Continental Shelf Research 120 (2016) 68–81

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Variability of the internal tide on the southern Monterey Bay continental shelf and associated bottom boundary layer sediment transport

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ARTICLE INFO

Article history:
Received 19 February 2016
Accepted 3 March 2016
Available online 16 March 2016

Keywords:
Internal tide variability
Monterey Bay
Upwelling
Relaxation
Suspended sediment transport

ABSTRACT

A 6-month deployment of instrumentation from April to October 2012 in 90 m water depth near the outer edge of the mid-shelf mud belt in southern Monterey Bay, California, reveals the importance regional upwelling on water column density structure, potentially accounting for the majority of the variability in internal tidal energy flux across the shelf. Observations consisted of time-series measurements of water-column currents, temperature and salinity, and near-bed currents and suspended matter. The internal tide accounted for 15–25% of the water-column current variance and the barotropic tide accounted for up to 35%. The subtidal flow showed remarkably little shear and was dominated by the 7–14 day band, which is associated with relaxations in the dominant equatorward winds typical of coastal California in the spring and summer. Upwelling and relaxation events resulted in strong near-bed flows and accounted for almost half of the current stress on the seafloor (not accounting for wave orbital velocities), and may have driven along-shelf geostrophic flow during steady state conditions. Several elevated suspended particulate matter (SPM) events occurred within 3 m of the bed and were generally associated with higher, long-period surface waves. However, these peaks in SPM did not coincide with the predicted resuspension events from the modeled combined wave–current shear stress, indicating that the observed SPM at our site was most likely resuspended elsewhere and advected along-isobath. Sediment flux was almost equal in magnitude in the alongshore and cross-shore directions. Instances of wave–current shear stress that exceeded the threshold of resuspension for the silty-clays common at these water depths only occurred when near-bed orbital velocities due to long-period surface waves coincided with vigorous near-bed currents associated with the internal tide or upwelling/relaxation events. Thus upwelling/relaxation dynamics are primarily responsible for variability in the internal tide, as well as transport of near-bottom sediment in the mid-self mud belt during the relatively quiescent summer months.

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1. Introduction

Numerous recent studies have demonstrated the significance of the semidiurnal internal tide on circulation, transport, and biological processes in the Monterey Bay region. Internal tides have been shown to be important in the formation of thin layers (McManus et al., 2005) and in the cross-shelf transport of plankton (Shanks et al., 2014). In the nearshore regions, shoaling internal tides provide a mechanism for vigorous mixing and sediment transport (Storlazzi et al., 2003; Woodson et al., 2011; Walter et al., 2012; Cheriton et al., 2014).

Initial studies indicated Monterey Submarine Canyon (MCS) as a generation site for the M_2 baroclinic tide in the bay (Petruncio et al., 1998). More recent modeling studies show that the primary source region for the generation of internal tides for the Monterey Bay area is more likely the Sur Ridge/Platform complex to the south of the bay (Carter et al., 2005, Carter et al., 2010; Johnston et al., 2011; Jachec, 2012; Kang and Fringer, 2012) and that MSC acts as a conduit for this baroclinic energy flux into the bay (Kunze et al., 2002; Hall et al., 2002; Wain et al., 2013). Few studies have focused on measuring the propagation across and/or generation of internal tides on the outer continental shelf of Monterey Bay, however. Measurements of microstructure profiles conducted by Carter (2005) showed enhanced dissipation and diapycnal diffusivities associated with both remotely and locally generated internal waves at the shelf break, but the measurements were somewhat limited in space and time.

Internal tides in the ocean are notoriously ephemeral in nature,

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http://dx.doi.org/10.1016/j.csr.2016.03.016
0278-4343/Published by Elsevier Ltd.

particularly on the continental shelf, and there are a multitude of potential reasons for observed variability in energy. Nash et al. (2012) surveyed data from different regions of the world's oceans, and found the internal tide to be difficult to predict. They point to a variety of reasons for variability; the remote nature of potential generation sites, interference and Doppler shifting between internal tides propagating from variable generation regions as well as interference between remotely and locally generated internal tides, and steering and refraction by complex bathymetry. Perhaps one of the most important reasons for temporal variability of the internal tide observed on the continental shelf, however, is the variability of the current and density structure of the ocean, with which a remotely generated internal tide must interact.

Most modeling studies use a single density profile to model the conversion of energy from barotropic to baroclinic (Hall et al., 2014a). In reality, the structure of water column stratification is highly variable in both space and time, particularly in the vicinity of strong upwelling, as is the case in Monterey Bay. There has been renewed interest in how the interaction of the internal tide with variable density structure can affect its propagation through the ocean (Zhao et al., 2012; Hall et al., 2014a, 2014b; Kerry et al., 2014). We hypothesize that upwelling is important in the propagation of internal tides across the Monterey Bay shelf by enhancing stratification, thereby providing a waveguide for internal waves.

