

Observations of Internal Lee Wave Generation

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LONGTERM GOALS

My interests are in oceanic phenomena that contribute to stirring and mixing with the ultimate goal of parameterizing their impact on larger scales through dynamical understanding. Phenomena of interest range from the mesoscale (10 km) to the microscale (1 cm), with an emphasis on their interactions, and 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 complicated 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 the mechanisms 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 corrugated continental slope with 2-3 km wavelength ridges and gullies crossing the slope. The corrugations, in combination with low-frequency alongslope flows associated with topographic Rossby waves, were thought suitable 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. Postdoctoral researcher Dr. Jonathan Nash is taking the lead in analysing the data, and interpreting it in the context of simplified internal wave models under my supervision.

Microstructure profiling (Polzin) indicates mixing is enhanced (eddy diffusivities greater than one hundred times background) between the 1000- and 1500-m isobaths of the study region. Our analysis of the spatial/temporal surveys are designed to elucidate the processes by which this enhanced mixing occurs.

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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. XCP velocity profiles were made absolute with GPS-referenced shipboard ADCP profiles. Vertical displacements $\xi(z)$ and horizontal energy-fluxes $\langle v'p' \rangle$ have been estimated for fluctuations relative to station-averages, and the dominant geostrophic and semidiurnal signals identified. Preliminary results were presented at the AGU Fall 2000 meeting (Nash and Kunze 2000) and in seminars by Dr. Nash at Oregon State University, University of British Columbia and University of Washington.

RESULTS

In contrast to expectations, internal lee waves were not observed above the 200-m high topographic undulations. 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 [$U < N\alpha / (k_x \sqrt{1 + f^2 / N^2 \alpha^2}) \sim 15 \text{ cm s}^{-1}$, where α is the slope and k_x the wavelength of the corrugations]. Instead, the velocity, vertical displacement, and shear signals are dominated by semidiurnal fluctuations. Near-inertial signals are weaker but possibly significant. Analysis of the observations indicate:

- The net internal-wave energy-flux is northward parallel to the continental slope at $O(1 \text{ kW m}^{-1})$ rather than on- or offshelf. It is predominantly first mode and semidiurnal;
- The near-bottom mean flow is *around* not *over* the topographic corrugations consistent with the mean flow being too weak to generate lee waves;
- Shear is intensified in the bottom 300 m and is predominantly semidiurnal. Estimation of turbulent dissipation based on the observed shear and the Gregg-Henyey parameterization (Henyey et al. 1986; Gregg 1989) is consistent with the HRP microstructure observations (Polzin);
- Enhanced dissipation and shear occur offshore of where the bathymetry is supercritical with respect to the M_2 semidiurnal tide.

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

- While the net energy-flux is predominantly alongslope, there are large cross-slope velocities, and an abrupt cross-slope phase shift near the 1000-m isobath;
- Local generation of internal tides directly from barotropic semidiurnal motions (Legg) is too weak to account for the observed shear or mixing;
- There is a cross-slope *convergence* of mode-1 energy-flux, which is approximately balanced by a cross-slope *divergence* of high-mode energy-flux (Fig. 1);
- Beams of high-mode flux radiate offshore near the bottom (Fig. 1). Well-mixed bottom boundary layers more than 10-m thick are only observed offshore of supercritical topography.

An along-gully cross-section (Fig. 1) shows (i) convergence of low-mode cross-slope energy-flux, (ii) an offshore-propagating high-mode beam near the bottom, and (iii) high diffusivities associated with

the bottom-intensified shear. The high-mode near-bottom beam forms near the 1000-m isobath, and is coincident with the region of elevated mixing.

