Observations of Internal Lee Wave Generation

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LONGTERM GOALS

My interests are in oceanic phenomena that contribute to stirring and mixing in order to understand their impact on larger scales. Phenomena of interest range from the meso- (10 km) to the microscale (1 cm), with an emphasis on their interactions. They include internal waves, tides, potential-vorticity-carrying finestructure (vortical mode), turbulence and double diffusion.

OBJECTIVES

My recent focus has been on how meso- and finescale flow fields interact with complex topography such as seamounts, canyons, ridges and the continental slope. Mixing in the stratified ocean interior is too weak to close the meridional thermohaline circulation (Ledwell et al. 1998). I am exploring whether topographically-enhanced turbulent mixing might be sufficient to do so, and determining what mechanisms are responsible for its generation.

APPROACH

During May 1998, I participated in a cruise off the Virginia coast in collaboration with Drs. Kurt Polzin, John Toole and Ray Schmitt (WHOI). This observational program (TWIST – Turbulence and Waves over Irregularly Sloping Topography) was designed to characterize the internal wave and turbulence climates above a continental slope with 2-3 km wavelength corrugations crossing the slope. Interaction of the corrugations with low-frequency alongslope flows associated with topographic Rossby waves was thought to be a likely mechanism for internal lee wave generation. I conducted surveys with expendable current profilers (XCPs) and expendable CTDs (XCTDs) to obtain 3-D snapshots of velocity (u, v), temperature T, salinity S and vertical displacement ξ over the full water depth. These measurements complement High-Resolution Profiler (HRP) fine- and microstructure profiling (Polzin) and moored array profile time-series (Toole). Postdoctoral researcher Dr. Jonathan Nash has taken the lead in analysing the data, and interpreting it in the context of simplified internal wave models under my supervision.

Microstructure profiling reveals near-bottom eddy diffusivities more than one hundred times background between the 1000- and 1500-m isobaths. Similar values are found using the Gregg-Henyey finescale parameterization for internal-wave-generated turbulence. Our analysis focusses on describing the processes responsible for this enhanced mixing.

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14. ABSTRACT
My interests are in oceanic phenomena that contribute to stirring and mixing in order to understand their impact on larger scales. Phenomena of interest range from the meso- (10 km) to the microscale (1 cm), with an emphasis on their interactions. They include internal waves, tides, potential-vorticity-carrying finestructure (vortical mode), turbulence and double diffusion.

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WORK COMPLETED

High-quality expendable data were collected along three transects – one along the slope crossing a ridge-gully pair, one crossing the slope along a ridge and the last crossing the slope along a gully. At each of 25 stations, four XCP/XCTD pairs were deployed over a 12-h period to allow isolation of semidiurnal from higher- and lower-frequency signals. Energy-fluxes $<v'p'>$ have been estimated for fluctuations relative to station-averages, and the dominant geostrophic and semidiurnal signals identified. A 2-D ray-tracing model has been developed to explain the observations in terms of a low-mode internal tide reflecting from the continental slope topography. Preliminary results were presented at the 2002 Ocean Sciences meeting (Nash, Kunze and Toole 2002) and in seminars by Dr. Nash at Oregon State University, Woods Hole Oceanographic Institution, University of Victoria, University of British Columbia, and University of Washington. A manuscript (Shear Intensification on the Continental Slope Through Critical Reflection of Low-Mode Internal Tides: J.D. Nash, E. Kunze, J.M. Toole, K.L. Polzin and R.W. Schmitt) is in preparation for submission to *J. Phys. Oceanogr.*

RESULTS

The past year has been spent refining our interpretation of the data. In contrast with expectations, we found no evidence for internal lee waves based on the absence of corrugation-scale finestructure in the water column. While the flow in the upper water column is in excess of 10 cm s^{-1}, the near-bottom flow was too weak to generate waves [$U < N\alpha/(k_x\sqrt{1+f^2/N^2\alpha^2}) \sim 15\ cm\ s^{-1}$, where α is the slope and k_x the wavelength of the corrugations]. Instead, the velocity, vertical displacement, and shear signals are dominated by larger scale semidiurnal fluctuations. Analysis indicates:

- The near-bottom mean flow is *around* not *over* the topographic corrugations consistent with the mean flow being too weak to generate lee waves;
- The vertically-integrated internal-wave energy-flux is northward parallel to the continental slope at O(1 kW m^{-1}) rather than on- or offshelf, and is predominantly semidiurnal;
- Shear is intensified in the bottom 300 m and is predominantly semidiurnal in the latter half of the sampling period when the expendable surveys took place.
- Enhanced dissipation and shear occur near the 1200-m isobath offshore of supercritical (M_2) across-slope bathymetry.

