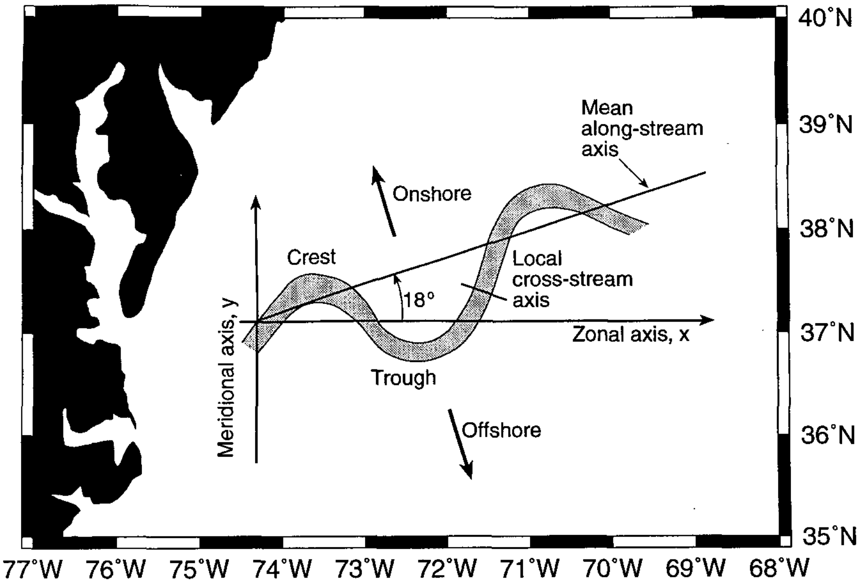

FIG. 1. Schematic of Gulf Stream (in gray shade), illustrating terms used in the text.

crest (crest to trough), a progressive wave will induce onshore (offshore) motion. The cross-stream displacement of particle trajectories relative to streamlines increases when the difference between u, the eastward speed and c_x, the meander's zonal phase speed, is small. Bower found that this model *qualitatively* reproduced many of the large-scale features of float behavior in the Gulf Stream, including the excursions across the stream between meander extrema, the entrainment and detrainment of fluid parcels near the edges, and the tendency for cross-stream displacements to be larger in the middle to lower thermocline, where u and c_x are of the same order, compared to the upper thermocline, where $u \gg c_x$.

Two recent observational studies have questioned the validity of Bower's kinematic model for describing particle motion in the Gulf Stream. In a study of vertical motion in the Gulf Stream based on current meter, IES and float data from the SYNOP experiment, Lindstrom and Watts (1994) report cases where strong vertical velocities are present as eastward-moving Gulf Stream meanders slow or become stationary. They argue that these observations directly contradict Bower's (1991) model results, which they interpret as predicting no vertical motion within a stationary meander. In a study of RAFOS floats released in the upper thermocline of the Gulf Stream, Song et al. (1995) report that some floats escape from the stream (i.e., they exhibit large cross-stream displacements) even though they apparently have large advective velocities compared to the phase speed. The authors suggest that Bower's kinematic argument cannot account for such escapes. In this paper we show how the results of Bower (1991), Lindstrom and Watts (1994), and Song et al. (1995) can be reconciled by taking a closer look at the relationship between float behavior in the Gulf Stream and meander propagation characteristics. Specifically, this paper details our efforts to quantify the relationship between propagating meanders and cross-stream motion using observational data from the Gulf Stream. This analysis is possible due to the recent work of Lee (1994), who completed a comprehensive study of meander phase speeds from digitized satellite images of the Gulf Stream's path from April 1982 to December 1989. This period includes the interval over which 37 RAFOS floats were released in the Gulf Stream as part of the RAFOS Pilot Experiment during 1984–85 (Bower et al. 1986). For this study we have matched the meander phase data to the float data for a direct comparison between meander propagation and float motion. In the next section, we present a revised and generalized kine-

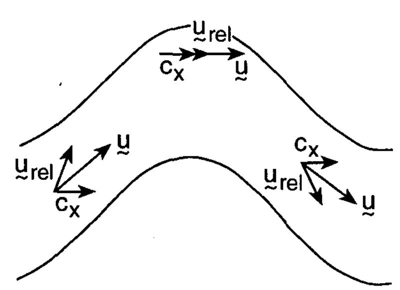

FIG. 2. Schematic of kinematic mechanism proposed by Bower (1991). The float's velocity in the stationary frame is denoted by **u**, the zonal phase speed is denoted by c_x, and the float's velocity in the moving frame is denoted by $\mathbf{u}_{\rm rel}$. Of note in this schematic is that the float velocity in the moving frame has a cross-stream component.

