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Trapped diurnal internal tides, propagating semidiurnal internal tides, and mixing estimates in the California Current System from sustained glider observations, 2006–2012

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ABSTRACT

From 2006–2012, along 3 repeated cross-shore transects (California Cooperative Oceanic Fisheries Investigations lines 66.7, 80, and 90) in the California Current System, 33 609 shear and 39 737 strain profiles from 66 glider missions are used to estimate mixing via finescale parameterizations from a dataset containing over 52 000 profiles. Elevated diffusivity estimates and energetic diurnal (D_1) and semidiurnal (D_2) internal tides are found: (a) within 100 km of the coast on lines 66.7 and 80 and (b) over the Santa Rosa-Cortes Ridge (SRCR) in the Southern California Bight (SCB) on line 90. While finding elevated mixing near topography and associated with internal tides is not novel, the combination of resolution and extent in this ongoing data collection is unmatched in the coastal ocean to our knowledge.

Both D_1 and D_2 internal tides are energy sources for mixing. At these latitudes, the D_1 internal tide is subinertial. On line 90, D_1 and D_2 tides are equally energetic over the SRCR, the main site of elevated mixing within the SCB. Numerous sources of internal tides at the rough topography in the SCB produce standing and/or partially-standing waves. On lines 66.7 and 80, the dominant energy source below about 100 m for mixing is the D_1 internal tide, which has an energy density of the D_2 internal tide. On line 80, estimated diffusivity, estimated dissipation, and D_1 energy density peak in summer. The D_1 energy density shows an increasing trend from 2006 to 2012. Its amplitude and phase are mostly consistent with topographically-trapped D_1 internal tides traveling with the topography on their right. The observed offshore decay of the diffusivity estimates is consistent with the exponential decay of a trapped wave with a mode-1 Rossby radius of 20–30 km. Despite the variable mesoscale, it is remarkable that coherent internal tidal phase is found.

1. Introduction

Mixing in the thermocline is produced mainly by breaking internal waves (Gregg, 1989; MacKinnon et al., 2013), which are forced predominantly by tides and winds (Alford, 2003; Ferrari and Wunsch, 2009; Garrett and Kunze, 2007). Much of the internal wave energy is in low vertical modes (i.e., in waves with horizontal wavelengths of 100 km or more) and propagates away from generation sites (Alford, 2003; Zhao and Alford, 2009). Smaller-scale internal waves may break near their generation site and contribute to mixing (Gregg et al., 1986; Nakamura et al., 2010; Alford and Gregg, 2001; Klymak et al., 2006). Here, we consider the contribution of not only the freely-propagating semidiurnal (D_2) internal tide (Garrett and Kunze, 2007), but also the subinertial diurnal (D_1) internal tide, which is topographically-trapped near its generation site. The latter topic has received much less attention in the literature. In our study area in the coastal ocean off of California, D_1 internal tides are often more energetic than D_2 in our observations and in previous work around the Southern California Bight (SCB) (Beckenbach and Terrill, 2008; Kim et al., 2011; Nam and Send, 2011).

Poleward of 30°, D_1 internal waves are subinertial and evanescent, since the Coriolis frequency (f) is >1 cycle day^{-1}. Considerable mixing may arise due to topographically-trapped internal tides because they likely dissipate in the same area where they are forced (Padman and Dillon, 1991; Nakamura et al., 2010), although alongshore propagation is possible with dissipation elsewhere at the topography. Such mixing may contribute to water mass formation (Tanaka et al., 2010) and higher primary productivity (Tanaka et al., 2013). Energy loss from the D_1 barotropic tide is a maximum around the Pacific rim (Egbert and Ray, 2003). A local maximum in this dissipation is found along the west coast of

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North America beyond $\sim 30^\circ$N. The sink for this energy is likely the topographically-trapped D_1 internal tide, which in turn dissipates turbulently.

To assess the contributions of topographically-trapped D_1 and freely-propagating D_2 internal tides to mixing in the coastal ocean, we use an extensive dataset to estimate diffusivity using parameterizations based on observed current shear and/or isopycnal strain (Gregg, 1989; Polzin et al., 1995; Gregg et al., 2003). Six years of sustained glider observations in the California Current System (CCS) along three repeated California Cooperative Oceanic Fisheries Investigations (CalCOFI) cross-shore transects (lines 66.7, 80, and 90 in Fig. 1) provide over 52 000 profiles, at $\mathcal{O}(10\text{ m})$ vertical and $\sim$3-km horizontal resolution from the continental slope to 300–500 km offshore (Davis et al., 2008; Todd et al., 2011a, 2012). With this unique combination of spatial and temporal coverage, we can examine the seasonal and cross-shore structure of mixing estimates and internal tides. For example, D_1 internal tides may control the cross-shore decay scale at the continental slope and the seasonal cycle of mixing at the northern end of the SCB. At the Santa Rosa-Cortes Ridge (SRCR), a prominent feature of the SCB, D_1 and D_2 internal tides have similar energies and may contribute equally to mixing.

