Processes Coupling the Upper and Deep Ocean on the Continental Slope

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LONG-TERM GOALS

We seek to understand the physics of vertical coupling in ocean processes over topography.

OBJECTIVES

We wish to conduct a comprehensive investigation of the dynamical mechanisms of vertical coupling over topography. We seek a realistic characterization the observed potential vorticity (PV) distribution on density layers across the Gulf Stream. We wish to conduct new analyses on existing data to determine the vertical and lateral structure of topographic Rossby waves (TRWs) and to resolve their temporally evolving frequencies. We seek evidence of vertical coupling between the upper and lower layers, including an hypothesized feedback loop in which (a) TRWs near Cape Hatteras trigger meanders in the upper layer jet, which (b) propagate and grow to form steep troughs and rings farther downstream, and (c) in turn radiate new TRWs, that (d) propagate back to Cape Hatteras. We wish to test the degree to which model dynamics can account for the observed TRW characteristics.

APPROACH

Our studies on this project have proceeded through a sequence of steps, combining analyses of existing observations with theoretical and numerical modeling studies. This three-pronged approach has required a combination of expertise from R. Watts, G. Sutyrin, and I. Ginis (who have a coordinated ONR-supported study at URI) in a true collaboration of efforts. A graduate student, O. Logoutov, facilitates this collaboration by working jointly with all three scientists. This integrated approach has been designed to overcome the deficiencies in individual approaches to study vertical coupling processes.

WORK COMPLETED

We submitted a journal article (Logoutov et al. 1999) that develops a PV-gradient model of the Gulf Stream. The model was based on the Johns (1984) unique set of highly resolved observations that included synoptic density measurements from closely-spaced CTDs and absolute velocity measurements obtained with Pegasus (Figure 1). The PV-gradient model (PVG model) inverted the observed PV structure to generate the velocity fields by solving an elliptic problem. The corresponding inversion to find the density fields used geostrophic balance.