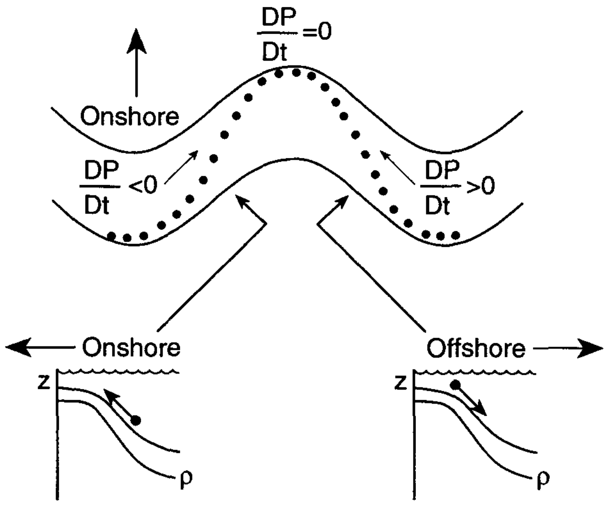

FIG. 3. Schematic of DP/Dt along the path of an isopycnal RAFOS float in the Gulf Stream. The dots indicate float positions over a series of days. The density (ρ) profile with depth (z) shows the movement of the float along the isopycnal as it traverses the stream from trough to crest (on the left) and crest to trough (on the right).

matic framework for float motion in the Gulf Stream. Data sources and methods are discussed in section 3, followed by results in section 4 and a summary in section 5.

2. The kinematic model

A characteristic signature of the isopycnal-following RAFOS floats released during both the Pilot (Bower et al. 1986) and SYNOP (Song et al. 1995) Experiments is the large pressure change along the trajectories. Bower and Rossby (1989) have attributed these pressure changes to float motion along the Gulf Stream's sharply sloping isopycnals. As a float moves from the onshore (offshore) side of the current to the offshore (onshore) side, its pressure increases (decreases), as illustrated in Fig. 3. In the development of a testable kinematic model linking meander propagation to cross-stream motion we want to take advantage of this large pressure signal, thus we diverge from Bower's strict definition of cross-stream flow as cross-*streamline* flow. Instead, we choose a framework where the isobars define the Gulf Stream and where cross-isobar flow is interpreted as cross-stream flow.

Given pressure, $P = P(x, y, \sigma, t)$, where the potential density σ serves as the vertical coordinate, the material derivative of pressure along a surface of constant potential density yields

$$DP/Dt = \partial P/\partial t + u\partial P/\partial x + v\partial P/\partial y, \qquad (1)$$

where the notation is standard. For our analysis we chose to express Eq. (1) in a coordinate system aligned with the instantaneous axis of the Gulf Stream defined by the isobars. With these assumptions Eq. (1) becomes

$$DP/Dt = \partial P/\partial t + |\mathbf{u}|\cos\theta\partial P/\partial n, \qquad (2)$$

where $\partial P/\partial n$ represents the cross-stream pressure gradient ($\mathbf{n}$ is the unit vector normal to the isobars) and $|\mathbf{u}|\cos\theta$ is the cross-stream velocity component, with $\mathbf{u}$ the total horizontal velocity vector of the float, $\mathbf{u} = (u, v)$, and θ the angle between the velocity vector and the cross-stream axis. The alongstream pressure gradient is zero by definition. In Eq. (2) it is evident that pressure changes along the path of a float result from a temporal change in the local pressure field (the isopycnal may shoal or deepen) and/or from the cross-stream advection of the parcel along a sloping isopycnal. We hypothesize that the *dominant* contributor to the first term on the right-hand side of Eq. (2) is the temporal variability created by the propagation of meanders past a fixed locale. The growth and decay of a meander, in so much as they create a shift in the front, are subsumed by this term, as will be explained further in section 4d. Thus, if we choose a reference frame moving at the speed of the meander, this first term can be combined with the second term to produce

$$DP/Dt = |\mathbf{u} - \mathbf{c}|\cos\theta\partial P/\partial n, \qquad (3)$$

where $\mathbf{c}$ is given by $\mathbf{c} = (c_x, c_y)$ and θ is now measured from the $\mathbf{u} - \mathbf{c}$ vector to the cross-stream axis, as shown in Fig. 4. In this formulation Lagrangian pressure change is a result of the cross-isobar motion in a frame moving with the meander. Unlike Bower's model where the extent of cross-streamline flow depends on the difference between the zonal velocity u and the zonal phase speed c_x, in this model the cross-isobar flow depends on the full vector relationship between $\mathbf{u}$ and $\mathbf{c}$. Another difference from Bower's model is that

