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A Simple Kinematic Mechanism for Mixing Fluid Parcels Across a Meandering Jet

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Introduction

Recent observations of fluid parcel pathways in the Gulf Stream based on isopycnal RAFOS float trajectories have revealed a striking pattern of vertical and cross-stream motion which is closely linked to the meandering of the jet. Floats consistently upwell and cross the jet from right to left (looking downstream) between meander troughs and crests, and downwell and cross from left to right between crests and troughs. Cross-stream displacements away from the jet axis on the order of +/- 20 km are common as the floats travel between meander extrema, and sometimes floats cross out of the current altogether. Analysis of the trajectories suggests that: 1) fluid is most often lost from the current at the trailing edges of meander troughs and crests, while entrainment takes place primarily at the leading edges of meander crests; 2) exchange occurs much more readily in the lower main thermocline than in the upper layers; and 3) cross-stream motions and entrainment and detrainment of fluid are enhanced when the curvature of the Gulf Stream path is very large (see Bower and Rossby, 1989, for details). This note briefly describes a simple mechanism for fluid exchange in the Gulf Stream region which appears to reproduce many of the lagrangian observations. A kinematic, two-dimensional model of a

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Modelling the Gulf Stream: What Next?

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In most of science, observation leads theory. While there are spectacular exceptions, including Stommel's (1957) prediction of a Deep Western Boundary Current, it is usually the case that major new observations provoke strong challenges to traditional theory or models and motivate new theoretical advances. With the conclusion of the field components of SYNOP and REX, as well as the "expiration" of GEOSAT, models of the Gulf Stream will be pushed hard to accomodate the new data. They will be tested against these data in ways only discussed in hypothetical terms up till now. Expectations are high for these models, even to the point of using them for routine predictions of Gulf Stream evolution. Are these expectations warranted? Are we too optimistic?

Models of the Gulf Stream have become sufficiently realistic so that observationalists actually bother to compare model "data" with their own field results. The pioneering studies of Holland and Schmitz in the early 1980's (e.g. Schmitz and Holland, 1982), using fairly idealized domains and forcing functions, began this process and have led to comparisons with more realistic geometries and forcings in eddy resolving models. These comparisons have gone beyond evaluation of low order statistics in roughly comparable geographical locations between model and ocean. For example, in a recent paper (Thompson and Schmitz, 1989) model/data intercomparisons were attempted in specific geographical

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Prediction of the Gulf Stream Path from Upstream Parameters

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In this short note, we want to describe how a Wiener (least squares optimal) filter using upstream conditions as inputs can forecast the Gulf Stream path in the region between Cape Hatteras and 71 W. Tests on ('old') 1983-1985 IES data have been very encouraging. Using the upstream position as an input, the adaptive Weiner filter can forecast up to 8 days ahead the path position 140 km downstream of the Inlet, and up to 20 days ahead at 240 km downstream, (figure 1). In order to be brief, we will give a basic description of how to construct and implement the filter in forecast mode. More details will follow soon (hopefully) in a refereed journal article.

A Weiner filter assumes that the variability in the output depends on the variability of the input. Mathematically the dependence can be written as a convolution between time lagged weights and the input time series, so that if $\widehat{y(t+m)}$ using upstream conditions as inputs is the forecasted downstream displacement and **x(t)** is the vector containing the Inlet parameter time series (e.g. position as component 1, angle as component 2...), then,

$$\widehat{y(t+m)} = \sum_{i=0}^{p} \mathbf{h}_i \mathbf{x}(t - i) \qquad (1)$$

where $\mathbf{h}_i$ is the row vector of weights for each parameter at time lag i. Equation 1 is the filter. We don't expect to predict the long term variability, therefore the filter length of $m + p$ time units might span only 1-1.5 months Also, since the highest meander frequency is about (4 days)$^{-1}$, using a sample rate higher than this in the convolution provides redundant information. Therefore if only one Inlet parameter is used, equation 1 is a summation of maybe 5 terms.

