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Observations of the internal tide on the California continental margin near Monterey Bay

Samantha R. Terker [a], James B. Girton [a,*], Eric Kunze [a], Jody M. Klymak [b], Robert Pinkel [c]

[a] Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Seattle, WA 98105-6698, USA
[b] School of Earth and Ocean Sciences, University of Victoria, P.O. Box 3055, STN CSC, Victoria, BC, V8W 3P6, Canada
[c] Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0213, USA

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ABSTRACT

Observations of the semidiurnal internal tide on the California continental margin between Monterey Bay and Point Sur confirm the existence of northward energy flux predicted by numerical models of the region. Both a short-duration tide-resolving survey with expendable profilers and a multi-week timeseries from *FLIP* measured northward flux in the mean, supporting the hypothesis that topographic features off Point Sur are the source of the strong internal tides observed in Monterey Canyon. However, the observed depth-integrated semidiurnal flux of 450 ± 200 W m^{-1} is approximately twice as large as the most directly-comparable model and *FLIP* results. Though dominated by low modes with O(100 km) horizontal wavelengths, a number of properties of the semidiurnal internal tide, including kinetic and potential energy, as well as energy flux, show lateral variability on O(5 km) scales. Potential causes of this spatial variability include interference of waves from multiple sources, the sharp delineation of beams generated by abrupt topography due to limited azimuthal extent, and local generation and scattering of the internal tide into higher modes by small-scale topography. A simple two-source model of a first-mode interference pattern reproduces some of the most striking aspects of the observations.

1. Introduction

Establishing and quantifying sources, pathways, and sinks of internal (baroclinic) tidal energy is imperative to closing the global tidal energy budget, yet the processes influencing internal tide propagation and dissipation are less well understood than generation (Bell, 1975; Baines, 1982; Garrett and Kunze, 2007; Nycander, 2005).

We are not far from achieving realistic global maps of internal tide generation. Satellite altimetry and numerical models have characterized the geography of the energy lost from the barotropic (surface) tide (Egbert and Ray, 2001), and more recent work has focused on the partition of this loss between dissipation and internal tide generation (Carter et al., 2008). Using a global numerical model, Simmons et al. (2004), found that most of this generation occurs at a limited number of topographic features (~75% at 20 sites). *in situ* measurements at the Hawaiian Ridge (Klymak et al., 2006; Lee et al., 2006; Nash et al., 2006; Rainville and Pinkel, 2006), Mendocino Escarpment (Althaus et al., 2003), Luzon Strait (Lien et al., 2005), and the Bay of Biscay (New, 1988) essentially confirm generation of the internal tide at sites highlighted by the global maps.

Once generated, the propagation of the waves through an inhomogeneous medium, their subsequent interactions with topography, and interactions among different waves become increasingly complicated, particularly as the end results of dissipation and fluid mixing are approached. Initial steps toward global maps of propagation have been made. The first-mode internal tide (*i.e.*, the largest baroclinic length scale) generated by a simple topographic feature like the Hawaiian Ridge is relatively straightforward to observe and has been traced over thousands of kilometers (Ray and Mitchum, 1996; Alford, 2003; Zhao et al., 2010), though where the energy is ultimately dissipated remains unknown. At the same time, internal tides (particularly higher modes) may be refracted by mesoscale features and changing water depths (Martini et al., 2007; Park and Watts, 2006; Rainville and Pinkel, 2006), modified through wave–wave interactions (MacKinnon and Winters, 2005), and can produce multiple-source interference patterns (Nash et al., 2007; Rainville et al., 2010; Simmons et al., 2004), complicating interpretation of maps and point measurements alike.