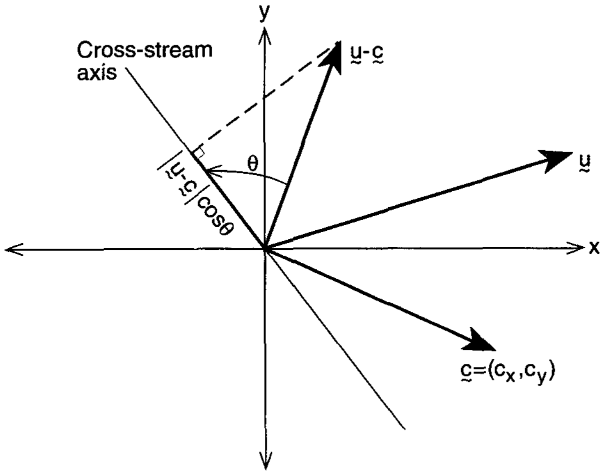

FIG. 4. Schematic of the vector relationship between **u** and **c**. Also shown is the cross-isobar component of the float velocity *relative* to the meander.

the dependence of vertical motion on meander speed is explicit with this kinematic formulation: Because pressure can be used as a proxy for depth with only minimal error ($<1\%$ at thermocline depths), the left-hand side of Eq. (1) is proportional to the vertical velocity (i.e., $-DP/Dt \sim dz/dt = w$). In the discussion to follow we will use $-DP/Dt$ interchangeably with vertical motion. Given this, we now note that nonzero vertical motions, such as those reported by Lindstrom and Watts (1994), are possible even if c is zero. This does not however, contradict the results of Bower's model, which predicts no cross-*streamline* flow when c is equal to zero. Particles may cross isobars in the presence of a stationary meander, leading to a pressure change (i.e., vertical velocity), but they will not cross instantaneous streamlines.

If meander propagation is the most important contributor to local pressure changes ($\partial P/\partial t$), the terms on the right-hand side of Eq. (3) should be a good predictor of the pressure changes following a fluid parcel. Below we use float data and estimates of phase propagation from Lee (1994) to quantitatively assess the validity of this equation. We have no estimates of $\partial P/\partial n$ along the float trajectories, but we assume that the synoptic density structure of the Gulf Stream and thus the cross-stream slope of the isopycnals varies much less than DP/Dt and $|\mathbf{u} - \mathbf{c}|\cos\theta$ (Halkin and Rossby 1985).

3. Data and methods

The float data used in this study were obtained as part of the RAFOS Pilot Program (Bower et al. 1986), conducted over the years 1984–85. Thirty-seven isopycnal RAFOS floats were launched sequentially in the main thermocline off Cape Hatteras and tracked acoustically downstream for 30 or 45 days. The data processed from these floats generated the geographical position, pressure, and temperature along the path of each float at an interval of 8 hours. Horizontal velocities were obtained from the time rate of change of position over 16 hours using a simple centered difference.

To obtain phase speed information during the time of the float deployments, we have relied on the analysis of Lee (1994), who used infrared images of the sea surface temperature from the AVHRR (Advanced Very High Resolution Radiometer) to digitize the Gulf Stream path for the period of April 1982 to December 1989, which covers the period the RAFOS Pilot floats were in the water. He chose a rectangular grid from 22° to 48°N, 76° to 45°W that covers the full latitudinal range of the Gulf Stream from its separation near Cape Hatteras to its bifurcation near the Tail of the Grand Banks. Composites were made every two days with a spatial resolution of 1 km. Using a method described by Cornillon et al. (1994) the location, wavelength, and amplitude of individual meanders were objectively determined from these composites. Both meridional and zonal phase speeds (c_y and c_x, respectively) for individual meanders were then calculated by the change in meander location from one observation to the next (i.e., over a two-day period). Further details of the dataset are contained in Lee (1994).

