

# Processes Coupling the Upper and Deep Ocean on the Continental Slope

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Award Number: N000149710138

## LONG-TERM GOALS

Our goal is to understand the physics of vertical coupling in ocean processes over topography.

## OBJECTIVES

We seek to conduct a comprehensive investigation of the dynamical mechanisms of vertical coupling over topography.

- To construct a realistic model of the potential vorticity (PV) distribution on density layers across the Gulf Stream, generated from high-resolution density and velocity observations.
- To demonstrate evidence of vertical coupling between the upper and lower layers in a hypothesized feedback loop, as follows:
  - (a) Topographic Rossby Waves (TRWs) passing under the Gulf Stream near Cape Hatteras trigger small amplitude meanders in the upper layer jet, which
  - (b) propagate downstream and grow to form steep troughs and rings, which
  - (c) in turn radiate energetic new TRWs, that
  - (d) propagate back along the continental slope to Cape Hatteras.
- To test, in collaboration with Ginis and Sutyrin at URI, the degree to which model dynamics can account for the observed coupling between energetic deep eddies and variability of strong baroclinic upper jets – particularly as affected by continental slope topography.

## APPROACH

Our studies combine analyses of existing observations with theoretical and numerical modeling studies. This three-pronged (observations / theory / modeling) approach requires 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.

## WORK COMPLETED

A graduate student, O. Logoutov, completed his M.S. last year under this project (Logoutov, 2000), working jointly with all three above scientists. Logoutov's thesis thoroughly summarizes TRW

# Report Documentation Page

*Form Approved*  
*OMB No. 0704-0188*

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1. REPORT DATE <b>30 SEP 2001</b>	2. REPORT TYPE	3. DATES COVERED <b>00-00-2001 to 00-00-2001</b>			
4. TITLE AND SUBTITLE <b>Processes Coupling the Upper and Deep Ocean on the Continental Slope</b>		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Graduate School of Oceanography,,University of Rhode Island,South Ferry Road,,Narragansett,,RI, 02882</b>		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>	<b>Same as Report (SAR)</b>	<b>6</b>	

properties and dispersion relevant to the slope region off Cape Hatteras, in various realistic  $N(z)$  stratifications, with and without realistic mean current structures. The properties under these general background PV states were calculated as a 2-D eigenvalue problem, and compared under various simplifications with analytical theory. A sloping bottom eliminates orthogonality of the wave modal structure – opening the possibility of mode coupling and, in particular, baroclinic / barotropic coupling.

We have completed our objective to construct a realistic potential vorticity gradient (PVG) model of the Gulf Stream structure, as documented in a published journal article (Logoutov, Sutyrin and Watts, 2001). These results are being used by Ginis, Sutyrin, and Frolov to construct dynamically balanced initial fields (i.e., qualitatively improved feature models) with which to initialize model runs of the Gulf Stream region.

We have also assembled, for the area near Cape Hatteras and in the downstream Gulf Stream meander region, historical moored current meter and simultaneous satellite thermal imagery data sets that provide now good observational evidence, which supports the hypothesized feedback loop (see Objectives). In fact, we and others have demonstrated and reported upon the latter three steps of the feedback loop over the past several years:

Process (b) downstream propagation of meanders, steep growth and ring-formation, documented by a sequence of studies by Watts's group and Cornillon's group at URI;

Process (c) radiation of TRWs by GS meanders and ring-formation, and process (d) propagation of TRWs back to Cape Hatteras, were studied in combination and documented by Hogg (1981, JMR), Pickart (1995, JPO), and Watts *et al.* (2001, JPO).