In this paper we examine the variability of the internal tide on the continental shelf of southern Monterey Bay with a 6-month record of water column currents and temperature and salinity, and relate these measurements to the general circulation and upwelling/relaxation dynamics. We also explore sediment dynamics on this portion of the shelf to determine if and under what conditions sediment resuspension and transport occurs on the mud belt of southern Monterey Bay. We will show that while the internal tide may be important for transport of material on the inner shelf, the subtidal flow, which is predominantly wind-driven, is not only responsible for propagation of the internal tide, but also primarily responsible for near-bottom transport on the deeper portions of the shelf.

2. Study area

The southern portion of Monterey Bay consists of a broad, flat shelf bounded to the north and west by MSC, with a shelf break at approximately 110 m (Fig. 1). The seafloor geology consists of modern sands in the shallower reaches, fining to silts and clays in deeper water. The primary source of sediment to the shelf in south Monterey Bay is the Salinas River, which discharges on average 1,308,125 m^3 of sediment per year (Griggs and Hein, 1980). A distinct mud belt lies on the central to northern part of the shelf, with moment mean grain size from 63 μm to 3.9 μm in water depths ranging from 30 to 100 m. The eastern boundary of the mud belt follows isobaths; the southern boundary of the belt runs cross-isobath, with sands predominant in deeper water to the south of the mud belt (Edwards, 2002). The seafloor geology of the shelf break seaward of the mud belt exhibits sands and rock outcrops.

The surface wave climate in Monterey Bay is bimodal during the summer months; short period northwest wind swell (< 10 s) driven by the strong northwest regional winds and longer period southwest swell (> 14 s) that originates from storms in the Southern Ocean (Xu, 1999).

In order to distinguish between local bathymetry surrounding the study area and the general coastline of California when discussing observed flow patterns, in this paper, 'along-shelf' refers to the orientation of the isobaths of the study area, whereas 'along-coast' refers to the regional coastline of central California.

3. Methods

3.1. Moored instrumentation

Time-series instrumentation was deployed on two platforms; a bottom boundary layer (BBL) tripod and a combined sub-surface/S-tether surface taut-wire mooring at a location of 36.730°N, 121.904°W in 90 m water depth (Table 1). Platforms were deployed on 10 April 2012 and recovered on 30 October 2012 aboard the *R/V Point Sur*. A Sontek Hydra acoustic Doppler velocimeter (ADV) was placed 0.7 m above bottom (mab), thereby setting the

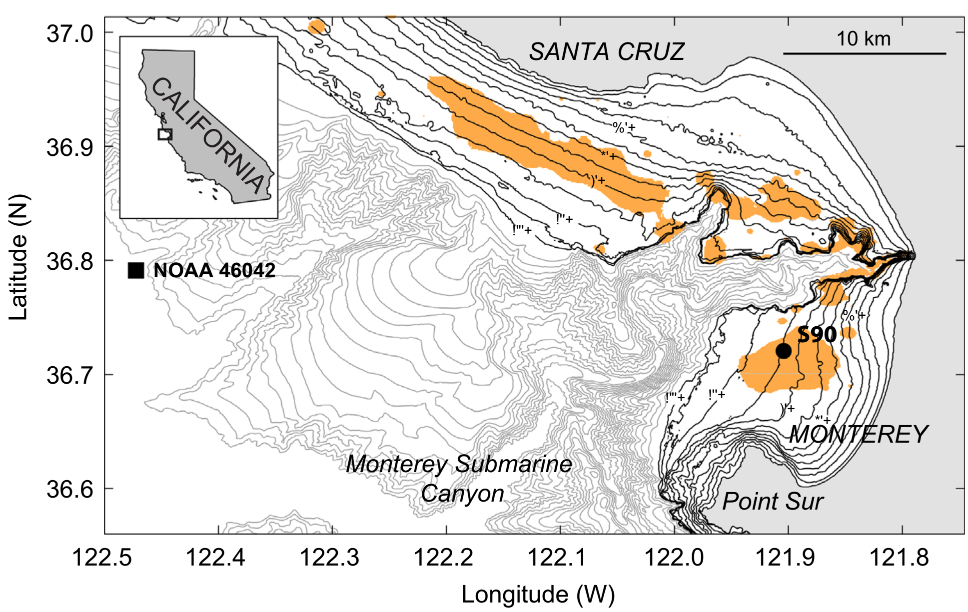

Fig. 1. Map of Monterey Bay, California showing location of the study site (S90) on the southern shelf, as well as the offshore NOAA 46042 buoy (square). The approximate location of the mid-shelf mud belt is indicated by the orange overlay (data originally published in Edwards, 2002). Black bathymetric contours are in 10 – m increments from 0 to 120 m, and gray contours are in 100 – m increments from 200 to 2000 m. The inset map shows location of Monterey Bay along the coast of California, USA.