A major effort in determining the influence of propagating meanders on cross-isobar motion lies in establishing the phase speed of Gulf Stream meanders at the time the floats were in the water. Because the Gulf Stream at any time is characterized by a number of meanders that move at different speeds (Lee 1994), it is important that there is a spatial as well as a temporal match between the float position and a meander. To achieve this objective the location of a float was superposed on a digitized path of the Gulf Stream (from NOAA/NESDIS[1] charts of sea surface temperature) that was also marked with the positions of the meander observations that occurred within a half-day of the float observations. The match between float and phase observation was then subjectively determined based on a visual assessment of which meander the float was embedded within. If a meander could not be identified or if there was ambiguity regarding two or more meanders, no phase speed was linked to the float observation.

Once a phase speed had been identified with each float position the terms in Eq. (3) (except for $\partial P/\partial n$) could then be calculated. A central difference was used to compute DP/Dt, after the pressure record was smoothed using a five-point moving box-car filter. Such smoothing was performed to filter high-frequency noise due to small-scale oceanographic phenomena such as internal and inertial waves. In doing so, the timescale of the pressure record is put on par with the observed timescales of the phase data. Without such smoothing, incompatible timescales for float and phase events would result. Smoothing necessarily decreases the magnitude of DP/Dt; with the smoothing applied in this study the magnitudes for DP/Dt are generally on the order of 20% lower than the unsmoothed magnitudes. Because we essentially want the average change over a two-day phase observation, it is more appropriate to use the smoothed values.

In the computation of the term on the right-hand side of Eq. (3), a coordinate system was defined in order to evaluate the cross-stream components. From each satellite image of the Gulf Stream a cross-stream axis was defined at the location of the float. This axis was chosen such that the gradient of the surface isotherms defining the stream was maximized. [With this definition we are assuming that the surface thermal pattern is a good indicator of the subsurface current, in accordance with the work of Cornillon and Watts (1987) and Song et al. (1995).] The velocity vector and phase

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[1] National Oceanic and Atmospheric Administration/National Environmental Satellite Data Information Service.

vector were mapped with their terminus at the float location. The vector $\mathbf{u} - \mathbf{c}$ was computed from the observed zonal and meridional components of **u** and **c** and then mapped onto the local cross-stream axis, as shown in Fig. 4. In sum, for each float location, the quantities DP/Dt and $|\mathbf{u} - \mathbf{c}| \cos\theta$ were computed from the combination of float data, phase speed data, and digitized images of the Gulf Stream path.

4. Results

a. Time series of Lagrangian pressure change and phase speed

Time series of $|\mathbf{c}|(t)$ and $DP/Dt(t)$ were constructed to document the relationship between phase propagation and cross-isobar motion. From the pool of 37 floats, 9 float trajectories with almost complete time series for both the float and phase data were recovered. This small recovery is due in part to the gaps created in the phase data by cloud cover, but also due to gaps in float data. Some float records were too short to be used (we wanted to see how a float responded to changes in the phase speed over time), some floats had recorded no pressure information, and others had little or no tracking information. Time series for representative floats are shown in Fig. 5. There is an obvious difference in the continuity of $|\mathbf{c}|(t)$ and $DP/Dt(t)$. The Lagrangian pressure change varies uniformly with time as the parcel moves smoothly back and forth across the stream, as schematically represented in Fig. 3. However, because a float stays within a single meander (characterized with the same phase speed) for several days, the changes in phase speed along the float path occur stepwise rather than uniformly. At the depth of the main thermocline the wave period of the meanders (~30–45 days) that populate the Gulf Stream exceeds the advective timescale (~5 days) for a float to move through a meander. Thus, a single phase speed is associated with a float over a period of several days. For the purpose of our discussion here the duration of time for which a float is associated with the same phase speed is referred to as a phase event. Generally, phase events change for two reasons: Either the float moves out of one meander and into another (that is moving at a different speed) or a meander significantly accelerates or decelerates. Thus, the length of phase events varies, according to the speed of the float as it travels through the meanders and according to the timescale for the acceleration or deceleration of a meander. The combination of these effects yield phase events that last on average 5 days.

