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Coastal circulation driven by short-period upwelling-favorable winds in the northern Baja California region

Hector S. Torres, Jose Gomez-Valdes *

Physical Oceanography Department, CICESE, Carretera Tijuana-Ensenada No. 3918, Zona Playitas, C.P. 22860, Ensenada, Baja California, Mexico

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ABSTRACT

Coastal upwelling in the California Current System depends on the synoptic variability of wind stress fields. In this system, the effects of short-period (days) wind stress fluctuations on coastal ocean circulation are particularly important south of Point Conception. Upwelling and relaxation events in northern Baja California's coastal waters are examined using shipboard measurements of water properties and currents during October 2009. Satellite-derived variables are also included in the analysis. An upwelling event and a relaxation event, both with short periods (4–3 days), are reported here. The quasigeostrophic theory is used to elucidate differences in upwelling and relaxation ocean behavior. There are noticeable differences in the potential vorticity budget on two typical isopycnals from the study area, namely, the 24.1σ_θ and the 26.0σ_θ. Planetary vorticity is the leading term (10^{-9}) on the two isopycnals not only during upwelling but also during relaxation. However, in the upper isopycnal, relative vorticity is larger during upwelling than during relaxation, while the stretching term is of the same order in both events; conversely, in the lower isopycnal, relative vorticity is of the same order in both events, while the stretching term is larger during upwelling than during relaxation. As a consequence of the conservation of potential vorticity, two ageostrophic circulation cells are established during upwelling, one in the upper isopycnal and the other in the lower isopycnal. The upwelling front dynamics generates the upper ageostrophic circulation cell, and the symmetric instability generates the lower ageostrophic circulation cell. The ageostrophic circulation cells are missing during relaxation.

1. Introduction

Coastal wind-driven upwelling and relaxation from upwelling events occur frequently in eastern boundary current coastal zones. They have been widely studied in the California Current System, where the synoptic-scale is the dominant scale in the wind stress field. The changes in the strength and position of the North Pacific High over the sea and the thermal low over the western United States cause seasonal changes (Reid et al., 1958). Off northern California, in particular, upwelling events occur frequently during the spring and summer (Shulman et al., 2010); in these seasons, the upwelling-favorable winds are regularly strong, persistent and organized over the continental shelf (Winant et al., 1988). Synoptic scale perturbations occur by the anomalous migration of the North Pacific High driven by climate mode variability, such as the El Niño-Southern Oscillation (ENSO) (Lynn et al., 1998) and Arctic Oscillation (Cohen et al., 2010). Local scale processes such as the inversion of the marine layer also generate perturbations of the wind stress field (Nuss et al., 2000).

South of Point Conception, the continental influence is also a factor in the synoptic variability. Winant and Dorman (1997) reported that the wind stress field in this region is affected by California's topography. Harms and Winant (1998) observed that the periods of upwelling-favorable wind stresses in the Santa Barbara Channel are approximately 4 days long from spring to fall; they also reported that the relaxation periods of the upwelling-favorable wind stresses are approximately 4 days long. Zaytsev et al. (2003) reported that shorts periods (5 days) of upwelling-favorable wind stress occur in the coastal zone of Baja California (at 30 °N) during the spring. Gomez-Valdes and Vazquez (2011) found that upwelling-favorable wind stresses and relaxations occur frequently and are regularly of short duration in northern Baja California. They reported a modal of 4 days for both wind patterns. In this paper, we focus on an upwelling-favorable wind event with a 4-day period (short period upwelling-favorable wind) and a relaxation event of 3-day duration.

Few scientific surveys have been carried out to study upwelling in the Baja California region. For example, Barton and Argote (1980) examined the ocean's response during June 1976 to summer wind stress conditions; they found that variations in the intensity of upwelling followed variations in the intensity of upwelling-favorable wind stress. Pérez-Brunius et al. (2006) used shipboard observations made between May 1997 and June 2004 to study the effects of the 1997–1998 and 2002–2004 ENSO events

* Corresponding author.

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on coastal upwelling. They reported a strong upwelling event in May 2002 in which the halocline reached the continental shelf. However, studies on the ocean's response to relaxation from upwelling events in the Baja California region are lacking in the literature.

The dynamics of the coastal upwelling process under variable wind stresses is three-dimensional and time dependent (Wang, 1997; Gan and Allen, 2002) and follows a primitive equation model. However, some of its characteristics can be studied using idealized models of coastal upwelling. For example, the two layer coastal jet model of Csanady (1977) explains the basic features of the spring transition off northern California. Additionally, quasi-geostrophic theory is a useful tool to analyze the vertical structure of fronts (Pollard and Regier, 1992; Pallas-Sanz et al., 2010) and to analyze the characteristics of the wind-driven circulation via the use of potential vorticity (PV) (Deremble et al., 2014). Because the upwelling process involves the generation of a coastal front by the upwelling-favorable wind stress, quasigeostrophic theory can be applied to the front dynamics if the front is sufficiently far from the topography.

