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Internal bore seasonality and tidal pumping of subthermocline waters at the head of the Monterey submarine canyon

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ABSTRACT

This study utilizes more than a year of observations made in shallow waters (∼30 m) at the head of the Monterey Submarine Canyon to assess variability in the physical environment and internal bore field. The interaction of the internal tide with the canyon rim results in a semidiurnal tidal period pumping of cold–water masses (subthermocline waters) onto the adjacent shelf (i.e., internal bores). These internal bores are shown to be significantly coherent with the local sea surface height with minimal spatial variability when comparing two sites near the canyon head region. During the summer months, and periods of strong regional wind-driven upwelling and shoaling of the offshore thermocline, the canyon rim sites display elevated semidiurnal temperature variance. This semidiurnal variability reaches its annual minimum during the winter months when the regional upwelling favorable winds subside and the offshore thermocline deepens. Additionally, the observed internal bores show a distinct asymmetry between the leading (gradual cooling with velocities directed onto the shelf) and trailing edges (sharp warming with velocities directed into the canyon). It appears that the semidiurnal internal tide at the canyon head is a first-order control on the delivery of subthermocline waters to the nearshore coastal environment at this location.

1. Introduction

Internal gravity waves are a widespread feature of the coastal ocean and are generated in stably stratified waters when surface (barotropic) tides flow over sloping bottom topography (Garrett and Kunze, 2007). This process displaces density surfaces (isopycnals) vertically at tidal frequencies, and thus these features have been termed internal tides (i.e., internal gravity waves at a tidal frequency). Large amplitude internal waves and tides are a ubiquitous phenomenon along the continental margins of Monterey Bay, CA and are dominated by the semidiurnal (M_2 tidal constituent) frequency component (Shea and Broenkow, 1982; Petruncio et al., 1998; Kunze et al., 2002; Zhao et al., 2012; Hall et al., 2014; etc.). Semidiurnal internal tides in this region are also enhanced by the presence of the Monterey Submarine Canyon (MSC), one of the largest submarine canyons on the west coast of the United States. The MSC acts to trap and focus surface and internal tide energy in the canyon interior, resulting in internal tides that are an order of magnitude more energetic than the open ocean internal wave field (Kunze et al., 2002). Numerical modeling efforts and field observations have documented a substantial incident semidiurnal baroclinic energy flux at the canyon mouth and have concluded that the main offshore generation site is likely near the Sur Slope/Ridge; however, additional generation and interaction between the remotely and locally generated fields likely occurs in the canyon interior and shelf break region (Jachec et al., 2006; Petruncio et al., 1998, 2002; Kunze et al., 2002; Carter, 2010; Kelly and Nash, 2010; Kang and Fringer, 2012; etc.).

The internal tide also manifests itself shoreward of the canyon interior through a process known as tidal pumping (Shea and Broenkow, 1982; Petruncio et al., 1998, 2002). Tidal pumping refers to a process whereby the thermocline crests the shelf/canyon edge due to water displacement associated with the internal tide [see Shea and Broenkow (1982) for a description of this process in terms of volume convergence/divergence and continuity and their Fig. 7 for a schematic]. The resulting uplifted cold–water masses are transported onto the adjacent shelf along the canyon rim and lead to the formation of higher frequency nonlinear internal waves (NLIWs), solitons, and boluses (bores) (Venayagamoorthy and Fringer, 2007). In this contribution, we will refer to the cold–water surges/boluses as bores following the non-canonical description in Walter et al. (2012) (see Section 3.2), even though the typical (canonical) bore has an initial shock-like front that is not seen in the features described here (see Venayagamoorthy and Fringer,

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2007; Walter et al., 2012; Martini et al., 2013; and the references therein). The presence of NLIWs and bores in the Monterey Bay region has been documented in field observations near the canyon edge (Shea and Broenkow, 1982; Carter and Gregg, 2002; Carter et al., 2005), as well as on the adjacent shelf (Storlazzi et al., 2003; Woodson et al., 2011; Walter et al., 2012, 2014a, 2014b; Cheriton et al., 2014a, 2014b). The documented cold–water features near the canyon edge appear to be correlated to the surface tide (e.g., 1 week observations of Shea and Broenkow (1982)), while the features on the shelf occur intermittently and are not well correlated with surface tides (Booth et al., 2012; Walter et al., 2012). The latter is consistent with observations from other continental margin locations (Kelly and Nash, 2010; Nam and Send, 2011; see also Nash et al. (2012)).

NLIWs and bores are ubiquitous phenomena along continental margins and are known to have a significant effect on shelf circulation and exchange processes, turbulent dissipation and mixing dynamics, nutrient cycling, larval transport, sediment transport, and intermediate nepheloid layers (Shea and Broenkow, 1982; Pineda, 1994; Boehm et al., 2002; Carter and Gregg, 2002; Carter et al., 2005; Woodson et al., 2011; Walter et al., 2012, 2014a, 2014b; Cheriton et al., 2014a; Suanda et al., 2014; etc.). Furthermore, tidal pumping and the NLIW/bore field can significantly enhance the delivery of subthermocline waters to the nearshore, a process that is critical for understanding dissolved oxygen (DO) variability and coastal hypoxia, the transport of low pH waters to the nearshore and ocean acidification, and the design of future desalination plants that seek to access deep subthermocline waters (Booth et al., 2012; Walter et al., 2014b). NLIWs and bores in the stratified coastal ocean thus represent an important scientific and practical problem, with considerable implications for many biological and physical processes along coastal boundaries.