In Fig. 5a the pressure changes for RAFOS 008 for a 25-day period are shown in tandem with the associated phase events. Overall, the sign of the pressure changes from crest to trough, and from trough to crest, are as documented by Bower and Rossby (1989) and repeated here: The float experiences negative pressure change from trough to crest, positive change from crest to trough and negligible pressure change in the meander extrema. However, the *amplitude* of these pressure changes is variable and appears to be correlated with the meander phase speed, as seen in Fig. 5a. From day 132 to day 139 the phase speed is between 3–5 cm s^{-1} and the float generally has small amplitude pressure changes. At day 139 a large phase speed event passes through and the float responds with an increase in the magnitude of its pressure change. Near day 145 the phase speed drops to nearly zero and the associated pressure changes are also nearly zero over a 3-day period. The pressure change increases when a larger phase speed occurs at approximately day 149. Finally, it is unclear what the pressure response is to the phase event starting on day 154 due to the termination of the record. From this 25-day float record, it is apparent that the amplitude of pressure changes generally increases in response to large phase speeds. RAFOS 015 exhibits a similar pattern (Fig. 5b). The largest observed pressure changes occur when the phase speeds are approximately 27 and 35 cm s^{-1} during days 117–120 and 123–128, respectively. Conversely, small pressure changes are present when the phase speeds are much reduced. An exception is the large pressure change centered on day 111 when a small phase speed is present (<10 cm s^{-1}). RAFOS 024 also clearly illustrates this qualitative dependence of the pressure changes on the magnitude of the phase speed (Fig. 5c). Initially the float experiences large pressure changes that decrease in amplitude as the phase speed decreases near day 341. When the phase speed drops to approximately 6 cm s^{-1} the pressure change becomes negligible on this scale. The float's pressure change clearly responds to the new phase event with its associated larger phase speed near day 349.

b. Dependence of Lagrangian pressure change on phase speed

A simple quantification of the relationship that appears to exist between phase speed and pressure change (from the time series of Fig. 5) would be the linear correlation between these two variables. However, for a constant phase speed the Lagrangian pressure change varies as a float travels from crest to trough and back again to a crest. Thus, a single phase speed would be associated with negative, positive, and zero pressure changes. To bypass this difficulty and to allow for independent realizations, we have chosen to find the correlation between phase speed and pressure change using only one observation during each defined phase event. (The reader is reminded that a phase event lasting five days will have 15 observations of vertical velocity, since the floats are fixed every 8 h.) To best indicate the amplitude of the pressure changes, the pressure change with the largest magnitude during each phase event was chosen to be compared to the phase speed of the event.

