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Power Estimates Associated With Internal Tides From the Monterey Bay Area

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ABSTRACT. Numerical modeling has proven to be a useful method for simulating internal tides within the coastal ocean. Monterey Bay is a location that experiences energetic semidiurnal internal tides, and they are pronounced within Monterey Submarine Canyon. Numerical simulations and field measurements indicate that the baroclinic energy fluxes there are spatially variable, leading to locations of positive and negative baroclinic energy flux divergences. Results derived from a SUNTANS (Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator) model simulation show that Monterey Submarine Canyon's baroclinic power is net dissipative (–8.3 MW). However, sources and sinks exist throughout the canyon, and they permeate the study domain. One way to understand internal tide power is related to the ratio of the bathymetric slope (γ) to the linear internal wave characteristic slope (*s*). Results show large and consistent integrated surpluses of baroclinic power between $0.5 \leq \gamma/s \leq 5.5$ (includes the critical ratio); some net surpluses exist when $\gamma/s > 5.5$, but are mixed with dissipative power results. When $\gamma/s < 0.5$, integrated power is net dissipative.

INTRODUCTION

Results from the 1994 Internal Tide EXperiment 1 (ITEX1) reveal near-bottom tidal currents within Monterey Submarine Canyon in excess of 20 cm s^{-1} along the canyon thalweg[1] (Petruncio et al., 1998). Furthermore, Petruncio et al. (1998) determined that the M_2 internal tide contribution is responsible for 15–20 cm s^{-1} of the observed current. The numerical simulation results of Jachec et al. (2007) showed that a horizontal grid resolution of roughly 250 m on the shelf could achieve M_2-fit results similar to ITEX1 data, and Jachec et al. (2006) determined that the Sur Platform region, south of Monterey Bay, is the primary source for the M_2 internal energy flux observed within Monterey Submarine Canyon. Hall and Carter (2011) and Kang and Fringer (2012) obtained similar results. While energy flux divergences of Jachec et al. (2006) showed internal tides being generated and dissipated throughout the domain, this overall domain yields a net power of +52 MW, but particular bathymetric features are net dissipative. The goals of this work are twofold: to compute the net production/dissipation of semidiurnal internal tidal power within Monterey Submarine Canyon and to determine how power is partitioned among slope ratios within the entire study area.

PHYSICAL SETTING AND SETUP OF SIMULATIONS

Monterey Bay, California, is located 150 km south of San Francisco in northern California. Figure 1 shows the bay's bathymetry and surrounding area. The region consists of the prominent Monterey Submarine Canyon flanked to the north and south by numerous smaller canyons, ridges located to the north of the canyon, and a continental slope and break region. Depths range from 0 to 3,500 m, with locally steep topographic gradients. Although internal tides are generated when barotropic tides flow over topography in a stratified fluid, the character of the internal

[1] The line defining the lowest points along the length of the canyon.

tide is partly governed by the topography. Many locations within Monterey Bay and the surrounding area have the potential to generate a specific type of internal tide, known as an internal tidal beam. In Figure 2, gray shading indicates regions in which bottom slopes are within ±10% of the critical slope for generation of semidiurnal internal tides. Here, the linear semidiurnal internal wave slope is computed with

$$s = \left(\frac{f^2 - \omega^2}{\omega^2 - N^2} \right)^{1/2}, \qquad (1)$$

where ω is the semidiurnal (M_2) frequency, f is the inertial frequency, and N is the local buoyancy frequency. Similar to Petruncio et al. (2002) and Legg (2004), the magnitude of the bathymetric gradient is computed as

$$\gamma = \|\nabla h\| = +\sqrt{\left(\frac{\partial h}{\partial x}\right)^2 + \left(\frac{\partial h}{\partial y}\right)^2}, \qquad (2)$$

where h is the seafloor elevation, and x and y are Cartesian coordinates. From this figure, it is evident that the area containing the greatest potential for generation of semidiurnal tides is over Sur Ridge, both because the slope ratio is critical (γ/s = 1) and because, as depicted in Figure 3, a component of the barotropic tidal flow is directed across the isobaths, similar to the cross-ridge flows of Holloway and Merrifield (1999). Although this figure provides likely generation locations of internal tides, the details are absent. Field programs have been carried out, but they can be limiting in spatial and temporal resolution; therefore, numerical simulations complement those efforts.

