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Transition from partly standing to progressive internal tides in Monterey Submarine Canyon

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ABSTRACT

Monterey Submarine Canyon is a large, sinuous canyon off the coast of California, the upper reaches of which were the subject of an internal tide observational program using moored profilers and upward-looking moored ADCPs. The mooring observations measured a near-surface stratification change in the upper canyon, likely caused by a seasonal shift in the prevailing wind that favoured coastal upwelling. This change in near-surface stratification caused a transition in the behaviour of the internal tide in the upper canyon from a partly standing wave during pre-upwelling conditions to a progressive wave during upwelling conditions. Using a numerical model, we present evidence that either a partly standing or a progressive internal tide can be simulated in the canyon, simply by changing the initial stratification conditions in accordance with the observations. The mechanism driving the transition is a dependence of down-canyon (supercritical) internal tide reflection from the canyon floor and walls on the depth of maximum stratification. During pre-upwelling conditions, the main pycnocline extends down to 200 m (below the canyon rim) resulting in increased supercritical reflection of the up-canyon propagating internal tide back down the canyon. The large up-canyon and smaller down-canyon progressive waves are the two components of the partly standing wave. During upwelling conditions, the pycnocline shallows to the upper 50 m of the watercolumn (above the canyon rim) resulting in decreased supercritical reflection and allowing the up-canyon progressive wave to dominate.

1. Introduction

Monterey Submarine Canyon (MSC) is a large, sinuous canyon situated in Monterey Bay, California. It is the largest submarine canyon along the west coast of the United States and has been the focus of several internal tide observational programs (Key, 1999; Kunze et al., 2002; Johnston et al., 2011; Kunze et al., 2012) and numerical modelling studies (Petruncio et al., 2002; Jachec et al., 2006; Wang et al., 2009; Kang and Fringer, 2012). In stratified seas, barotropic (surface) tidal flow across the sloping topography typical of submarine canyons can generate internal tides (internal gravity waves with tidal frequencies) by vertically displacing density surfaces (Bell, 1975; Baines, 1982). Submarine canyons are also thought to trap internal waves and internal tides originating outside the canyon, through reflection from the sloping topography, and channel the energy towards the canyon floor (Gordon and Marshall, 1976) and canyon head (Hotchkiss and Wunsch, 1982). Elevated internal wave energy near the canyon floor and head has been observed in several submarine canyons worldwide (e.g., Wunsch and Webb, 1979; Hotchkiss and Wunsch, 1982; Wang et al., 2008; Lee et al., 2009) and the mechanism is thought to be responsible for high turbulent mixing rates measured near the head of MSC (Lueck and Osborn, 1985; Carter and Gregg, 2002).

MSC is a "Type-2" canyon (Harris and Whiteway, 2011) in that it incises the continental shelf but does not connect to a major river. It extends over 100 km, from the abyssal plain at the base of the continental slope, to within 100 m of Moss Landing in the centre of the Monterey Bay. The bathymetry of MSC is complex, featuring a pair of large meanders (San Gregorio and Monterey Meanders) near the mouth of the bay and a smaller meander (Gooseneck Meander) closer to the canyon head (Fig. 1a,b). In the upper reaches, the canyon rim is ~100 m deep, increasing to roughly 200 m near the canyon mouth.

The first quantitative measurements of internal tides in MSC were made in April and October 1994 during two "Internal Tide

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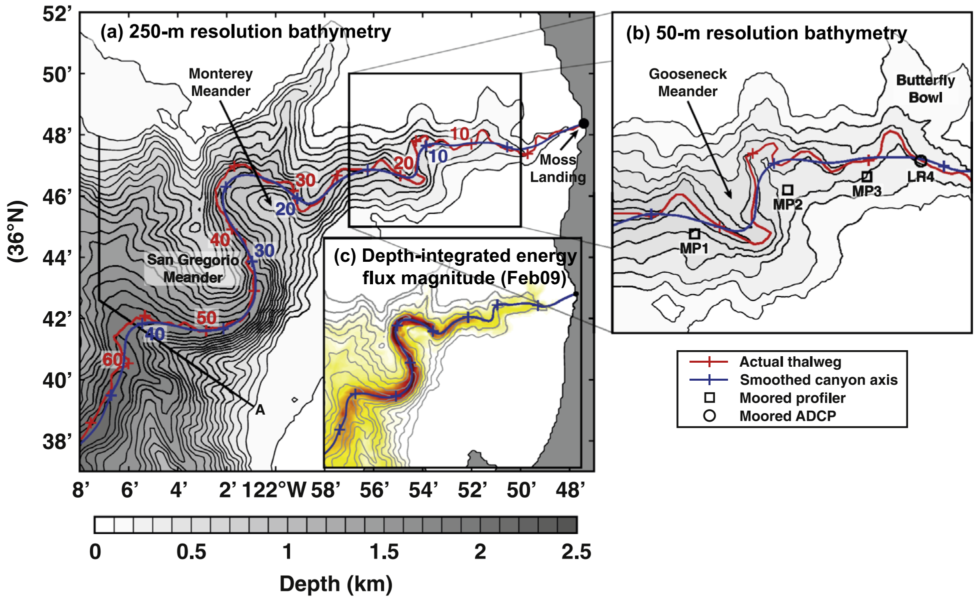