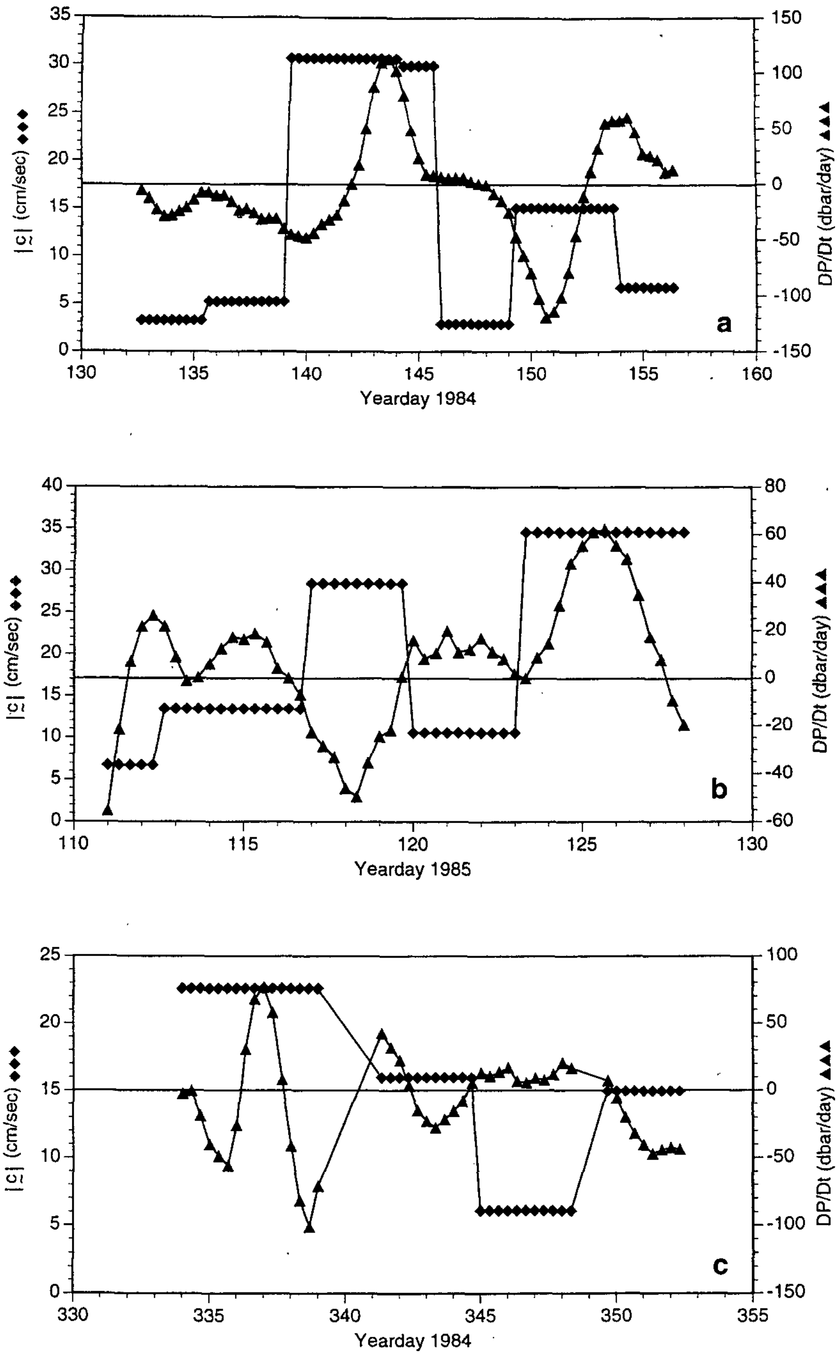

FIG. 5. Time series of |c| and *DP/Dt* for (a) RAFOS 008, (b) RAFOS 015, and (c) RAFOS 024.

From the 9 floats used in the study 32 phase events were identified. To ensure that a float was clearly within a given phase event rather than transitioning between two events, each event was windowed at the beginning and end by 1 day (3 data points) before selecting the maximum pressure change. We required a phase event to span at least 1 day after the windowing, thus phase events were selected if there were 9 or more float data points in the event. Thus, short-lived events, such as the first event in the record of RAFOS 015 and the last event of record RAFOS 008 were excluded from this portion of our study. From the windowed phase events, the pressure change with the largest magnitude was selected and correlated with the phase

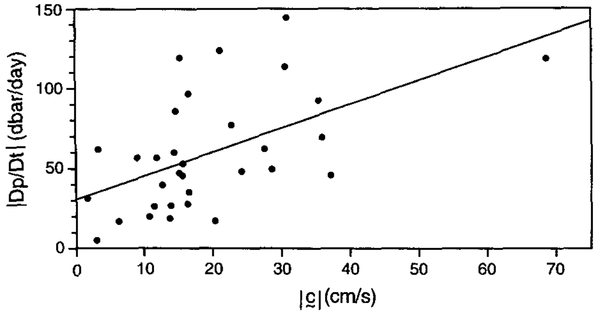

FIG. 6. Plot of $|DP/Dt|_{\max}$ as a function of $|\mathbf{c}|$ for 32 identifiable phase events.

speed, as shown in Fig. 6. A general trend for larger phase speeds to be associated with larger amplitude Lagrangian pressure changes is evident, however, the linear correlation coefficient is only .539. While it is apparent that large phase speeds generally have large pressure changes, pressure changes are not necessarily small when the phase speed is small. In fact, sizable pressure changes are seen to occur for quite small phase speeds, in agreement with the Lindstrom and Watts (1994) observation that strong vertical motions can be found in the presence of stationary meanders. Likewise, weak vertical motions are also found in the presence of nearly stationary meanders. This case is exemplified by three events in Fig. 5 (days 146–148 for RAFOS 008, days 120–124 for RAFOS 015, and days 345–349 for RAFOS 024), where the phase speed is small (<5 cm s^{-1}) and the corresponding pressure changes are nearly zero. Clearly, the results of this subsection confirm that the vertical motion is not completely set by the *magnitude* of the meander phase speed, in agreement with Eq. (3).

c. Dependence of Lagrangian pressure change on cross-isobar flow

To test whether cross-isobar motion in a frame moving with a Gulf Stream meander is strongly correlated with vertical motion, $DP/Dt_{\max}$ is plotted as a function of $|\mathbf{u} - \mathbf{c}|\cos\theta$, in Fig. 7. The sense of direction is such that a positive $|\mathbf{u} - \mathbf{c}|\cos\theta$ is assigned to the onshore component of the cross-isobar velocity and a negative value is assigned to the seaward component. In all but one of the 32 cases the signs are consistent, with pressure increasing as the float moves offshore and pressure decreasing as the float moves onshore. A least squares regression analysis of this data results in a correlation coefficient of .902, establishing the validity of Eq. (3) in describing float motion in the Gulf Stream: Vertical motion, indicated by pressure changes along a float's path, depends on the magnitude of $\mathbf{u} - \mathbf{c}$ and on this vector's orientation to the cross-stream axis. There are enough degrees of freedom in Eq. (3) to preclude a simple generalization of vertical motion based on either the float or phase speed.