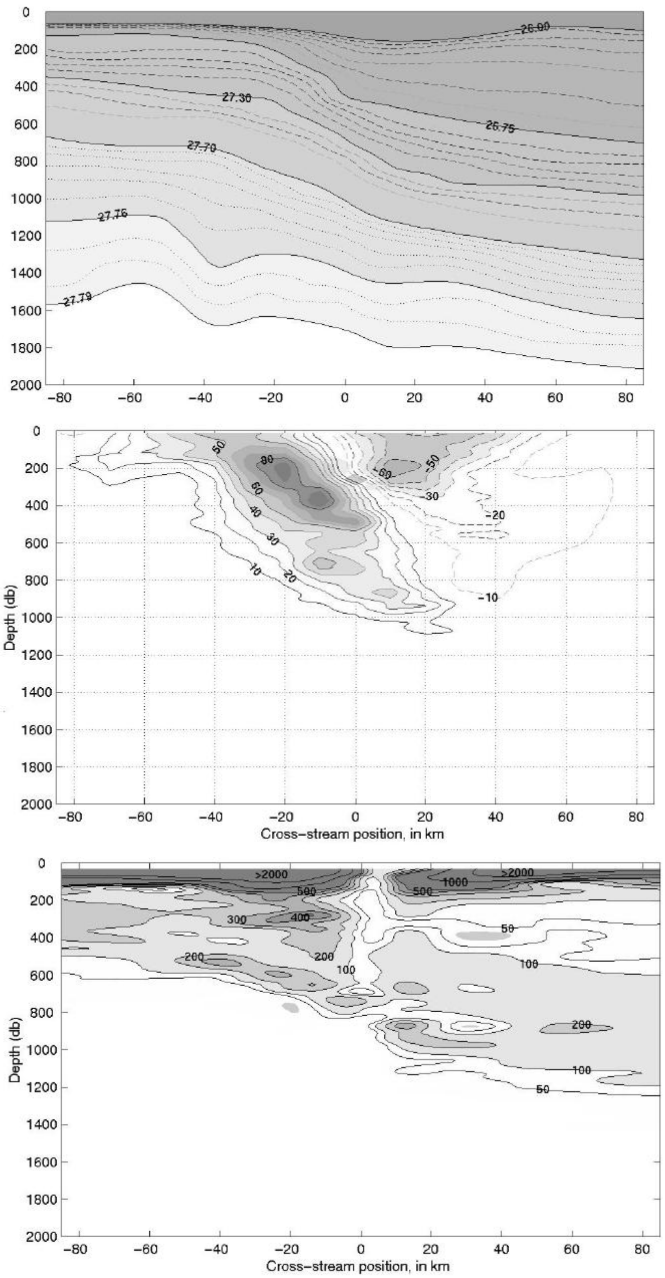

Figure 1. (top) Potential density σ_θ across the Gulf Stream from the Johns (1984) CTD-Pegasus transect off Cape Hatteras. Solid lines separate density layers in the PVG-model. Contour interval is 0.1 for dashed lines and 0.01 for dotted lines. (middle) Relative vorticity excluding only the $-\rho^{-1} f \cdot \partial\sigma_\theta / \partial z$ of the Ertel PV expression, expressed in percent of planetary vorticity. (bottom) Total Ertel PV (units of 10^{12} m^{-1} s^{-1}).

We examined the available current meter data to determine the abyssal topographic wave properties at subinertial frequencies on the continental slope near Cape Hatteras. We conducted numerical studies of the modal structure of the TRWs over topography, which included realistic stratification in both 1- and 2-dimensional problems.

We have examined the available datasets for correlations between TRW signals and meandering of the upper-layer Gulf Stream jet. Specifically, we looked to see whether the TRW signals in current meter datasets off Cape Hatteras were either preceded by large meandering events farther downstream or followed by new meanders in the path of the Gulf Stream.

RESULTS

We found that inverting a simple idealization of the potential vorticity structure across the front could reproduce many characteristic features of the Gulf Stream velocity structure. Specifically, we found that potential vorticity gradients (PVG) needed to be specified in only three layers of the six-layer model in order to capture most of the observed velocity and density structure. This "3-PVG-layer" representation, shown in Figure 2, has a strong positive PV gradient in the 18C-water layer, plus a weak positive PVG in the upper main thermocline and a weak negative PVG in the lower main thermocline. The associated velocity structure, also shown in Figure 2, captures the core velocity throughout the upper main thermocline as well as the width, the vertical tilt, and the asymmetry of the flow with higher lateral shear on the cyclonic side. A simpler 1-PVG-layer approximation captured many of these features also, although the velocities at all levels were smoother.

