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Research papers

Coastal upwelling seasonality and variability of temperature and chlorophyll in a small coastal embayment

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ABSTRACT

While the seasonality of wind-driven coastal upwelling in eastern boundary upwelling systems has long been established, many studies describe two distinct seasons (upwelling and non-upwelling), a generalized framework that does not capture details relevant to marine ecosystems. In this contribution, we present a more detailed description of the annual cycle and upwelling seasonality for an understudied location along the central California coast. Using both the mean monthly upwelling favorable wind stress and the monthly standard deviation, we define the following seasons (contiguous months) and a transitional period (non-contiguous months): "Winter Storms" season (Dec-Jan-Feb), "Upwelling Transition" period (Mar and Jun), "Peak Upwelling" season (Apr-May), "Upwelling Relaxation" season (Jul-Aug-Sep), and "Winter Transition" season (Oct-Nov). In order to describe the oceanic response to this upwelling wind seasonality, we take advantage of nearly a decade of full water-column measurements of temperature and chlorophyll made using an automated profiling system at the end of the California Polytechnic State University Pier in San Luis Obispo Bay, a small (~ 2 km wide near study site) and shallow (~ 10 m average bay depth) coastal embayment. Variability and average-year patterns are described inside the bay during the various upwelling seasons. Moreover, the role of the local coastline orientation and topography on bay dynamics is also assessed using long-term measurements collected outside of the bay. The formation of a seasonally variable upwelling shadow system and potential nearshore retention zone is discussed. The observations presented provide a framework on which to study interannual changes to the average-year seasonal cycle, assess the contribution of higher-frequency features to nearshore variability, and better predict dynamically and ecologically important events.

1. Introduction

Equatorward winds drive coastal upwelling in eastern boundary current upwelling systems around the world (cf. Chavez and Messié, 2009). In the California Current System (CCS), the wind-driven upwelling is forced by the atmospheric circulation and geostrophic winds around the North Pacific High (NPH), a feature that fluctuates seasonally (Huyer, 1983). Along the coastline, the presence of a coastal boundary and highly polarized alongshore winds (see Fewings et al., 2016 and the references therein) results in a shallow offshore (Ekman) transport of surface waters. This process is driven by the earth's rotation (Coriolis) and causes upwelling of cool, nutrient-rich waters from below the surface Ekman layer to the coastal environment. The upwelled waters occur along a narrow 5–30 km band adjacent to the coastline, a cross-shelf distance that scales latitudinally with the internal Rossby radius of deformation (Checkley and Barth, 2009). These nutrient-rich waters result in elevated levels of primary production and higher trophic level production (Huyer, 1983; Pennington and Chavez, 2000; Chavez and Messié, 2009 and the references therein). Due to the low pH and dissolved oxygen (DO) content characteristic of subthermocline waters, upwelling can also significantly affect nearshore hypoxia and ocean acidification (OA) (Boehm et al., 2015 and the references therein).

The seasonality of regional upwelling favorable winds in the CCS has long been established, with many studies describing two distinct seasons: the summer upwelling season and the winter non-upwelling season (Huyer, 1983; Dorman and Winant, 1995; Checkley and Barth, 2009 and the references therein; García-Reyes and Largier, 2012 and the references therein; Walter et al., 2014b; Walter and Phelan, 2016). As noted by García-Reyes and Largier (2012), the more widely adopted bimodal (upwelling and non-upwelling) description of upwelling does not encapsulate seasonality features that are important for nearshore

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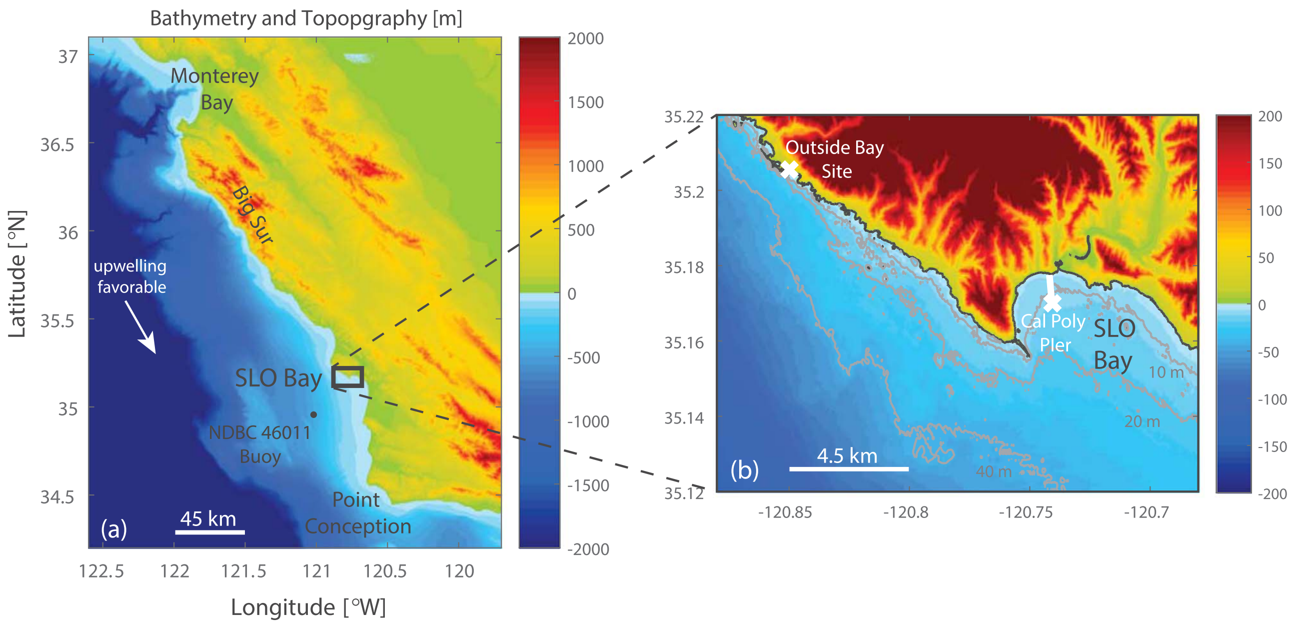