The scatter of the points around the line in Fig. 7 can be attributed to several causes. These include the error involved in identifying the appropriate phase event, in measuring the phase speed, in determining stream direction and in selecting the maximum pressure change. Additionally, temporal changes in the pressure field, besides those caused by the displacement of the meander, may create local pressure changes. Finally, errors may be introduced if the cross-stream pressure gradient is not constant along or across stream. An examination of a Gulf Stream cross-sectional temperature profile derived from the Pegasus data taken near 73°W (Halkin and Rossby 1985) reveals that the slope of the 12°C isotherm (the target isotherm for these floats) can vary by a factor of 2 depending upon the float's position relative to the stream's center.

d. The contribution of meander growth and decay toward cross-isobar motion

In the development of Eq. (3) it was assumed that the temporal variability of the Gulf Stream's pressure field is dominated by the propagation of meanders. In fact, the decay and growth of meanders also contributes to the stream's variability and, as documented by Song and Rossby (1995), contributes to the displacement of the SYNOP floats across the Gulf Stream. Our analysis of the Pilot Experiment floats confirms this observation: Floats are entrained or detrained as a meander's amplitude changes. Amplitude changes in the Gulf Stream are manifested by a meridional shift in crests and troughs of the Gulf Stream. Temporal changes in the meridional position of a meander have been assigned meridional phase speeds by Lee (1994) so that the speed of growth or decay of a meander is represented by a meridionally propagating phase meander. For the kinematic model developed here this representation is sufficient. Although the dynamics of a growing or decaying wave are different from those of a periodic wave, they have a kinematic equivalence. A nonzero c_y, whether created by the growth or decay of the front or by the lateral

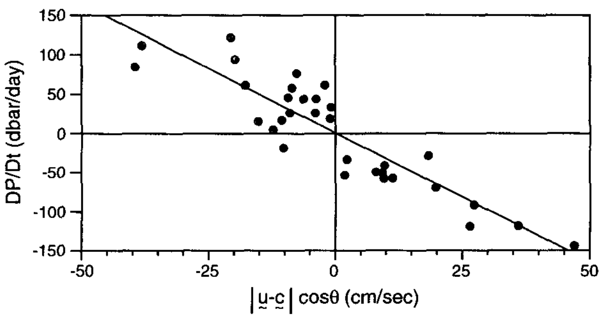

FIG. 7. Plot of $DP/Dt_{\max}$ as a function of $|\mathbf{u} - \mathbf{c}|\cos\theta$ for 32 identifiable phase events. The linear correlation coefficient is .902.

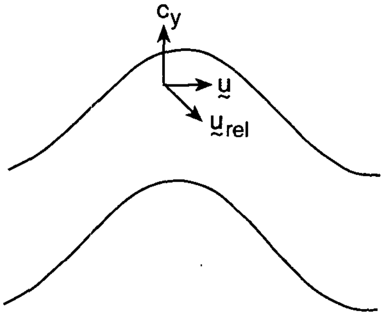

FIG. 8. Schematic of the kinematic mechanism considering a meridional phase speed only. The float's velocity in the stationary frame is denoted by **u**, the meridional phase speed is denoted by c_y, and the float's velocity in the moving frame is denoted by $\mathbf{u}_{\text{rel}}$.

displacement of the front, effectively creates a cross-stream displacement of the float, as illustrated in Fig. 8.

The inclusion of c_y along with c_x in our model is not academic. Shown in Fig. 9 is a comparison between the orthogonal components of the phase vector for an axis aligned with the long-term mean path of the Gulf Stream, which has been estimated by Lee to be positioned 18° to the north of east. From this plot it is evident that the cross-axis component $c_{y'}$ can be comparable in magnitude and at times larger than the along-axis component $c_{x'}$, and thus any attempt at quantifying the role of propagation on the float's motion relative to the meander must include its effect. If we had ignored the contribution of the meridional phase propagation Eq. (3) would be modified as

$$DP/Dt = [(u - c_x)^2 + v^2]^{1/2} \cos\theta \partial P/\partial n, \quad (4)$$

where now only the zonal component of the phase speed has been considered. As shown in Fig. 10, the Lagrangian pressure change is not as strongly related to the cross-isobar motion when c_y is excluded. The correlation coefficient from a linear regression analysis drops to .80 for this case, but perhaps more importantly there are several instances where the pressure change is not consistent with the inferred cross-stream direction of the float. Including the cross-stream component corrects the sign of the cross-stream velocity, validating the need to generalize the kinematic model.