Fig. 1. (a) Model bathymetry of Monterey Submarine Canyon. (b) High-resolution bathymetry of the upper canyon showing the locations of the moored profilers and moored ADCP. The contour interval is 100 m. The red and blue lines are the actual thalweg and smoothed canyon axis respectively. For both canyon axes, along-canyon distance from Moss Landing is marked with a cross at 5-km intervals. (c) Depth-integrated baroclinic M_2 energy flux magnitude in the canyon region for the *Feb*09 model run.

Experiments" (ITEX1 and ITEX2, Petruncio et al., 1998) and focused on the region between Gooseneck Meander and the canyon head. One of the key findings was an apparent change in the behaviour of the internal tide from an up-canyon propagating progressive wave during April (ITEX1) to a horizontally standing wave during October (ITEX2). Petruncio et al. (1998) attributed the change in behaviour to an increase in stratification between the two experiment periods and down-canyon reflection of the internal tide from bathymetry near the canyon head during ITEX2.

In a more recent experiment ("Internal Tide and Mixing in Monterey and Ascension Canyons"), Zhao et al. (2012) observed a change in the behaviour of the internal tide in the upper reaches of MSC from a partly standing wave during February 2009 to a progressive wave during late March/April 2009. Details of this experiment are given in Section 1.2. Further observational evidence of a progressive internal tide during April 2009 was presented by Wain et al. (submitted for publication).

Numerical modelling studies of internal tides in the MSC region (Jachec et al., 2006; Carter, 2010; Hall and Carter, 2011; Kang and Fringer, 2012) have shown that the internal tide observed in the canyon is likely generated on Sur Slope, roughly 40 km to the south of the canyon mouth. Hall and Carter (2011) presented evidence that more remote generation sites in the region, including two offshore seamounts, have only a minor influence on the internal tide in the canyon.

1.1. *Standing and partly standing internal waves*

Standing internal waves are the superposition of two equal-amplitude progressive internal waves propagating in opposite directions, as described by Petruncio et al. (1998) and Nash et al. (2004, 2006). For a perfectly standing mode-1 internal wave over a flat bottom, the horizontal energy flux parallel to the axis of wave propagation is zero, but, the horizontal energy flux perpendicular to the axis is non-zero and varies sinusoidally. This transverse energy flux has maxima and minima distributed every $\lambda/4$, where λ is the horizontal wavelength of the component progressive waves. Horizontal kinetic energy (HKE) and available potential energy (APE) also vary sinusoidally along the axis of wave propagation, but are out of phase such that the HKE/APE ratio goes from zero to ∞ at $\lambda/4$ intervals. If the standing wave is setup by reflection from a vertical boundary, the transverse energy flux and HKE/APE ratio are zero at the boundary.

Partly standing internal waves occur when the component progressive internal waves have unequal amplitudes. The mode-1 standing internal wave energy equations were generalised to include partly standing waves by Martini et al. (2007). For a partly standing mode-1 internal wave, the parallel energy flux is uniform and in the direction of the major (i.e., largest amplitude) component wave. Like a perfectly standing wave, the transverse energy flux, HKE, and APE all vary sinusoidally along the axis of wave propagation; the locations of the maxima and minima are determined by the relative phases of the component waves. The range of HKE/APE decreases from ∞ as the amplitude difference between the component waves increases.

If the amplitude of one of the component waves goes to zero, the result is a purely progressive internal wave. Parallel energy flux is uniform and in the direction of wave propagation; transverse energy flux goes to zero; and both HKE and APE are uniform. HKE/APE goes to $(\omega^2+f^2)/(\omega^2-f^2)$ (Gill, 1982), where ω is the angular frequency of the wave and f is the inertial frequency.

1.2. *Mooring observations*

Three McLane Moored Profilers (MP1, MP2, and MP3) and four moorings with upward-looking 75-kHz Acoustic Doppler Current Profilers (ADCPs) were deployed in the upper reaches of MSC between February and April 2009. The moored profilers measured near-full-depth vertical profiles of temperature, salinity, and current velocity; allowing the calculation of internal tide energy fluxes. One ADCP mooring (LR4) included a chain of nine temperature loggers to allow a similar calculation. The locations of the moored profilers and LR4 are shown in Fig. 1b. Most of the instruments recorded from approximately yearday[1] 48 to 106, with the exception of MP1 which failed on yearday 59. Full details of the mooring deployments and data analysis can be found in Zhao et al. (2012).

[1] We refer to time using yearday, defined as decimal days since midnight on 31 December 2008 (e.g., noon on 31 January 2009 is yearday 30.5).