SUNTANS (Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator), a three-dimensional, nonhydrostatic, nonlinear, unstructured coastal ocean model, was used to carry out the numerical simulations (Fringer et al., 2006). Jachec et al. (2006, 2007) and Jachec (2007) provide mesh construction, topography, boundary and initial conditions, and parameter choices. The model simulated the time evolution of the semidiurnal internal tide field, which included the barotropic and baroclinic velocity field and pressure over complex topography. These results were used to compute the depth-integrated, period-averaged baroclinic energy fluxes and energy flux divergences at each planview element.

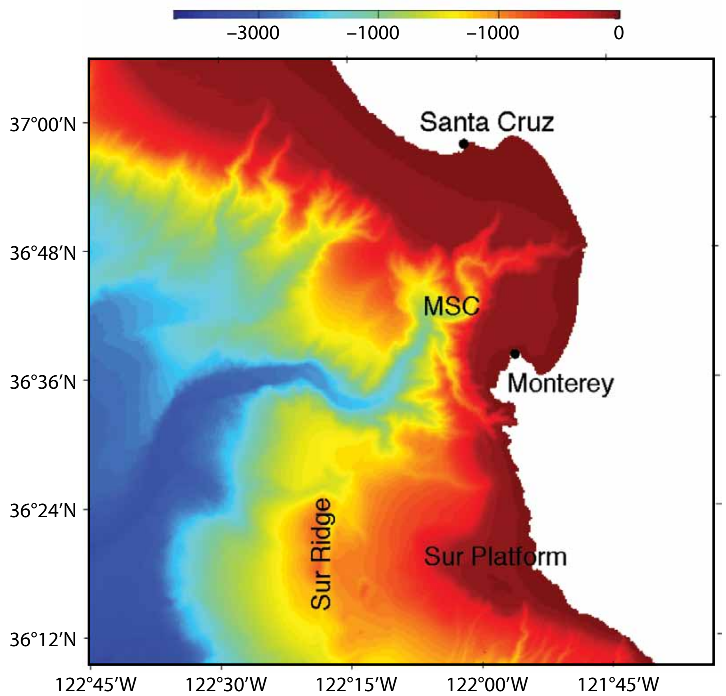

Figure 1. Topography (in meters) of Monterey Bay and the surrounding area. The Monterey Submarine Canyon (MSC) is shown near the center of the Bay.

NET INTERNAL TIDE POWER

Although the net power for the domain has been computed at +52 MW (Jachec et al., 2006), individual topographic features have not been partitioned with respect to their power contributions. Following Monterey Submarine Canyon's thalweg, this assessed region stretched from the canyon head to near 122°12'N. Within this region, the baroclinic flux divergences were summed, showing that Monterey Submarine Canyon is net dissipative at –8.3 MW. This result suggests that submarine canyons, which compose approximately 20% of the shelf break between Alaska and the equator and up to 50% of the edge in some locations (Hickey, 1995), are dissipative features. Given that the entire domain is net positive but the canyon is net negative suggests that internal tide generation and dissipation sites are variable, as demonstrated by Jachec et al. (2006).