The weights are determined by minimizing the mean square error of the filter output and the observed forward time lagged downstream displacement, $y(t+m)$:

$$\frac{\partial}{\partial h_i}\left\langle\left[\widehat{y(t+m)} - y(t+m)\right]^2\right\rangle = 0 \qquad (2)$$

This gives a linear relationship between the autocorrelation matrix of the Inlet parameter(s) and the cross-correlation between the forward lagged downstream displacement and past and present Inlet parameter(s).

$$\langle \mathbf{xx} \rangle \mathbf{h} = \langle \mathbf{xy} \rangle \qquad (3)$$

Assuming the autocorrelation matrix is nonsingular, equation 3 can be solved
for the weights.

First, in order to eliminate biases in the correlations due to trends, a 120 day high pass filter should be run on the upstream parameter(s) and downstream displacement. This will separate the data into the low and high frequency components. For each day, the weights can be found from equation 3 using correlations of the past 4-5 months of the high passed data. The weights are then convolved to the high passed Inlet data according to equation 1 to get the forecasted downstream displacement. To get the forecasted downstream position, the present low frequency component (our pseudo-mean) must be added to the forecasted displacement.

A prediction scheme such as this which is based entirely on upstream conditions will fail downstream of 71°W where ring-stream interactions effect the path. However it appears to do remarkably well, better than persistence, in the region between Cape Hatteras and 71°W. Figure 1 shows the observed Inlet position time series, in the upper plot. The high passed Inlet position was used to forecast 8 days ahead the path position 140 km from the Inlet (middle plot) and 20 days ahead at 240 km (bottom plot). The dashed lines are the forecasts and the solid lines are the observed path positions. The rms error of the 8 day forecast at 140 km is ~11 km and for the 20 day forecast at 240 km, the rms error is ~20 km.

We would like to emphasize that this is a very simple, but effective prediction scheme in the region between 74°W and 71°W. With telemetry IESs and/or satellites providing path information, this forecast filter could be run real time.

XBT Systematic Depth Error and Correction

Randy Watts, Kifayath Mohammed, and Erik Fields

Tom Rossby noted on one of the "Anatomy of a Meander" cruises that Sippican T-7 XBT's were producing roughly 5 - 6% shallower depths compared to some corresponding CTD depth profiles. We were quite concerned, since such an error could cause the thermocline depths to appear 30 - 40 m too shallow, and it would affect all our IES calibrations against XBT's.

XBT's give a T(z) profile. The temperature measurement comes from a thermistor (quoted accuracy +/- 0.2°C) on the probe. The depth is determined from the time interval after the probe first hits the water. Depth errors would arise from fall rate errors, which in turn might be temperature (viscosity) dependent. The latter suggestion arises because in the estimated Reynold's number range for the falling probe, the boundary layer may be near transition to turbulent flow and the drag might be sensitive to viscosity and hence temperature(Seaver and Kuleshov, 1982).

Several other scientists have reported earlier testing of XBT accuracy, (Heinmiller et al., 1983 ; Flierl and Robinson, 1977; Hanawa and Yoritaka, 1987) in which they found depth errors more typically around 2 - 3% shallow, which might be regionally dependent if the fall-rate really turns out to be temperature sensitive. One of our additional concerns was whether new XBT's might might be from a slightly different mold or otherwise fall differently than earlier batches. Sippican could not provide new information on fall rates.

We decided to try to resolve the question better on our August-Sept. 1989 SYNOP cruise aboard R/V Oceanus. We compared 36 XBT's against CTD profiles. The CTD was raised and lowered ("YO-YO'd") to coincide with each XBT drop. Each XBT was dropped about midway through the CTD profile to optimize the simultaneity of the measurements. To test for temperature dependent fall rate the work was conducted at seven stations, spanning from the Slope Water side to the Sargasso. Of the 36 XBT's 24 were new and 12 were from a 4-year old batch that Peter Cornillon provided. The different XBT's would be used to examine the possibility that fall rate may vary with production batch.