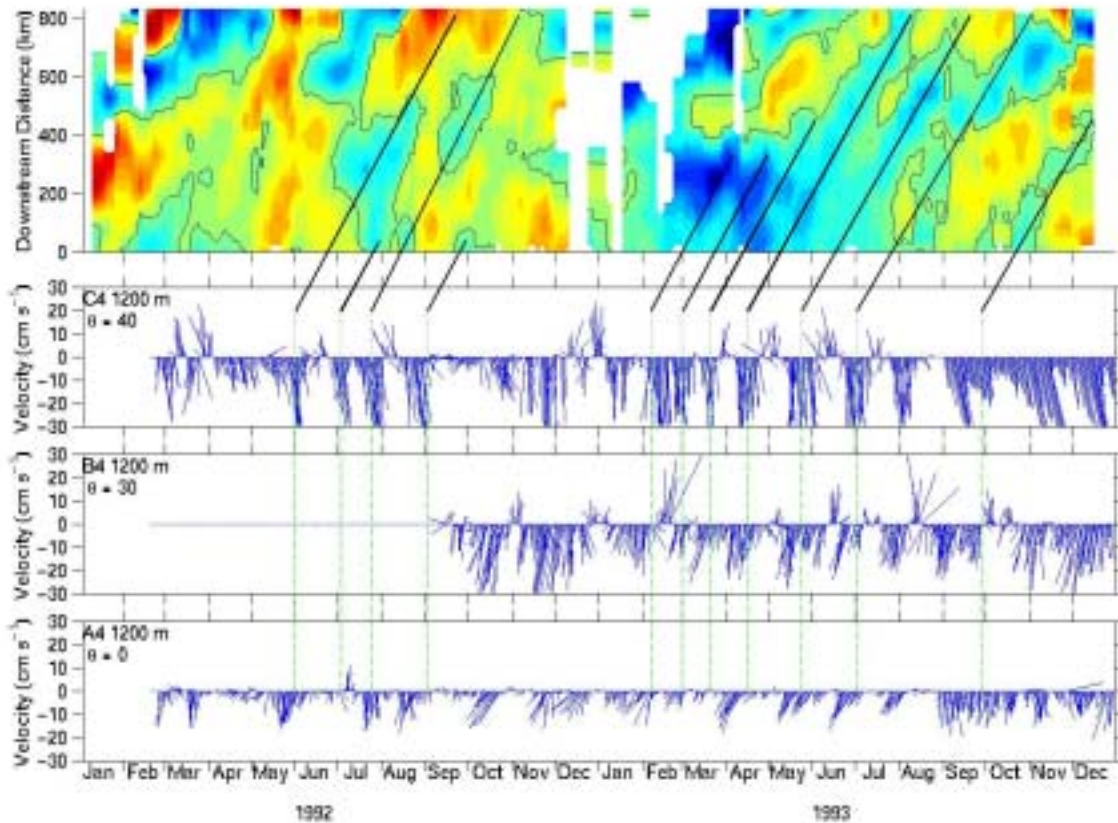
In last year's report we showed a figure combining satellite imagery and SYNOP deep current data which strikingly illustrated processes b, c, and d.

In the Results below, we show observational evidence supporting the missing link, process (a), which has until now mainly theoretical support (e.g., Pickart, 1995, JPO). The dynamical mechanism of coupling can be motivated from the vertical stretching exerted upon the upper layer jet by TRW currents, which exert a nearly barotropic influence and have a component of the current crossing the front. Theory suggests that perturbations introduced onto the unstable Gulf Stream at Cape Hatteras with the right wavenumber and frequency would be expected to grow rapidly. The observed zonal wavenumbers and the ~20-60 d periods (Pickart, 1995) match well to the most unstable meander modes of the upper jet (Kontoyiannis, 1997, DAO).

## **RESULTS**

Watts, Qian, and Tracey (2001) used bottom pressure records and current meter measurements at 3500m from SYNOP at 12 sites under the Gulf Stream near 68°W to map the current and pressure fields. This paper documents the methods of combining these measurements and geostrophic leveling of the pressure records. Case studies show deep-level cyclones and anticyclones that spin up jointly with steep troughs and crests of the upper jet. Another sequence of maps illustrates TRWs propagating with characteristic phase velocity downslope and slightly equatorward, while the associated group velocity is mainly equatorward alongslope. Animations of these results may be found at our website, <http://www.po.gso.uri.edu/dynamics/WBC/index.html>.