Next, we provide some background on mixing parameterizations (Section 2.1), previous observations of mixing in the SCB and other coastal locations (Section 2.2), and possible energy sources for mixing (internal waves and frontogenesis in Sections 2.3 and 2.4). In Section 3, our methods are described including a basic outline of the mixing parameterizations with further details in Appendix A. Section 4 shows an example transect from line 90 and time-mean transects (i.e., binned in depth and cross-shore distance) of the data and harmonic fits from lines 80 and 90 (line 66.7 is similar to line 80). In Section 5, depth-mean diffusivity estimates are binned in time or cross-shore distance and are then related to similarly averaged internal tides and mesoscale flows. A seasonal cycle is composited for line 80 (Section 5.4). A discussion and summary of our findings follow in Sections 6 and 7.

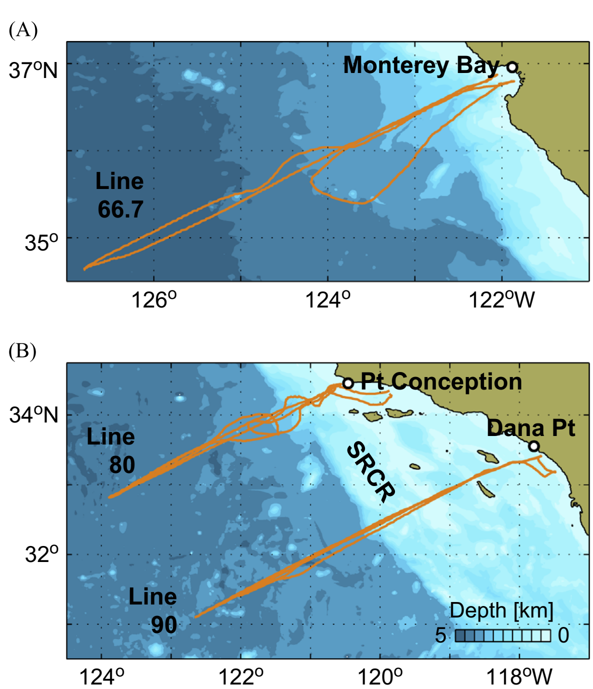

Fig. 1. Example tracks (orange) from glider missions 12801401, 12801101, and 12803001 along (a) line 66.7 and (b) lines 80 and 90 are shown over the bathymetry (blue colors) off the California coast. The origins of the cross-shore coordinate (x) are denoted by the circles near Monterey, Point Conception, and Dana Point. The Santa Rosa-Cortes Ridge (SRCR) extends roughly south-southeast from Point Conception and is a key topographic feature on line 90. Lines 66.7 and 80 have relatively narrow shelves, while line 90 extends over the rough bathymetry of the Southern California Bight. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

2. Background

2.1. Finescale mixing parameterizations

Direct measurements of either mixing via tracer release or turbulent fluctuations via specialized microstructure instruments occur of necessity during infrequent research cruises of usually several weeks duration. Only recently moored microstructure measurements have become possible (Moum et al., 2013). However, finescale or $\mathcal{O}(10-\text{m})$ scale profiles of shear and strain are readily available from many platforms including the gliders described in this paper. Turbulent dissipation (ϵ) and diapycnal diffusivity (K_ρ) can be estimated from these finescale measurements using parameterizations based on the idea of a downscale energy transfer via weakly interacting internal waves (Gregg, 1989; Polzin et al., 1995; Gregg et al., 2003; Kunze et al., 2006; MacKinnon et al., 2013). Assuming there is a steady state transfer, by measuring the finescale variance in shear and strain, we estimate the downscale energy transfer or dissipation at a scale much larger than the actual turbulence. The parameterizations relate ϵ to the ratio of the observed finescale variance to the variance in the empirical Garrett–Munk (GM) spectra of the internal wave field.

The GM spectrum is used to compare internal wave energy levels in locations with different stratification and latitude. For example, over the SRCR, a site of internal tidal generation, some example shear and strain spectra are within a factor of three of GM (Appendix A). For further comparison, the mission-mean spectrum from glider measurements east of Luzon Strait, which averages over regions of both weak and strong internal wave activity, is consistent with a level of 4 times GM (Rudnick et al., 2013). These values appear reasonable and reinforce the well-known utility of the GM spectrum in a wide variety of conditions.

Finescale parameterizations have been applied to diverse data sets over large areas with appreciable tidal and inertial signals (Kunze et al., 2006; MacKinnon et al., 2013; Whalen et al., 2012; Waterhouse et al., 2014). These methods under a variety of conditions are considered accurate to a factor of 2–4 at best (MacKinnon et al., 2013, and references therein) compared to specialized microstructure instruments, which measure the actual turbulent fluctuations (Klymak and Nash, 2009; Thorpe, 2005). In this paper, we estimate mixing in the coastal ocean using such parameterizations (Section 3.3 and Appendix A).

2.2. Previous observations of mixing in coastal waters

With rough topography, varying stratification, and numerous local and remote sources of internal waves in our study region, considerable spatial and temporal variability of mixing is expected. Using our methods, we can examine variability in the cross-shore direction along with tidal and seasonal variability, which complements previous moored or ship-based process studies, which have greater temporal resolution, but are limited in temporal or spatial extent.

Such variability in mixing over a semidiurnal tidal period, over a spring-neap cycle, and over variable topography is found in a bay situated between two distinct sources of internal tides near Oahu, Hawaii (Alford et al., 2006; Martini et al., 2007). Also the two sources of internal tides are of unequal strength and produce partially-standing internal waves. This interference pattern varies