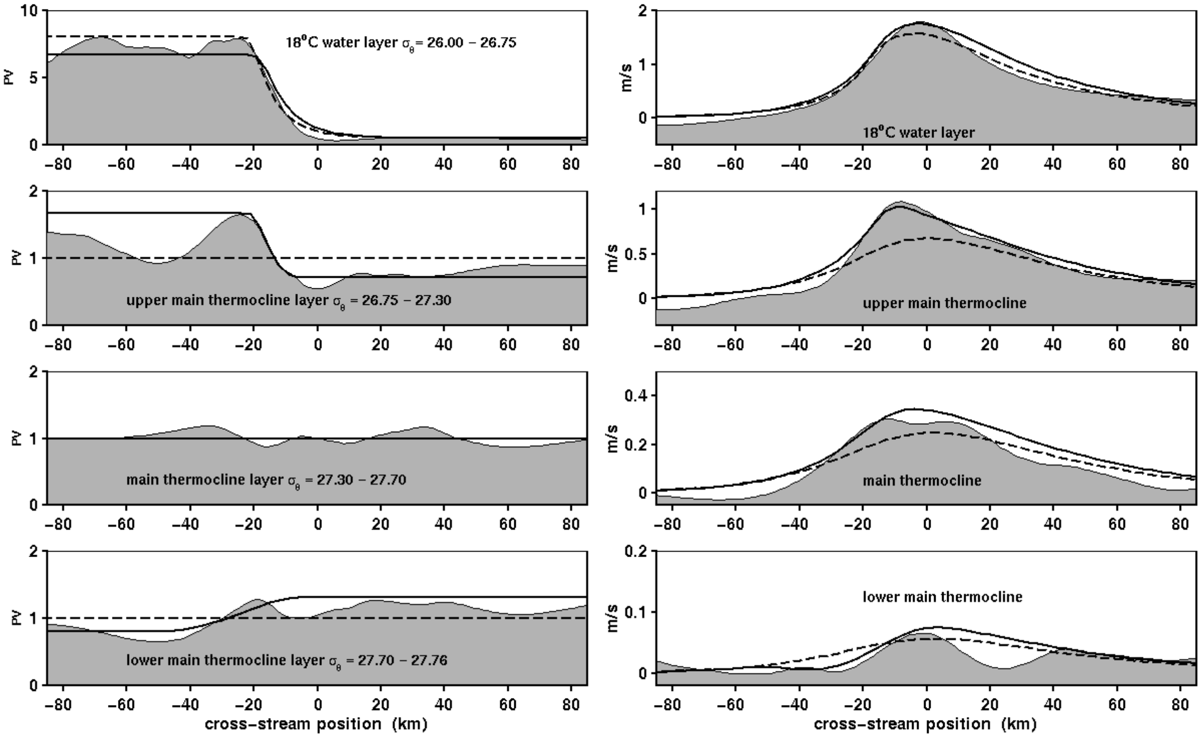

Figure 2. (left panels) Layer PV normalized by D_i/f, where D_i is the average thickness of a layer. (right panels) Observed and model velocities in density layers. In all frames, filled portions indicate the observed PV for the density field shown in Figure 1 and the observed baroclinic velocity, solid lines indicate 3-PVG-layer approximation and the corresponding velocities, and dashed lines show the 1-PVG-layer approximation and the corresponding velocities.

Previous theoretical studies of TRWs (Rhines 1970) have used a constant Brunt-Vaisala frequency (N) and found that the resulting current structure is nearly barotropic, bottom-intensified, and topographically controlled over sloping-bottom topography. We introduced realistic stratification to the problem, allowing N to vary with depth, which resulted in the sloping-bottom modes being no longer orthogonal. In particular, non-zero correlation was found between the quasi-barotropic and baroclinic modes, thus allowing dynamical coupling between them. Just as in the constant N case, we found that the barotropic mode over a sloping bottom became bottom-intensified. However, with the inclusion of the realistic stratification, we could also examine the baroclinic modes. We found these modes effectively escape the topographic control by shifting their deepest node to the sea floor, thus becoming "bottom-damped."

We have also solved the corresponding two-dimensional problem, in which a mean baroclinic flow is geostrophically balanced with the density structure over topography. Thus in this problem, the N profile varies laterally. While our analysis used the approach of Kontoyiannis (1997), we examined both the stable and unstable modes. We found both a topographic class and a mean-flow trapped class of waves. Although we found differing dispersion characteristics for the two classes of waves, Malanotte-Rizzoli et al. (1995) discuss the possible vertical coupling between the two modes when a third dimension is added to the problem.

We found observational evidence supporting the linkage between the upper and lower variability. We identified time periods during which meandering events in the SST front determined from AVHRR data over an 800 km path-segment were associated with pulses in the deep along-shore currents off Cape Hatteras. Some of the deep current bursts were followed by southerly displacements in the SST paths near Cape Hatteras. These meanders were observed to propagate downstream, where they sometimes stalled, developed into steep troughs, and formed rings. After these strong meandering events, bursts of TRW energy were observed in the deep currents back at Cape Hatteras about one month later. These data suggest a "feedback loop" whereby TRWs are generated downstream under steep meanders and propagate back to Cape Hatteras, where they trigger new meanders that in turn propagate downstream, grow steep, and generate more TRWs.

The mechanism of coupling can be motivated dynamically from the vertical stretching exerted upon the upper layer jet by the quasi-barotropic currents of the TRWs crossing it. While the data are not sufficient to conclusively demonstrate this process, the zonal wavenumbers and ~20-60 d periods match well to the most unstable meander modes of the upper jet (Kontoyiannis, 1997). So small perturbations introduced at Cape Hatteras with the right wavenumber and frequency may be expected to grow rapidly.

IMPACT/APPLICATION

Current models have not captured the importance of the deep eddy variability, nor do they capture the feedback between the upper and lower layers. We hope to improve this situation and understand the physics.

TRANSITIONS

Our work indicates that it is crucial to know the deep eddy current and/ or pressure field in order to successfully predict the evolution of the upper baroclinic front. This will have an important impact on strategies for observations, data-assimilation, and modeling. We currently have a field program underway in the Japan/East Sea to observe vertical coupling between the upper and lower layers.

RELATED PROJECTS

This work is closely integrated with that of I. Ginis and G. Sutyrin who are conducting modeling studies of the coupling processes. Using a PVG-model initialization, Ginis, Frolov, and Sutyrin have recently demonstrated truly substantial improvement in long-term model performance (i.e., achieving realistic resilience and contiguity of the model Gulf Stream in runs spanning many model months.)

REFERENCES

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PUBLICATIONS

Logoutov, O., G. Sutyrin, and D. R. Watts, 1999: Potential vorticity structure across the Gulf Stream: Observations and a PV-gradient model. *J. Phys. Oceanogr.,* submitted.