Internal Wave Energetics and Bottom Boundary Layer Thickness in Monterey BayCanyon

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Introduction

Physical processes in the Monterey Bay Canyon are important because they influence nutrient and sediment budgets, which ultimately influence local productivity. Canyons serve an important role as a conduit for exchange between the open ocean and the continental shelf and have high rates of mixing. Due to the canyons' sloping bottoms and variable topography, internal waves are intensely energetic and contribute to boundary mixing. Kunze et al. (2002) investigated internal waves in the Monterey Bay Canyon and observed a loss of energy going shoreward along the canyon axis. The greatest energy loss occurred at the second bend along the canyon axis at 900 to 1100-m depth (Fig. 2). Internal waves become less energetic as they travel along the canyon axis, with the greatest loss of energy through this region. We thus hypothesize that boundary friction is most intense in the 900 to 1100-m depth range, and expect changes in bottom mixed layer characteristics and boundary layer velocity shear to be more intense in this region compared to deeper and shallower sites in the canyon.

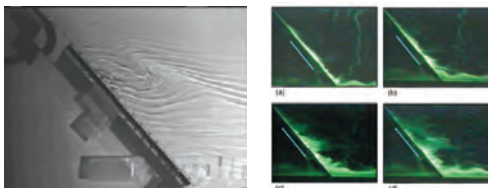


Figure 1. Laboratory views of internal-wave driven boundary mixing. The left panel shows a shadowgraph image of a subcritical internal wave breaking against a sloping boundary. The right panel shows fluoresceine-tagged boundary-layer fluid spreading into the interior as a result of mixing events (McPhee-Shaw and Kunze 2002).

Methods

- CTD (conductivity, temperature, depth) profiles from eleven stations
  - Casts repeated over a 12-hour period
  - Density profiles generated using Matlab
  - Bottom mixed layers identified and buoyancy frequencies calculated
- XCP (expendable current profiler)
  - Velocity profile of water column
  - Law of the wall and frictional bottom boundary layer (BBL) heights calculated
- Mooring
  - ADCP (Acoustic Doppler Current Profiler)
  - Velocity profile of water column over 3-month period

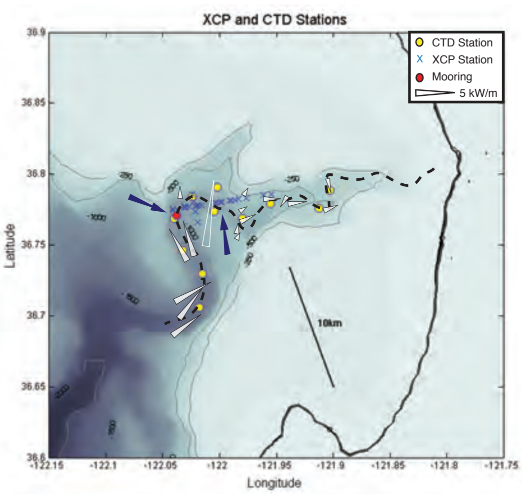


Figure 2. CTD stations and XCP stations sampled during August 2008 cruise. Energy fluxes (white arrows) are steered by the canyon axis. Energy flux data are from Kunze et al. The region between the blue arrows along the canyon axis represents the region where the frictional bottom boundary layers are thickest.

Energy Fluxes

Energy fluxes are likely steered upcanyon by topography. Near the canyon mouth and towards the first bend in the canyon, energy fluxes are 5 kW m^{-1}. After the second bend, energy fluxes drop to 1 kW m^{-1}. At the shallowest station near the canyon head, energy flux is oriented downcanyon (from Kunze et al.). The decrease in upcanyon energy flux (flux convergence) indicates a turbulent sink. The increase in upcanyon energy flux (flux divergence) indicates a net internal wave source. These sources and sinks for internal tide energy are equally important in describing the energy

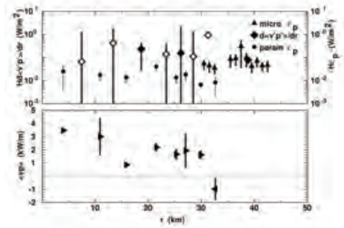


Figure 3. (top) Vertically-integrated energy-flux convergences (open diamonds) and divergences (solid diamonds) as well as estimates of vertically-integrated turbulence production rate inferred from microstructure measurements (triangles) (from Kunze et al. 2002). (bottom) Vertically-integrated upcanyon energy fluxes (from Gregg et al. 2005).

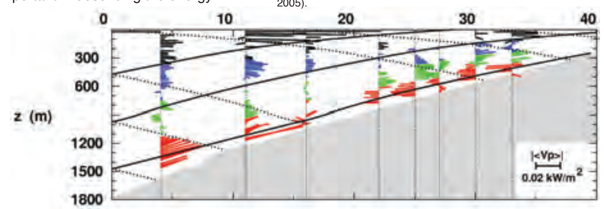
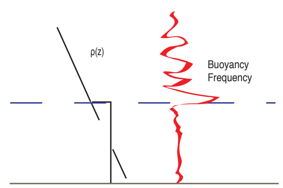


Figure 4. Depth vs. distance along the Monterey Canyon axis showing along-axis energy flux vectors. Bathymetry along the canyon axis is shaded gray. Distance in km from the canyon mouth is shown at the top. Below the 1000-m isobath and in the bottom few hundred meters, fluxes are upcanyon. At shallower depths, energy fluxes are downcanyon (from Kunze et al. 2002).