The end products of dissipation and mixing are still more difficult to map out, as these processes tend to be intermittent and localized, involving a cascade to smaller scales, wave breaking and turbulence. Internal tide dissipation may be gradual through internal wave/wave interactions (McComas and Müller, 1981a,b)

* Corresponding author. Tel.: +1 206 543 8467; fax: +1 206 543 6785.
E-mail addresses: sbrody@apl.washington.edu (S.R. Terker), girton@apl.washington.edu (J.B. Girton), kunze@apl.washington.edu (E. Kunze), jklymak@uvic.ca (J.M. Klymak), rpinkel@ucsd.edu (R. Pinkel).

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and scattering from small-scale rough topography (St. Laurent and Garrett, 2002) or abrupt due to parametric subharmonic instability equatorward of 28° (Alford et al., 2007; Hazewinkel and Winters, 2011; MacKinnon and Winters, 2005), reflection to high wavenumbers at near-critical bottom slopes (Nash et al., 2004; Nash et al., 2007), and shoaling onto shelves (Lien et al., 2005; Moum et al., 2002). While all these processes are likely to occur, it is unknown which dominate, though observations of long-range propagation of low-mode tides (as mentioned earlier) suggest that gradual dissipation processes are weak so the abrupt processes play a substantial role.

As a potential site for unusual internal wave dynamics and strong mixing, the shelf and canyon topography of the Monterey Bay region were the focus of several observational programs and modeling efforts in the 1990s and 2000s (Carter and Gregg, 2002; Kunze et al., 2002; Petruncio et al., 1998, Rosenfeld et al., 2009; Kunze et al., 2012). These studies found topographically steered baroclinic tidal currents of $\sim$20 cm s^{-1}, more than twice as large as the barotropic currents. Microstructure measurements also showed high depth-average dissipation rates ranging from O(4×10^{-8} W kg^{-1}) in the mid-canyon (400–1200 m water depths) to O(1.1×10^{-6} W kg^{-1}) at the head (shallower than 400 m), peaking along the canyon axis during spring tide (Carter and Gregg, 2002; Kunze et al., 2012).

Regional numerical models suggest internal tide generation by features outside Monterey Bay, including the Sur Ridge, Sur Platform, Guide Seamount and Davidson Seamount (Carter, 2010; Hall and Carter, 2011; Jachec et al., 2006; Wang et al., 2009). Though differing in detail, these models all suggest that the majority of the internal tide enters the canyon from the south in a beam originating from submarine topography west of Point Sur (including both the Sur Ridge and Sur Platform; Fig. 1). The purpose of the study described in this paper is to characterize lateral variability in internal tide properties on scales smaller than the robust and coherent internal wave beam but larger than the resolution of the finer models (Carter 2010; Jachec et al., 2006). Even for a relatively well-studied deterministic process such as internal tides, convergence between high-resolution models and observations is far from being achieved in this region (Rosenfeld et al., 1999; Rosenfeld et al., 2009; Wang et al., 2009).

This paper is organized as follows: Section 2 describes the measurement program on the California continental margin between Point Sur and Monterey Canyon (Fig. 1), including initial results and a comprehensive evaluation of uncertainties. Section 3 documents the surprising (given the low-mode character, relatively simple geometry, and modeled smoothness of the internal tide) complexity at O(5 km) spatial scales. Section 4 evaluates potential hypotheses for this complexity, including constructive and destructive interference resulting from superposition of waves propagating from multiple sources (Rainville et al., 2010) and the abrupt gradients in energy flux that can arise at the edges of beams of limited width. The complexity underscores the importance of considering spatial and temporal resolution in oceanographic field experiments in which observations are often limited by the high cost of instruments and ship time.

2. Methods

2.1. Field measurements

The AESOP (Assessing the Effectiveness of Sub-mesoscale Ocean Parameterizations) experiment was conducted in the Monterey Bay region during August–September 2006 as part of the "MB06" suite of activities coordinated by the Office of Naval Research. This experiment was designed to test and improve the representation of small-scale processes in coastal regional numerical models. It provided a unique opportunity to make full-water-column profiles of velocity, temperature and pressure with high spatial resolution in an area with complex bathymetry and an energetic internal wave field.