The goal for some oceanographers is to predict large-scale motion within ocean basins that include these small-scale internal tide power generation and dissipation sites. The application of numerical simulations to understanding and forecasting ocean circulation is paramount, yet small-scale

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(i.e., subgrid-scale) motions are not adequately simulated with these coarse grid resolutions although small-scale processes, such as internal tides, may be important to the overall energy budget (Polzin et al., 1997). Therefore, it would be ideal to have a parametrization to model the effects of internal tides on the larger, resolved-scale circulation. Although progress has been made on the parametrization of dissipation and diffusivity due to internal waves, a physically based model is an ongoing challenge. Many of the present parameterizations have been created with the open ocean in mind, but when applied to coastal areas with rough bathymetry, such as Monterey Submarine Canyon, they under-predict the enhanced dissipation (Kunze et al., 2002). Therefore, the need for a model that can accommodate internal tidal effects within the coastal ocean is necessary for general circulation modeling to be effective in predicting quantities, such as dissipation.

Although energetics may be plotted versus many different parameters, a choice is made to focus on the slope ratio. Existing observational evidence suggests that three-dimensional bathymetric features and slopes will be useful in any parametrization used in larger basin-scale modeling (Wunsch and Ferrari, 2004; Decloedt and Luther, 2010). Furthermore, the slope ratio is chosen because it is easily computable for basin-scale domains by knowing the buoyancy frequency, tidal frequency, and topography. The bathymetric dataset is the most restricting: it is either difficult to acquire, does not have the needed resolution (Decloedt and Luther, 2010), or, if available, may be filtered (Simmons et al., 2004), thus modifying potential generation sites or altering the character of the waves. Figure 4 shows a histogram of power computed as the product of the energy flux divergence and the planview grid element area from the SUNTANS runs of Monterey Bay versus the slope ratio. Positive power values indicate sources, while negative values represent power sinks. The black vertical line designates the critical ratio, $\gamma/s = 1$. The major internal tidal power sink occurs when $\gamma/s \leq 0.5$; sporadically, between $5.5 \leq \gamma/s \leq 10$, there are sinks as well. The most consistent and greatest sources of internal tide power are most common between $0.5 \leq \gamma/s \leq 5.5$. Both sources and sinks of internal tidal power occur for subcritical ($\gamma/s < 1$) and supercritical ($\gamma/s > 1$) slope ratios. At the critical ratio,

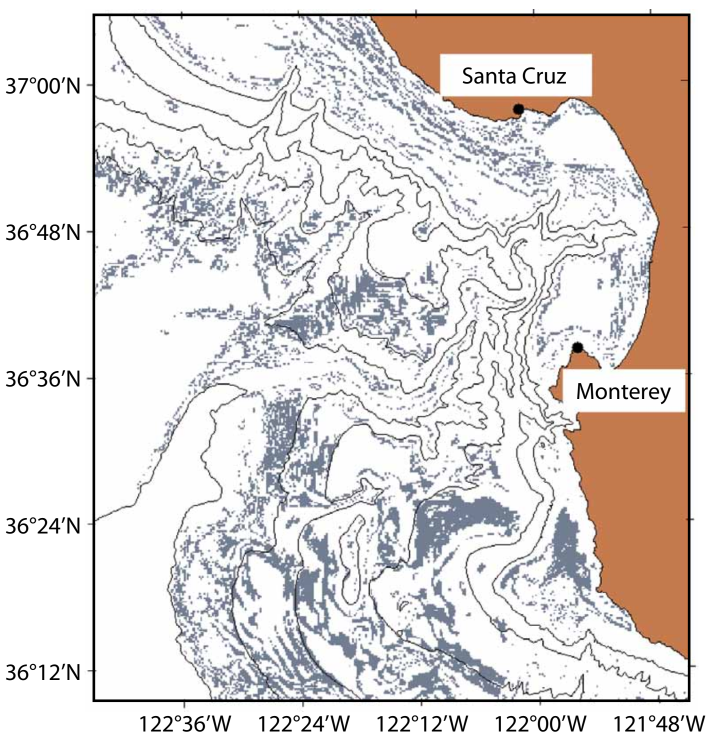

Figure 2. Critical slopes for M_2 internal tides using a summertime stratification. Gray shaded regions are ±10% of the critical ratio. Black contours are at −200, −500, −1,000, −1,500, −2,000, and −3,000 m.