Bottom Mixed Layer

Bottom mixed layer heights were determined from CTD-density profiles and identified as having nearly uniform density over a particular depth. To determine the intensity of stratification, the Brunt-Väisälä frequency was calculated.

$$N^2 = -\frac{g}{\rho}\cdot\frac{\partial\rho}{\partial z}$$



Bottom mixed layer showing uniform density. The buoyancy frequency is nearly constant in the mixed layer.

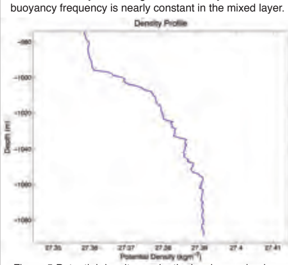
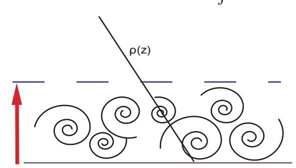


Figure 5.Potential density vs. depth showing a mixed bottom boundary layer of nearly uniform density.

Frictional Bottom Boundary Layer

Using XCP-velocity data and the law of the wall, the natural log of the height off the bottom was plotted against the velocity. A linear fit was assigned to the plot, and the slope was used to calculate the shear velocity. The frictional BBL height was calculated from the shear velocity and the Coriolis parameter.

$$u_* = mk \qquad h = 0.4\cdot\frac{u_*}{f}$$



Frictional BBL formed from velocity shear and turbulence.

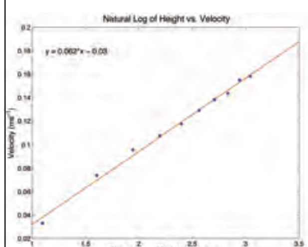


Figure 6. Log-scale graph of velocity profile showing a linear fit. The slope is then used to calculate the shear velocity.

Results

The bottom mixed layer heights were less than the calculated frictional BBL heights. Boundary layer heights were greatest between 11 and 17 km. These thick frictional BBLs correspond with sites along the canyon axis that are turbulent sinks, where boundary friction is most intense. Variation in heights and buoyancy frequencies at one site show how bottom boundary characteristics are not stationary and are affected by internal tides. Figure 8 shows how tidal oscillations affect the velocity magnitude.

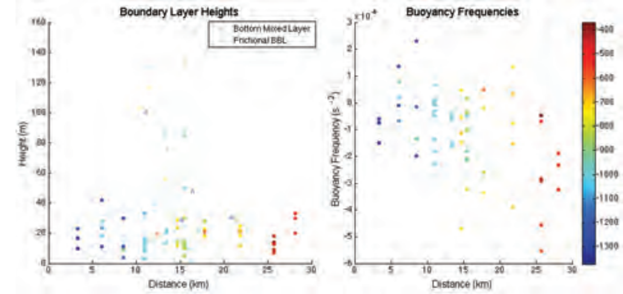


Figure 7. (Left) Bottom mixed layers and frictional BBLs from CTD stations, XCP stations and a deployed mooring. Boundary layer heights are plotted against their along-axis distance. (Right) Buoyancy frequencies of mixed layers from CTD stations plotted against their along-axis distance. Depths of boundary layers and buoyancy frequencies are also shown.

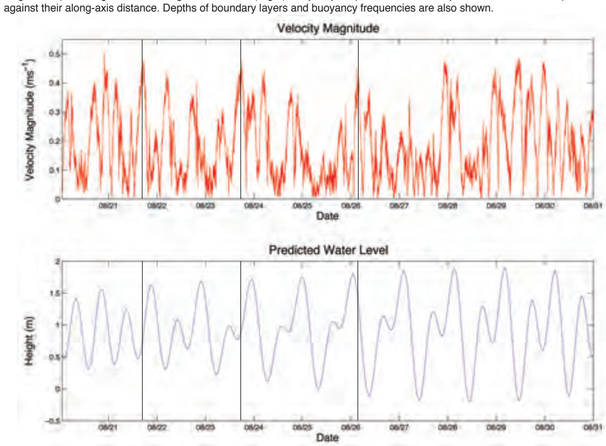


Figure 8. (Top) Data from moored ADCP (1150 m depth) showing the velocity magnitude from 11.77 m off the bottom as a function of time. (Bottom) Predicted water level due to the tides. Velocity magnitudes are greatest when the tide is coming in or out.

Conclusions

- Frictional BBLs thicker than bottom mixed layers
- Variation in heights and buoyancy frequencies show that bottom boundary characteristics vary temporally and spatially
- Frictional BBL thickness consistent with along-axis energy flux
- Turbulence is likely driven by semidiurnal internal tides
- The lack of thicker bottom mixed layers in this region suggests rapid restratification due to benthic-interior exchange

Literature Cited

Gregg, M.C., G.S. Carter and E. Kunze, 2005: Corrections to Mixing Rates in Two Papers about Monterey Submarine Canyon, Carter and Gregg (2002) and Kunze et al. (2002). Journal of Physical Oceanography, 35, 1712-1715.

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