We hypothesize that enhanced semidiurnal shear and mixing is associated with reflection of low-mode, semidiurnal internal waves from near- and supercritical bathymetry. In support of this:

- While the net energy-flux is predominantly alongslope, cross-slope velocities exceed alongslope velocities, and there is an abrupt cross-slope phase shift near the 1000-m isobath. Theory indicates that an *alongslope* energy-flux is to be expected within one-quarter wavelengh of the slope for an *across-slope* standing mode;
- Local generation of internal tides directly from barotropic semidiurnal motions (Legg p.c. 2001) is too weak to account for the observed shear or mixing;
- There is a cross-slope *con*vergence of mode-1 energy-flux, which is approximately balanced by cross-slope *di*vergence of high-mode energy-flux plus turbulent dissipation (Figs. 1 and 2);

• Beams of high-mode flux radiate offshore from near the 1000-m isobath coincident with high shear and turbulence signals (Fig. 1). Well-mixed bottom boundary layers more than 10-m thick are only observed offshore of supercritical topography.

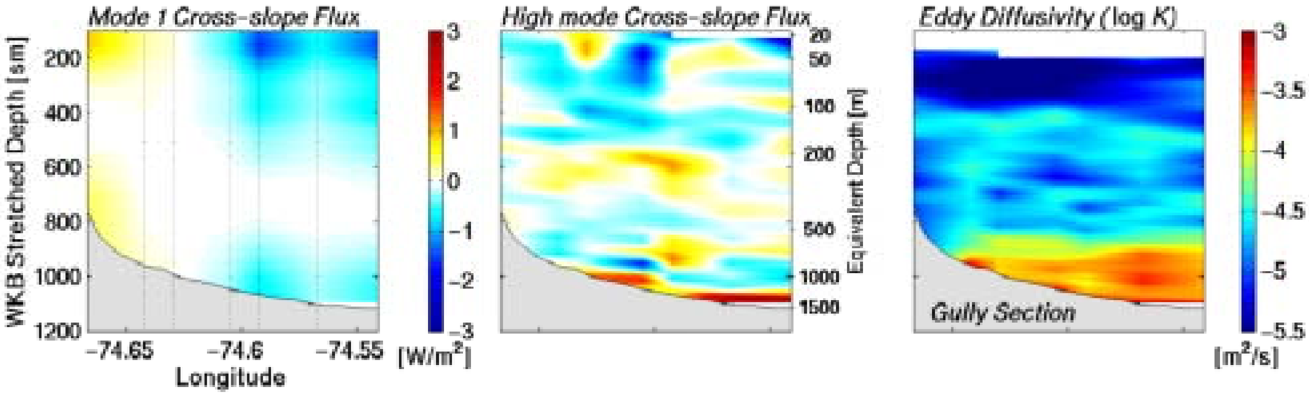

Figure 1: Across-slope sections show convergence of low-mode onshore energy-flux (left) and divergence of high-wavenumber offshore flux in the form of an intense near-bottom beam (middle). Inferred turbulent eddy diffusivities using the Gregg-Henyey scaling (right) are enhanced only offshore of the near-critical, 1000-m isobath in the depth-range of the high-wavenumber beam.

