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Spatial variability of internal waves in an open bay with a narrow steep shelf in the Pacific off NW Mexico

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ABSTRACT

Small scale spatial patterns (< 10 km) in nearshore internal wave fields are rarely reported on, yet can have a large impact on nearshore mixing and productivity. In this study, the spatial pattern of internal wave characteristics were explored in Todos Santos Bay, Baja California (Mexico), using time series of temperature and currents from moored and towed thermistor chains and acoustic profiling current meters, as well as cross-shore transects with a towed undulating CTD system. Spectra of temperature and currents showed significant spatial variability within the bay, with the northern sector dominated by the internal tidally-forced semidiurnal signal, and the southern sector dominated by wind-forced, sub-inertial, baroclinic, diurnal fluctuations, which decreased with distance from shore. Semidiurnal internal tidal waves were generated by the barotropic tide at various sites on the continental slope to the west of the bay. They traveled toward the NE and reached the observation site in the northern part of the bay, after bouncing once or twice off the surface and the bottom. Despite the narrowness of the shelf, the semidiurnal internal tides at this site presented a first-mode structure, although not completely formed at times. On average, the semidiurnal internal waves had a ~9 km wavelength, traveled in the form of an arc, and propagated with a phase velocity of ~20 cm/s. When they reached shallow waters near the coast, they disintegrated rapidly into groups of short, nonlinear internal waves, with 15–20 m amplitudes, 5–20 min periods, and 50–200 m wavelengths. The spatial patterns found in this study are most likely due to variability in distance from generation sites, complex bottom topography, and small scale (< 10 km) spatial variability in meteorological conditions such as winds.

1. Introduction

The internal tide plays an important role in continental shelf dynamics. It can be generated remotely or locally, at sites on the shelf edge or continental slope, from which it propagates across the shelf. Once on the shelf, the energy of the internal tide is dispersed in various ways, either through the creation of other internal waves, and/or through mixing. The generation of internal tides depends on bottom inclination, $\tan\alpha = (dh/dx)$, and on density stratification, as given by the Brünt–Väisäla frequency $N(z)$ (Baines, 1982; Graig, 1987; Holloway, 1987), combined with a forcing factor, such as winds or tides.

Theoretically, freely propagating internal waves are restricted to frequencies, ω, where $f < \omega < maxN(z)$, and f is the inertial frequency (LeBlond and Mysak, 1978). Therefore, for semidiurnal waves, the critical latitude in either hemisphere is about 75°, and for diurnal waves the critical latitude is about 30°. However, there are many cases of subinertial internal waves occurring beyond the critical latitude (Cudaback and McPhee-Shaw, 2009; Beckenbach and Terrill, 2008; Wallace et al., 2008; Albrecht et al., 2006, van Haren et al., 2002). Subinertial internal waves can occur if they propagate along a bathymetric barrier (such as the coastline or a sloping bottom), confined to within approximately one internal Rossby radius of the barrier (Emery and Thomson, 1997), and also can occur if they are generated locally, such as by local winds (Wallace et al., 2008).

Internal tides, commonly regarded as mode one internal waves, may be considered in a continuously stratified fluid as composed of the sum of two inclined waves traveling in the same horizontal direction but with opposed vertical directions. The resulting internal tide is an inclined internal wave where the angle at which the crests and troughs are inclined, $\theta(z) = arctg\{(\omega^2 - f^2)/(N(z)^2 - \omega^2)\}^{1/2}$, is

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determined by the buoyancy frequency $N(z)$, the inertial frequency f, and the internal wave frequency ω, which is 0.081 cycle/h for semidiurnal internal waves. The most effective transmission of energy from the barotropic to the baroclinic tide occurs at a critical value of the bottom slope angle (α) where $\alpha/\theta \approx 1$, when the slope angle of the shelf approximates the beam slope angle of the internal wave. If $\alpha > \theta$ (supercritical), the energy travels offshore, and if $\alpha < \theta$ (subcritical), energy is reflected towards the continental shelf (Baines, 1982; Miropolsky, 2001).

Because the generation, propagation and disintegration of internal tides depend on bottom topography and stratification, as described above, internal tides can show significant spatial variation. The velocity and vertical displacement of internal tides on the shelf can vary greatly over short distances (Rayson et al., 2012). Hydrographic conditions, as well, can vary on spatial scales of 5–30 km, also related with shelf morphology, with greater spatial variability on steep narrow shelves than on wider ones (DiMarco et al., 2010). It has been shown that spatial complexity of internal waves increases in areas with multiple generation sites, and where complex topography is present (Alford et al., 2006).