Fig. 1. (a) Bathymetry and topography of the central California coastline highlighting important locations including SLO Bay and the location of the offshore buoy used for upwelling seasonality analysis. The white arrow indicates the direction of upwelling favorable winds (150° from true north). (b) Zoomed in map of northern SLO Bay (~ 2 km wide near the Cal Poly Pier) showing the location of the automated profiling package (white x) at the end of the Cal Poly Pier (solid white line), as well as the thermistor location located outside the bay (white x). The 10, 20, and 40 m isobaths are shown as gray lines.

ecosystems. This includes the so-called "spring transition" from winter to strong upwelling conditions, an event that has profound consequences for higher-trophic levels (see review by Checkley and Barth, 2009). Additionally, the distribution and abundance of different phytoplankton species, including several species that lead to harmful algal blooms (HABs), fluctuates throughout the year, and particularly within the upwelling season, in response to changing environmental conditions and small-scale physical processes (Gentien et al., 2005; Kudela et al., 2005). A more detailed and temporally-resolved description of upwelling and the oceanic response, beyond the bimodal description, could be useful for the prediction of dynamically and ecologically important events.

Recognizing the importance of upwelling seasonality, García-Reyes and Largier (2012) used long-term wind data measured at offshore buoys along the central and northern California coast (~ 35–42°N) to describe the seasonal variability of upwelling favorable winds, as well as the response of the coastal ocean using sea surface temperature (SST) and surface chlorophyll concentrations. Based on the mean and standard deviation of the monthly upwelling-favorable wind stress, they defined three distinct upwelling seasons (with the remaining months categorized as transitional periods): the "Storm Season" (Dec-Jan-Feb) with weak mean and highly variable upwelling winds; the "Upwelling Season" (Apr-May-Jun) with strong mean equatorward winds and large standard deviations due to frequent reversals; and the "Relaxation Season" (Jul-Aug-Sep) with weaker upwelling-favorable winds and low variability (García-Reyes and Largier, 2012). Other studies have also included this third fall relaxation season (also sometimes called the "Oceanic Season"), particularly when describing central California upwelling (Skogsberg, 1936; Largier et al., 1993; Pennington and Chavez, 2000; García-Reyes and Largier, 2012). While the García-Reyes and Largier (2012) study built a strong foundation on which to examine seasonality in central and northern California, there were strong latitudinal differences in the timing, strength, and intensity of the upwelling-favorable winds, as well as the corresponding near-surface oceanic response.

In this contribution, we present a tuning of the annual cycle and upwelling seasons for an understudied location along the central California coast. Likewise, we build on the analysis of García-Reyes and Largier (2012) by considering the oceanic response throughout the entire water column. A further understanding of the effect of upwelling seasonality on water-column stratification, as well as the vertical distribution of chlorophyll, provides insight into various physical and biological processes such as the vertical mixing and flux of nutrients and other scalars to the surface photic zone, biogeochemical cycling, internal wave and bore dynamics and water column stability, HAB bloom dynamics and patterns of toxicity, and coastal hypoxia/OA (Pennington and Chavez, 2000; Gentien et al., 2005; Kudela et al., 2005; Ryan et al., 2008, 2014; Chavez and Messié, 2009; Checkley and Barth, 2009; Booth et al., 2012; Walter et al., 2012, 2014a, 2014b, 2016; Walter and Phelan, 2016). We take advantage of nearly a decade of full water-column measurements of temperature and chlorophyll made in a small (~ 2 km wide near the study site) and shallow (average bay depth of ~ 10 m) coastal embayment. Despite the ubiquity of small coastal embayments along eastern boundary currents worldwide, there are few long-term time series of full water-column measurements (cf. Pennington and Chavez, 2000). Here, we introduce an automated profiling system at the end of the California Polytechnic State University (Cal Poly) Pier located in San Luis Obispo (SLO) Bay. We describe the seasonal dynamics and average-year patterns of temperature and chlorophyll in relation to the upwelling seasons defined using local offshore wind characteristics. This represents one of the only studies documenting seasonal cycles of nearshore variability throughout the water column from a long-term data set in a poorly sampled region along the California coastline stretching from south of Monterey Bay and the Big Sur Coastline to north of Point Conception, the latter of which is a major marine biogeographic boundary (Blanchette et al., 2007; Checkley and Barth, 2009; Chao et al., 2017). The focus of this paper is the examination of seasonal variability; higher-frequency variability in response to upwelling and relaxation cycles and local diurnal wind forcing will be reported elsewhere (e.g., Walter et al., 2017). Finally, we consider the role that the local coastline orientation and topography have on bay dynamics and document the formation of a seasonally variable upwelling shadow and nearshore retention zone in the bay.