We used a Sea Bird CTD lent to us by Elijah Swift. The CTD was limited to 600 dbar depth; we post-calibrated its temperature and pressure sensors and found they had not changed (< 0.01C, and < 0.07 dbar) from the previous calibration. The XBT system was a Sippican MK9 deck unit connected to a PC data logger. The calibration of the MK9 resistance bridge was verified early, mid-way, and late in the cruise against precision resistors in the Sippican Model A4 test box. (We did not check the MK9's time base, on the assumption that a crystal-controlled unit inside a controlled temperature and humidity lab has time base specifications far better than the 2 - 6% depth error that we were concerned about.) All depth corrections listed in the following are relative to the recommended formula for z(t-to) in the Sippican MK9 manual, where "t" is time and "to" is the start of the drop.

The CTD pressures were converted to depths using Fofonoff's algorithm, ZETA(P, GLAT), that ignores dynamic height anomaly. CTD and XBT profiles were spline interpolated (without smoothing) and slightly subsampled to vertical intervals of 1.0 m for further comparisons.

In comparing the T(z) profile from an XBT with that from a CTD, it was important to us to distinguish offsets due to temperature measurement errors from those due to depth errors. We identified the depths at which prominent features were found in each profile. To focus on depth measurement differences, the derivative T(z) = dT/dz was calculated and plotted for each profile. In this way we traced corresponding peaks in CTD and XBT gradient profiles, using only those that clearly corresponded to the same ocean features in the profiles, rather than noise. Figure 1 shows the 125 pairs, (Zxbt,Zctd). A linear regression fit is very good:

$$Z_{true} = (1.045 \pm 0.004) * Z_{xbt} + 0.0$$

The intercept is indistinguishable from 0.0, and there are no statistically significant quadratic or higher order polynomial coefficients. The r.m.s. difference of the points from this straight line is 6 m. There was no difference in this result between the new and the 4-year old batch of XBTs. We have not noted a difference in this correction factor between Slope-ward vs. Sargasso-ward (i.e., colder vs. warmer) profiles. Our conclusion is to stretch our XBT depths uniformly by 4.5%. It should be noted that this correction is twice the stated depth accuracy (+/- 2%). Not only that it appears to be an error that has been present for quite a long time. For many obvious reasons it is important that the chronology of this offset be established.

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XBTs, Density and Tau

T. Rossby, URI

The T/S diagram is a compact yet powerful tool for displaying hydrostation data. Where the T/S curve is well-defined, it provides a quick check that the cast is consistent with past observations. In frontal regions where different water masses are brought into close proximity, the T/S diagram reveals complex distributions as the waters are stirred together. Thus, substantial inversions in temperature and salinity can occur as layers from one water mass penetrate into the other. Figure 1 shows a temperature and salinity section across the Gulf Stream this past January. Near 50 km there is a large inversion due to the presence of slope waters near the north wall. Temperature is not a monotonic function of depth. Inspection of T/S curves from the Gulf Stream show that for Sargasso waters salinity is well defined for temperatures below 18 ^{o}C, whereas on the slope water side the upper limit is about 11 ^{o}C (or 14 ^{o}C by late summer). However, in terms of vertical distance, the breakdown of the T/S relationship is actually quite modest and limited to the top 200 meters, which are subject to seasonal weathering (apart from downwelling by the Stream).