The principal observations presented in this paper are from 10 stations forming a 5-km × 5-km box west of Point Lobos in 1000 m of water, plus one station 6 km to the south, occupied by the R/V *Point Sur* during 13–15 August (Fig. 1). Full-depth profiles were collected with Lockheed-Sippican expendable current profilers (XCPs), a ship-lowered CTD/LADCP package, two shipboard RDI ADCPs (a 75-kHz Ocean Surveyor and 300-kHz BroadBand), and a Rockland Scientific Vertical Microstructure Profiler (VMP).

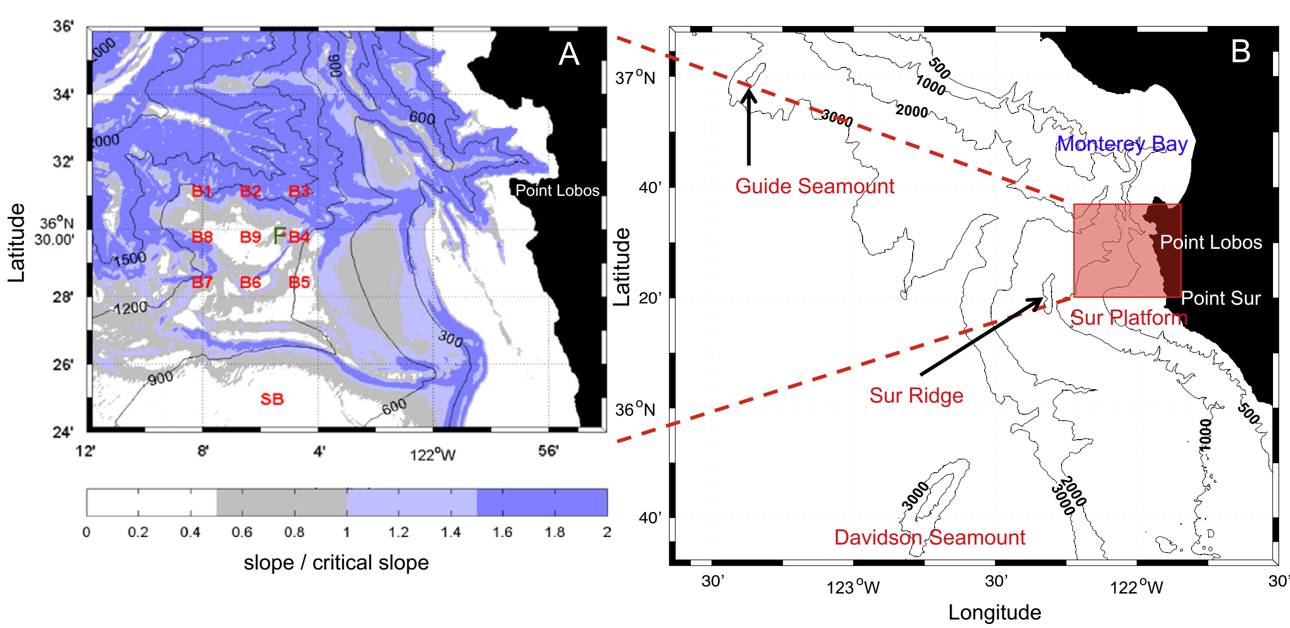

Fig. 1. (A) Overview of experiment site and station locations. Station names, B1–B9 (the survey box) and SB, are centered on the position of each respective station. The *FLIP* location is denoted by a green F. Bathymetry at 300-m intervals is contoured with black lines, and the bathymetric-to-critical slope ratio for the semidiurnal internal tide is indicated by the color shading (color bar). (B) A more extensive diagram of the region surrounding the survey-box (red square), including likely internal tide generation sites (red text). Bathymetry is contoured with black lines at 500-, 1000-, 2000- and 3000-m depths. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)