In this study, we compare the two-dimensional (x–z) structure of an upwelling event with the two-dimensional structure of a relaxation event, the two events driven by short-period synoptic-scale perturbations, using quasigeostrophic theory. The study is based on high-resolution (near to the submesoscale in the across shore direction) shipboard measurements carried out in October 2009 off the west coast of northern Baja California (Fig. 1) and on satellite-derived variables such as the wind, sea surface temperature, and sea surface height anomaly. The main goal is to study the near-slope dynamics in upwelling regions where the short-period synoptic-scale variability of the wind stress is significant. It is found that the ageostrophic component during the upwelling event is significant in the slope waters. The paper is organized as follows. Section 2 describes the methods of the satellite-derived variables and shipboard measurements. Section 3 describes the results of the satellite-derived variables and shipboard measurements. Section 4 describes theoretical models to explain the physical processes involved with the investigation. A discussion is conducted in Section 5. The conclusions are in Section 6.

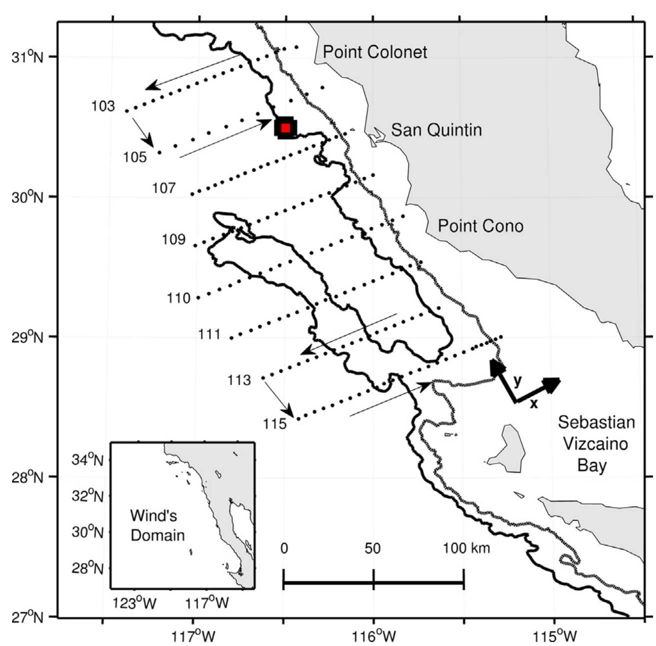

Fig. 1. Overview of the oceanographic campaign carried out in northern Baja California's upwelling region. The black dots represent the CTD/LADCP casts organized as lines. The line numbers follow the CalCOFI line nomenclature. The thin arrows indicate the ship navigation direction. The 500 m (continue line) and 1500 m (dashed line) isobaths are indicated. The coordinate system used in this study is also included. The inset is the wind's domain.

2. Methods

2.1. Satellite-derived variables

Sea surface winds (10-m) from the Cross-Calibrated Multiplatform (CCMP) database were analyzed. CCMP winds were retrieved from the NASA Physical Oceanography Distributed Active Archive Center. The horizontal and temporal resolutions of the CCMP winds were 0.25° and 6 h, respectively. Our analysis of the winds over the sea was concentrated on the area between latitudes 27°N and 35°N and longitudes 113°W and 125°W (inset in Fig. 1). The time series of the winds spanning from January 1992 to December 2011 were analyzed. The wind stress was calculated following Large and Pond (1981). The methodology for analyzing the wind stress fields was as follows.

To visualize the synoptic charts, a stream function fit was applied to the surface wind stress field (10-m) following Wei et al. (2008), who used a multivariate optimal interpolation method to examine the flow patterns of the Gulf Stream from shipboard Acoustic Doppler Current Profiler (ADCP) transects. We used an autocorrelation function of the form $F(r)=e^{-r^2/2L^2}$, where $r=\sqrt{(\Delta x)^2+(\Delta y)^2}$, $(\Delta x,\Delta y)=0.25^\circ$ and L is the decorrelation length scale. Our decorrelation length scale was 50 km.

To examine the sea surface temperature (SST) structures, the Level 3 database from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite was used, which was provided by NASA's Ocean Color Working Group. Its horizontal and temporal resolutions were 4 km and 1 day, respectively. Furthermore, to examine the sea surface height anomaly (SSHA) structures, data from AVISO was used, where the data resolutions were 25 km × 25 km in the spatial domain and 7-days in the temporal domain. The velocity field was calculated from the SSHA using the method of surface geostrophic currents from altimetry (Stewart, 2008).

Images of the SST and geostrophic velocities were analyzed from August to October 2009 on the same spatial domain as the wind stress products.

2.2. Shipboard measurements

An oceanographic survey was carried out from 9 October to 19 October 2009 in the southern part of the California Current (off the western coast of northern Baja California). The study area was between latitudes 31°07′31.10″ N and 29°06′44.49″ N and between longitudes 115°15′W and 117°30′W (Fig. 1). Eight cross-shore sections (lines) were occupied during the oceanographic survey, with each one aligned perpendicular to the coast. The line numbers follow the CalCOFI line nomenclature. The separation between adjacent lines was 37 km. Twenty stations were occupied in each line, except in Line 105 where only 11 stations were occupied. The distance from the coast to the first station was ~15 km for most lines. The distance between the stations was 5 km in any line, except for Line 105 where the distance was 10 km. At each station, conductivity–temperature–depth (CTD) casts were taken from the surface at 1000 m depth, depth permitting, using a SeaBird Electronics Inc., 9/11 CTD; a dissolved oxygen sensor SBE43 was integrated into this instrument. The measuring sensors were factory calibrated prior to the oceanographic survey. The CTD data were processed using the SeaBird software. The potential temperature, Practical salinity (hereinafter