Because of their strong modulation by bottom slope, propagation and disintegration of internal waves also depend greatly on the width of the continental shelf. On wide continental shelves, an internal oscillating bore forms as a result of the balance between nonlinearity and dispersion. Under these conditions, internal tidal waves usually have a first mode structure. With time, the oscillations turn into trains of solitary waves, and, as the water becomes shallower, these waves are destroyed (Liu, 1988; New and Pingree, 1990; Konyaev and Sabinin, 1992).

On very narrow shelves, the internal tide is an inclined wave, which propagates upward and onshore. Despite its reflection from the bottom and from the surface, it can remain inclined and be completely destroyed over the course of one wavelength (Konyaev and Sabinin, 1992). Due to the wave's reflection from the inclined bottom, the horizontal and vertical wave numbers increase when the wave approaches shallow waters; how much the wave number increases depends on the inclination of the bottom. The wave undergoes nonlinear transformations and overturns, forming several homogeneous temperature layers up to tens of meters thick (Filonov and Konyaev, 2003). The most intense disturbances are often observed near the bottom, where the slope angle approaches the critical value. There are very few data on internal tides under narrow-shelf conditions (Holloway, 1985; Rosenfeld, 1990; Filonov and Konyaev, 2006; Filonov, 2011).

The aim of this study was to provide a first description of the characteristics of internal waves in Todos Santos Bay (Fig. 1), Baja California (Mexico), from direct measurements using moored and towed instruments. We expected to find strong spatial variability in the internal wave signal and an incomplete formation of the modal structure prior to disintegration, due to the complex offshore topography and the narrow, steep nature of the slope. We identified several likely generation sites, described the patterns of propagation, and determined the forcing factors in the different parts of the bay.

2. Methodology

2.1. Study area

Todos Santos Bay is located on the west coast of the Baja California peninsula, 100 km south of the USA–Mexico border

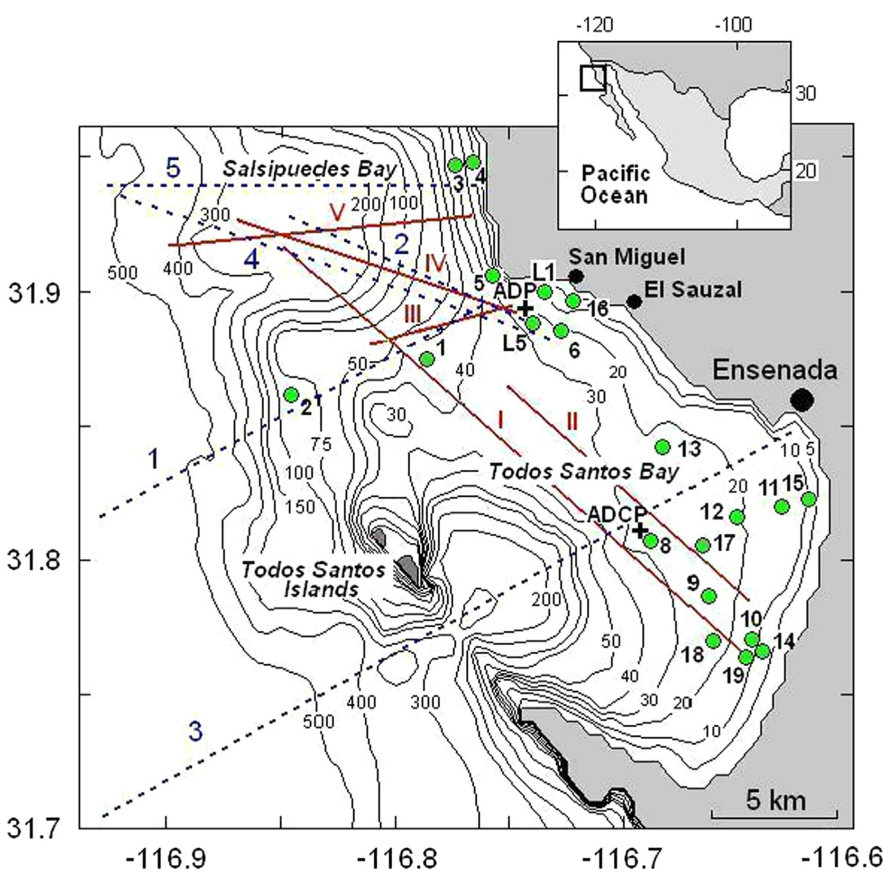

Fig. 1. Bathymetric map of Todos Santos Bay, Baja California, Mexico. The mooring (circles) and current meter (crosses) positions are shown. Dotted blue lines show the location of vertical transects of temperature and salinity taken with an undulating CTD (SBE-19plus). Continuous red lines indicate transects taken with a pair of towed chains of thermographs and an ADCP. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)