There is a growing number of field observations and numerical modeling efforts aimed at understanding the internal tide field and NLIWs/bores in the Monterey Bay region (Shea and Broenkow, 1982; Petruncio et al., 1998, 2002; Carter and Gregg, 2002; Kunze et al., 2002; Storlazzi et al., 2003; Carter et al., 2005; Jachec et al., 2006; Carter, 2010; Hall and Carter, 2011; Kang and Fringer, 2012; Zhao et al., 2012; Walter et al., 2012, 2014a, 2014b; Hall et al., 2014; Cheriton et al., 2014a, 2014b; etc.). Yet, previous computational studies necessarily concentrated on simplified and idealized setups. Likewise, the majority of observational studies concentrated on deeper canyon waters (100–1000+ m depths) over shorter time periods (days to weeks), or focused their efforts away from the canyon edge. Field observations near the canyon head, or along the canyon rim, were restricted to 1–2 week study periods using shipboard surveys and moored instruments (Shea and Broenkow, 1982; Carter and Gregg, 2002; Carter et al., 2005). Indeed, there is a paucity of long-term observations of NLIWs and bores near the MSC head in shallower waters, even though elevated semidiurnal internal wave energy has been observed near the head of several other canyon locations worldwide (cf. Petruncio et al. (1998) and the references therein; Hall et al. (2014) and the references therein). We also surmise that the canyon head could potentially be the site of enhanced delivery of subthermocline waters to nearshore shelf regions with important ecological habitats such as kelp forests (*Macrocystis pyrifera*) (e.g., see bore directionality in Walter et al. (2012)).

Long-term observations are critical to understanding the physical environment and internal tide field at the head of the canyon. For example, recent longer-term observations in the canyon and on the shelf have demonstrated the importance of wind-driven upwelling cycles and seasonality on the propagation and character of internal waves. Observations made over a two month period (mid-February to mid-April) by Zhao et al. (2012) and Hall et al. (2014) in deeper canyon waters (e.g., 150–600 m depths) revealed that changes in stratification driven by a seasonal shift in wind-driven upwelling resulted in changes to the behavior of the internal tide (i.e., progressive versus standing wave) and patterns of velocity, displacement, and energy flux in the upper reaches of the MSC. Walter et al. (2014b) showed that the strength and structure of nearshore internal bores in southern Monterey Bay was modulated by mid-shelf stratification and wind-driven upwelling/relaxation cycles. Cheriton et al. (2014b) illustrated that upwelling events led to the infiltration of dense water onto the shelf, which created a near-bottom pycnocline and enabled the propagation of NLIWs onto the southern shelf. The authors concluded that regional upwelling dynamics partially control the ability of internal waves to propagate through continental shelf waters. The recent review by Washburn and McPhee-Shaw (2013) discusses how seasonal upwelling, and transitions between upwelling/downwelling events and changes in stratification, may lead to the modulation of internal wave transport and the delivery of subthermocline waters to shallow coastal regions. While the above-mentioned studies have revealed significant insight into the influence of regional upwelling cycles on internal wave structure and transport, the studies were limited to observations over (up to) several months during a specific upwelling seasonality regime (García-Reyes and Largier, 2012). Observations encompassing a complete annual record documenting the seasonal variability in upwelling winds and the subsequent response of shallow water NLIWs and bores are needed as they would provide a seasonal context for this phenomenon. This will provide a basis for insight into a host of physical processes (see above) that underpin and interact with the coastal ecosystem, for example through the seasonal modulation of the flux of subthermocline waters (high nutrients, low DO/pH) to the nearshore.

In this study, we take advantage of long-term moored measurements made in relatively shallow waters (~30 m depth) at the head of the MSC in order to characterize the physical environment and the seasonality of NLIWs/bores. We expand on the observations of Shea and Broenkow (1982) with a more spatiotemporally resolved data set and a more detailed look into the dynamics at the head of the MSC. The spatial and temporal variability of the NLIW/bore field and the subsequent impact on the transport of subthermocline waters is also examined. Extension of the results to other locations, recommendations for future work, and ecological implications are briefly discussed.

2. Experimental setup and methods

2.1. Study site

Monterey Bay is a semi-enclosed embayment located along the central coast of California and within the highly productive CCLME (Fig. 1). It is also a biologically diverse marine system located within the Monterey Bay National Marine Sanctuary, and it is home to some of the world's largest kelp forests (*Macrocystis pyrifera*) and large commercial fisheries. The bay features a narrow shelf near the canyon head region where the canyon rim is closest to the shoreline and a relatively broad shelf elsewhere with roughly 80% of the bay shallower than 100 m (Breaker and Broenkow, 1994). The narrow shelf is cut by a system of submarine canyons, the largest of which is the MSC. The MSC is one of the largest submarine canyons on the west coast of the United States. The main axis of the MSC bisects through the approximate center of the bay and terminates at the canyon head, which is located within 100 m of the shore and entrance to the Moss Landing Harbor (Fig. 1).

General physical oceanographic conditions include a mixed semidiurnal tide with currents dominated by the M_2 (~12.42 h period) tidal constituent (Breaker and Broenkow, 1994). The intense