XBT data constitute by far the bulk of in situ observations of the Gulf Stream. They are used to locate the position and course of the Stream, and where the T/S relationship is tight they can be used to compute density and vertical shear, and summaries of thermocline depth

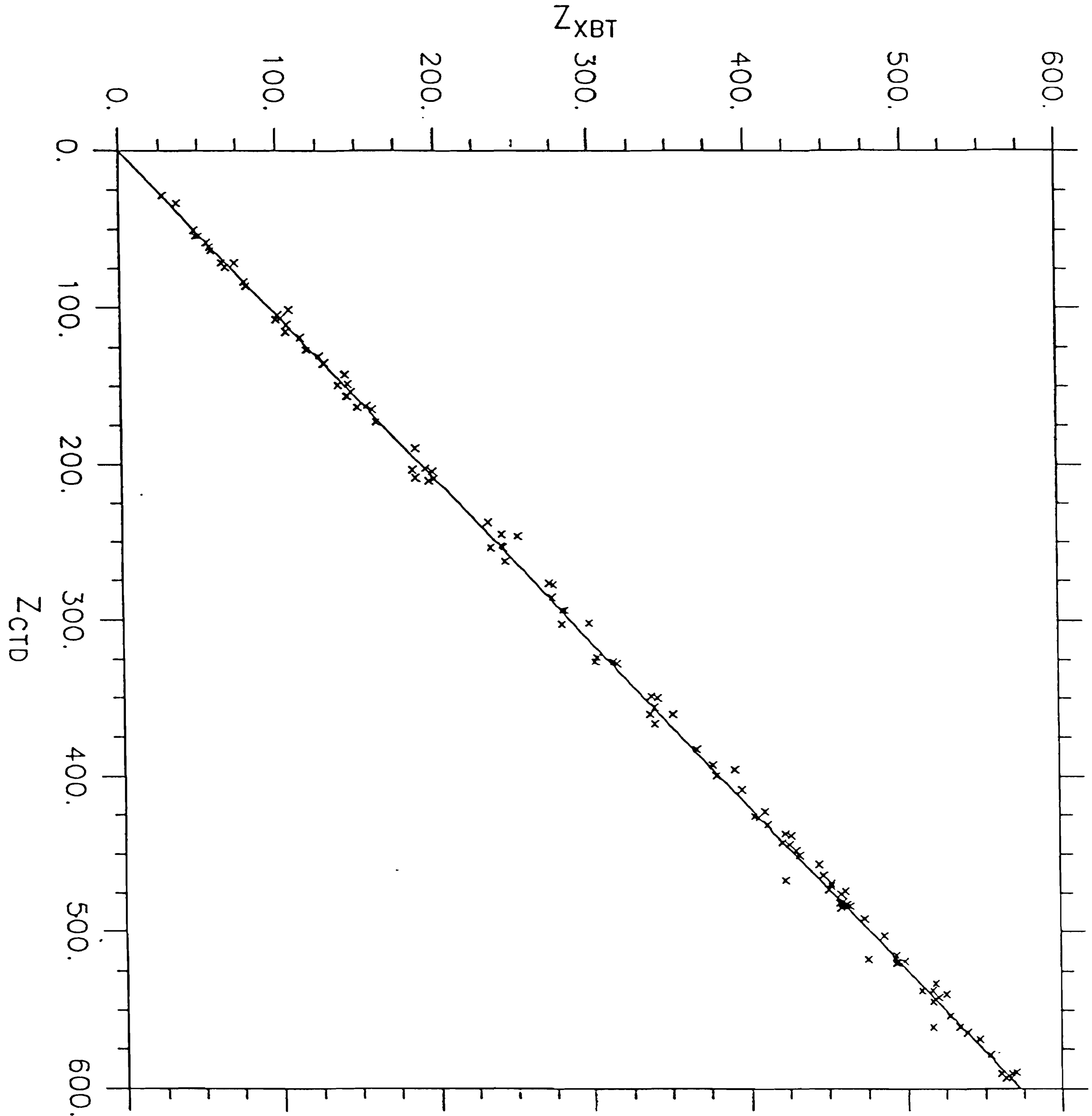

Figure 1: Regression plot using 125 Z_{XBT}, Z_{CTD} pairs. The resulting equation is

$$Z_{CTD} = (1.045 +/- 0.004) * Z_{XBT} + 0.0$$