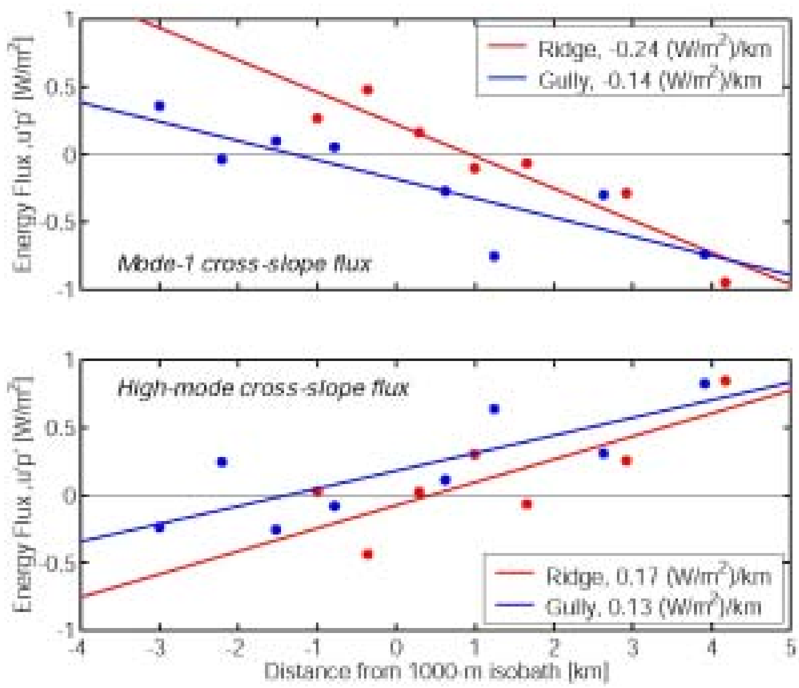

Figure 2: Convergence of mode-1 onslope energy-flux (–14-24 × 10^{-8} W/kg, upper panel) and divergence of high-wavenumber offslope energy-flux (13-17 × 10^{-8} W/kg, lower panel) within 300 m of the bottom almost balance. The 1-11 × 10^{-8} W/kg discrepancy consistent with observed dissipation rates.

To understand whether the observed semidiurnal shear could be associated with reflection of a low-mode internal wave from the continental slope, a simple ray-tracing simulation was performed. Bathymetry was assumed two-dimensional, ignoring alongslope corrugations. Boundary conditions consisted of an onshore-propagating mode-one internal tide of 2 cm s^{-1} amplitude prescribed 150 km from the slope. We note that this scheme is a WKB approximation and thus does not permit backscatter or diffraction of the impinging wave field by the topography. It nevertheless reproduces most of the features of the observations as well as those of a more sophisticated numerical model run by Parker MacCready (UW).

The simulations reproduce a reflected 200-m thick beam radiating downward and offshore from the slope inshore of the mooring. The model predicts horizontal velocities exceeding 10 cm s^{-1} and shears exceeding the stratification (Ri ~ 1). The modeled structure resembles mooring observations both in vertical phase structure and magnitude of velocity and shear.

IMPACT/APPLICATION

Our observations and model results suggest that the shear and mixing is associated with reflection of the low-mode internal tide with little dependence on the alongslope corrugations that originally drew our attention to the TWIST site. This represents a major simplification of the physics. In combination with model and satellite predictions of low-mode internal tide generation, this may allow estimation of turbulent mixing due to internal tide reflection from slope topography for the global ocean using extant topographic data sets. In laboratory experiments of internal waves reflecting off sloping topography, McPhee-Shaw and Kunze (2002) found that the exchange of fluid between the turbulent boundary layer and the quiescent interior was controlled by the turbulent mixing at the boundary which could in turn be diagnosed by the convergence of across-slope internal wave energy-flux. This bears on both boundary-interior fluid exchange, intermediate nepheloid production and its associated transport of shelf sediment to the deep ocean.

TRANSITIONS

The energy-flux estimation technique is being used on other projects by the PI and others to examine internal tide energy budgets in Monterey Submarine Canyon (Kunze et al. 2002), across Mendocino Escarpment (Althaus et al. 2002 submitted) and along the Hawaiian Ridge (HOME; Rudnick et al. 2002 submitted).

RELATED PROJECTS

Larger fluxes are found radiating away from Mendocino Escarpment and the Hawaiian Ridge, as well as into the mouth of Monterey Submarine Canyon. Turbulence levels along the bottom boundary of the Virginia continental slope are comparable to those observed over seamounts, escarpments and ridges. Drs. E. Kunze and J. Nash have submitted a proposal to NSF to make similar measurements on the Oregon continental slope where elevated near-bottom turbulence reported by Moum et al. (2002) may arise from a similar mechanism; historical current-meter records have been used to verify a low-mode flux-convergence onto the Oregon slope.

Existing evidence suggests that, except in abyssal waters below 4000-m depth, topographically-enhanced mixing, although 100-1000 times typical interior values (e.g., Kunze and Toole 1997), is not large enough to close the global conveyor belt as envisioned in Munk and Wunsch (1998). This would leave surface mixing as the only viable candidate for waters of 1-3 km depth in the temperate and tropical oceans (Sloyan and Rintoul 2001; Toggweiler and Samuels 1998).

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