Observational evidence is shown in Figure 1 of TRWs that, after having propagated equatorward along-shore to Cape Hatteras, trigger new meanders. This plot combines data from deep current meters (deployed by SAIC in 1991-92 under MMS funding), and satellite AVHRR data over an 800 km path northeast of Cape Hatteras. In the three lower panels we identify trains of TRWs with deep along-shore southward current pulses, with typically 25-42 d periods and equatorward group speed (about 8 km/day) indicated by the slightly sloped dashed green lines. The currents have been shown



**Figure 1.** Evidence that TRW currents near Cape Hatteras can trigger Gulf Stream meanders. **(lower three panels)** The currents are at 1200m depth at three sites along the 2000m isobath for nearly 2 years. Current vectors are rotated (labeled by  $\theta$ ) such that the y-axis is parallel to the local bathymetry. Sites A, B, C (labeled respectively from north to south) approach the location where the most baroclinic part of the Gulf Stream crosses the 2000m isobath as it leaves the continental margin to enter deep water. The equatorward current pulses are identified as TRWs from their periodicities, kinematics, and along-slope group speed (indicated by dashed green lines). The current pulses intensify southward as the bathymetry contours converge. **(upper panel)** Displacements of the Gulf Stream from its mean path contoured vs. time and distance,  $s$ , from  $74^\circ\text{W}$ . Southerly (northerly) displacements are blue (red) hues. 2-day composite satellite images  $74^\circ\text{W}$  to  $65^\circ\text{W}$  were provided by Cornillon (URI). Note that essentially every southward pulse of current in these TRW trains is accompanied by a southerly shift in the Gulf Stream, at least near  $s=0$ , where the tracking begins (about 100 km downstream of site C). Many of these small amplitude troughs propagate and grow downstream, as indicated by the solid black lines.

to clearly possess the kinematics, periodicities, and group speeds appropriate to TRWs. They intensify from site A to C as they enter steeper bathymetry near C, where they cross under the Gulf Stream. The color-shaded panel plots shifts of the Gulf Stream path from its temporal mean path, and black lines identify propagating meander troughs. Some of the meanders die out and others intensify as they propagate downstream. For example in the first year (1992) relatively few of the troughs traveled downstream, which we tentatively ascribe to the fact that the Gulf Stream path flowed somewhat north of its mean path, thus over steeper topography, which tends to inhibit the growth of meanders.

Remarkably, however, nearly every southward current pulse is accompanied at an appropriate small propagation-time delay by a southerly shift of the Gulf Stream path near  $74^{\circ}\text{W}$  (distance “0” on the color shaded panel). We contend therefore that the TRWs do trigger meanders, and then what happens – whether they grow or decay – depends upon the stability properties (in particular the slowly evolving mean path) of the upper baroclinic front.

## **IMPACT/APPLICATIONS**

Presently most numerical models do not capture the strength of the deep eddy variability, nor do they capture the feedback between the upper and lower layers. However, the collaborative modeling studies by Sutyrin and Ginis have focussed on this problem and do indeed show the generation of energetic deep eddies and TRWs under a meandering jet. We hope jointly to demonstrate the feedback of TRWs to the upper jet, and to understand that physical coupling. For example these processes may be highly influential in coupling the Gulf of Mexico Loop Current Eddies to strong deep eddies that have been observed along the continental margin.

Good and feasible strategies are evolving from these studies regarding what to measure and how to predict the Gulf Stream (or analogous strong baroclinic current) path. We hope to follow up with a combined observational / modeling program!

## **TRANSITIONS**

Our work indicates that it is crucial to know the deep eddy current and/ or pressure field in order to successfully initialize and predict the evolution of the upper baroclinic front. This will have an important impact on strategies for observations, data-assimilation, and modeling. Present studies in the Japan/East Sea, and future collaborations with NRL in the Gulf of Mexico will benefit from the methods developed here to observe, model, and understand vertical coupling between the upper and lower layers of the ocean.

## **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 demonstrated truly substantial improvement in long-term model performance.

## **PUBLICATIONS**

Logoutov, O., G. Sutyrin, and D. R. Watts, 2001: Potential vorticity structure across the Gulf Stream: Observations and a PV-gradient model. *J. Phys. Oceanogr.*, 31, 637-644.

Logoutov, Oleg G., 2000: *A Study of Coupling between Topographic Rossby Waves and the Gulf Stream in the Mid-Atlantic Bight*. M.S. Thesis, University of Rhode Island, Narragansett, 145 pp.

Watts, D. Randolph, Xiaoshu Qian, and Karen L. Tracey, 2001. Mapping Abyssal Current and Pressure Fields under the Meandering Gulf Stream. *J. Atmos. and Oceanic Technol.*, 18, 1052-1067.