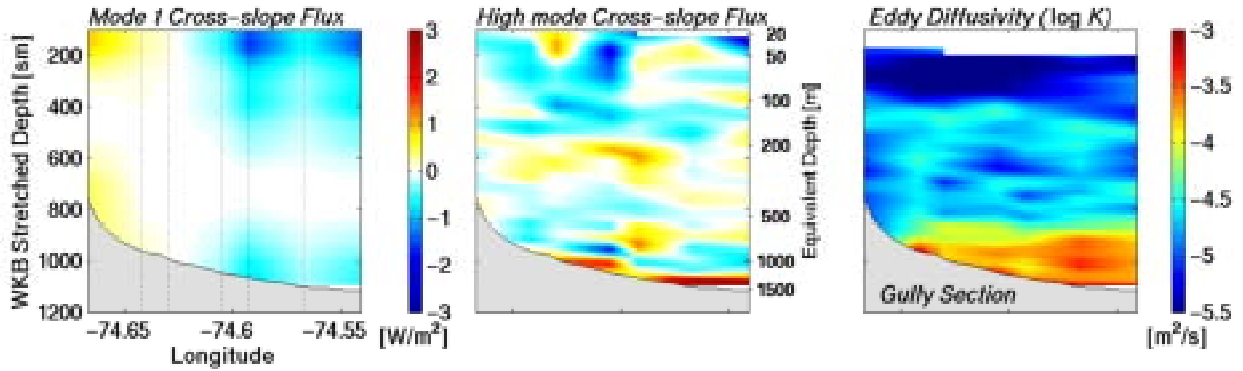


Figure 1: Along-gully sections show convergence of low-mode energy-flux (left) and divergence of high-mode flux in the form of a near-bottom beam (middle). Inferred turbulent eddy diffusivities (Gregg-Henyey, right) are enhanced only offshore of the near-critical, 1000-m isobath.

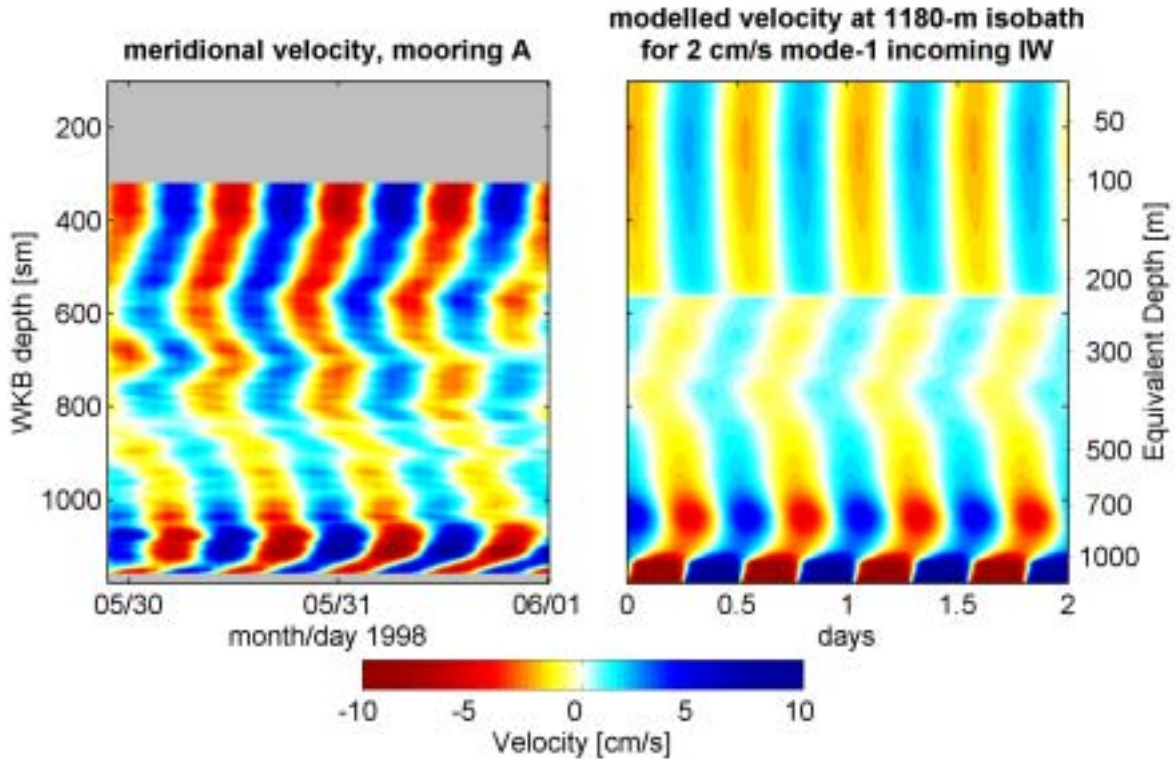


Figure 2: Comparison of observed (left) and modeled (right) semidiurnal velocity structure at the location of the moorings (see text).

To understand if the observed semidiurnal shear could be associated with reflection of a low-mode internal wave from the continental slope, a numerical simulation was performed. The bathymetry was assumed two-dimensional, and corrugations ignored. Boundary conditions consist of an onshore-propagating mode-one internal tide of 2 cm s^{-1} amplitude prescribed 150 km from the slope, consistent with Fig. 1 (left panel) and an energy-flux of 0.4 kW m^{-1} . A ray-tracing scheme was employed to predict the total velocity from the onshore- and reflected offshore-propagating wave fields.