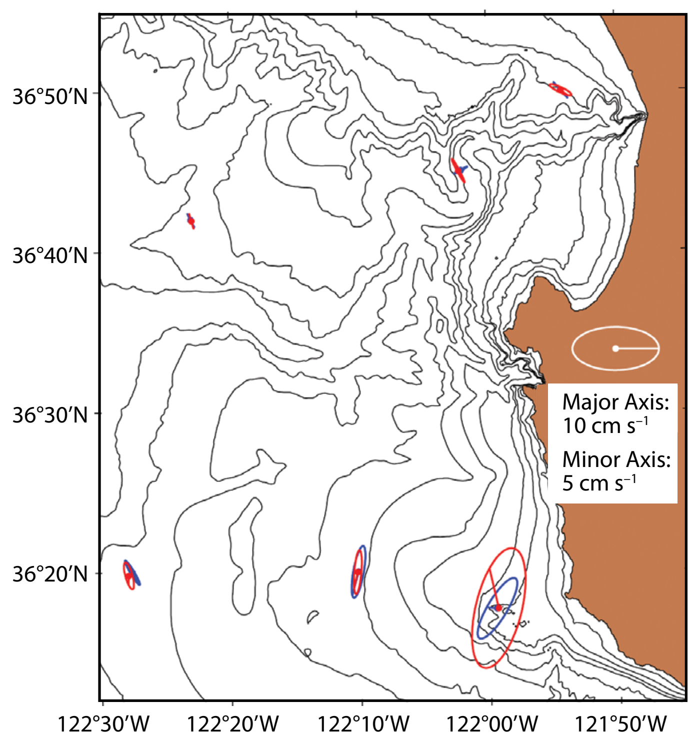

Figure 3. Semidiurnal barotropic tidal ellipses. Data = blue. Model = red.

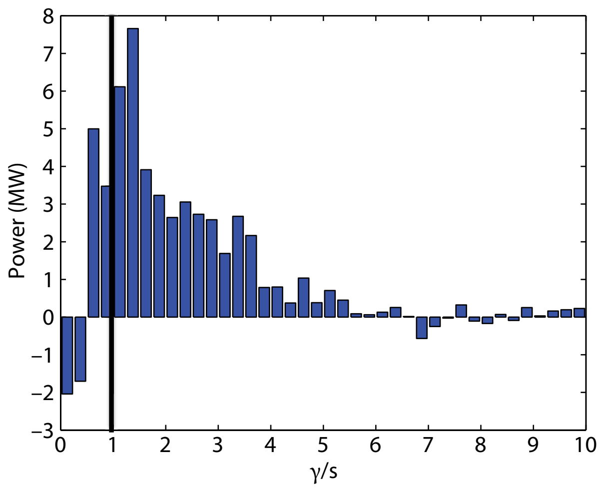

Figure 4. Power of internal tides as a function of slope ratio (γ/s) for the Monterey Bay domain. The black vertical line indicates critical ratio.

only net positive power is available. This does not mean there are no sinks of internal tidal power at the critical ratio, just that the integrated quantity is positive.

Internal tides have been numerically modeled and their energy flux divergences computed for the entire domain as well as for specific topography, such as the Monterey Submarine Canyon. Results show net positive power, with the greatest power near the critical slope ratio ($1 \leq \gamma/s \leq 2$). Slope ratios less than 0.5, which may be characterized as gradual topography, show a net power loss. Understanding the distribution of power in terms of slope ratio may be helpful toward parametrizing subgrid-scale processes into basin-scale circulation models. Care must be taken because the final plot shows the total power for a given slope ratio. A helpful next step may be computing the power variance for the slope ratio to better understand how variable it is across different topographic features.

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