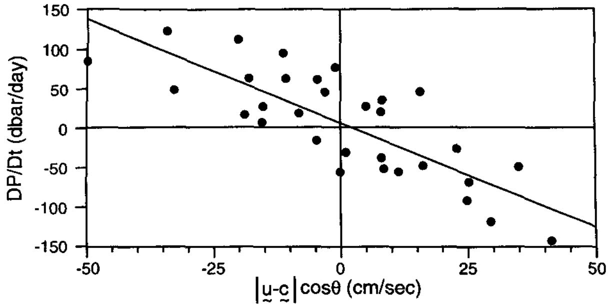

FIG. 10. As for Fig. 6 except for the exclusion of c_y. The linear correlation coefficient is .80 for this case.

Finally, the observation by Song et al. (1995) that floats escape from the Gulf Stream in spite of differences in u and c_x, is compatible with the kinematic framework presented here: Large pressure changes (which are generally associated with float escape to either side of the stream) are possible with a large $u - c_x$ because of the contribution of the meridional components of both the float and the phase velocity.

5. Summary

A kinematic model has been developed to explain the pattern of float excursions in the Gulf Stream. The model equates Lagrangian pressure change with cross-isobar motion in a reference frame moving with a propagating meander. The model differs from Bower's in that cross-isobar flow is diagnosed rather than cross-

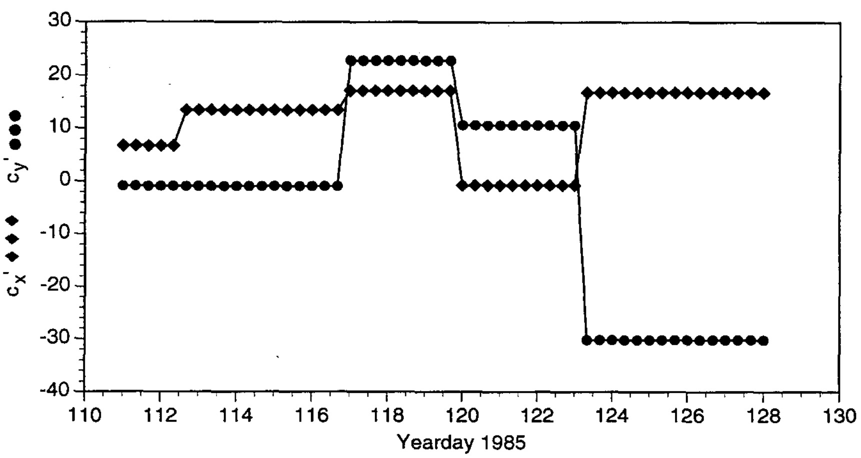

FIG. 9. Time series of $c_{x'}$ and $c_{y'}$ for RAFOS 015.

streamline flow. Casting the kinematics in terms of the pressure field along an isopycnal allows for a comparison between cross-isobar flow and vertical velocity and it allows for the model to be tested using the significant pressure signals along RAFOS pathways. This model also diverges from Bower's in that it generalizes the phase propagation to include the meridional component. An argument is made that this inclusion is adequate to kinematically model the effect that growing and decaying meanders have on the lateral displacement of a float.

From an analysis of float tracks and meander phase speeds the pressure changes along a float's path were shown to increase or decrease in amplitude in response to a change in the phase speed of a local meander. Generally, larger phase speeds increase the amplitude of the Lagrangian pressure changes. However, it was shown that it is not the magnitude of the phase speed that determines the extent of cross-stream motion, but the magnitude of the vector, $\mathbf{u} - \mathbf{c}$, and its orientation to the cross-stream axis. Thus, a measurable vertical velocity within a stationary meander is compatible with this kinematic mechanism, indicating that there is a sizeable cross-isobar advection created by the local dynamics of the stream.

Overall, meander propagation in the Gulf Stream affects cross-stream motion, yielding a pattern of periodic pressure changes along the path of RAFOS floats. The kinematic model presented in this paper successfully accounts for these observed pressure changes. The fact that the pattern of cross-stream exchange can generally be accounted for by the kinematics of the flow field, raises the interesting question as to whether the methods used in this work might be used to diagnose cross-frontal exchange across other midocean or coastal fronts.

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