The simulations produce a 200-m thick beam radiating downward and offshore from the near-critical and supercritical continental slope inshore of our mooring observations. The model predicts horizontal velocities exceeding 10 cm s^{-1} and shear which exceeds the stratification ($Ri \sim 1$). The modeled structure at the location of the moorings (Fig. 2) is very similar to the mooring observations in vertical phase (direction of energy propagation), and magnitude of velocity and shear.

IMPACT/APPLICATION

Our observations and model results suggest that the shear and mixing observed at the TWIST site is associated with reflection of the low-mode internal tide with little dependence on the slope corrugations that drew our attention to this site. This represents a major simplification of the physics. In combination with model and satellite predictions of low-mode internal tide generation, this knowledge may allow estimation of turbulent mixing due to internal tide reflection from slope and ridge topography for the global ocean using extant topographic data sets. The above program is part of ongoing investigation into topographically-enhanced fine- and microstructure in the wake of ONR's Topographic Interactions ARI over Fieberling Seamount.

TRANSITIONS

The energy-flux estimation technique is being used on other projects by the PI to examine internal tide energy budgets in Monterey Submarine Canyon, across Mendocino Escarpment and along the Hawaiian Ridge (HOME). It has also proven a useful diagnostic for numerical modellers (Lu et al. 2001; Merrifield et al. 2001; Cummins et al. 2001).

RELATED PROJECTS

The Virginia continental slope data can be compared with a similar data set collected on the continental slope outside of Monterey Bay. Energy-fluxes in the Monterey Slope data also are parallel to rather than across the slope. Larger fluxes are found radiating away from Mendocino Escarpment, the Hawaiian Ridge and 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. While too early to be certain, existing evidence suggests that, except in abyssal waters below 4000-m depth, topographically-enhanced mixing (e.g., Kunze and Toole 1997), although 100-1000 times higher than that in the ocean interior, 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).

REFERENCES

- P. F. Cummins, J. Y. Cherniawski and M. G. G. Foreman, 2001: North Pacific internal tides from the Aleutian Ridge: Altimeter observations and modelling. *J. Mar. Res.*, **59**, 167-191.
- E. Kunze and J. M. Toole, 1997: Tidally-driven vorticity, diurnal shear and turbulence atop Fieberling Seamount. *J. Phys. Oceanogr.*, **27**, 2663-2693.
- J. R. Ledwell, A. J. Watson and C. S. Law, 1998: Mixing of a tracer in the pycnocline. *J. Geophys. Res.*, **103**, 21,499-21,529.
- Y. Lu, D. G. Wright and D. Brickman, 2001: Internal tide generation over topography: Experiments with a free-surface z-level ocean model. *J. Atmos. Oceanic Tech.*, **18**, 1076-1091.
- M. A. Merrifield, P. E. Holloway and T. M. Shaun Johnston, 2001: The generation of internal tides at the Hawaiian Ridge. *Geophys. Res. Letters*, submitted.
- W. Munk and C. Wunsch, 1998: Abyssal recipes II: Energetics of tidal and wind mixing. *Deep-Sea Res.*, **45**, 1977-2010.
- J. D. Nash and E. Kunze, 2000: Internal flow over a rough continental slope. *EOS Transac.*, **81**(48), pF669.
- B. M. Sloyan and S. R. Rintoul, 2001: The Southern Ocean limb of the global deep overturning circulation. *J. Phys. Oceanogr.*, **31**, 143-173.
- J. R. Toggweiler and B. Samuels, 1998: On the ocean's large-scale circulation near the limit of no vertical mixing. *J. Phys. Oceanogr.*, **28**, 1832-1852.

PUBLICATIONS

- E. Kunze, 2001: A review of salt-fingering theory. *Prog. Oceanogr.*, accepted.
- K. L. Polzin, E. Kunze, J. M. Toole and R. W. Schmitt, 2001: The partition of finescale energy into internal waves and geostrophic motions. *J. Phys. Oceanogr.*, submitted.
- E. Kunze, 2001: Waves: Vortical Mode. *Encyclopedia of Ocean Sciences*. J. Steele, S. Thorpe and K. Turekian, Eds., Academic Press, accepted.
- McPhee, E.E., and E. Kunze, 2001: Boundary-layer intrusions from a sloping bottom: A mechanism for generating intermediate nepheloid layers. *J. Geophys. Res.*, accepted.
- Kunze, E., L.K. Rosenfeld, G.S. Carter and M.C. Gregg, 2001: Internal waves in Monterey Submarine Canyon. *J. Phys. Oceanogr.*, submitted.