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A resonant response of the California Current circulation to forcing by low frequency climate variability

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A B S T R A C T

Low frequency variability of the California Current System (CCS) is investigated using circulation estimates based on a 31-year (1980–2010) sequence of historical analyses of the CCS calculated using the Regional Ocean Modeling System (ROMS) 4-dimensional variational (4D-Var) data assimilation system. The leading 3-dimensional multivariate empirical orthogonal functions (3D EOFs) of the CCS circulation were computed and provide a detailed view of low-frequency circulation variability within the CCS. The 3D EOFs are used as basis functions for a linear inverse model of the circulation, and several Principal Oscillation Patterns (POPs) of the circulation are identified. The leading POPs have periods in the range $\sim 4 - 10$ years, and shed light on the 3-dimensional time evolving structure associated with low-frequency variability in the circulation. A particular focus here is coastal upwelling. In particular, a POP with a period close to 10 years appears to be preferentially excited as a resonant response to forcing associated with the regional expression of the Pacific Decadal Oscillation, the North Pacific Gyre Oscillation and the El Niño Southern Oscillation.

1. Introduction

The California Current is one of four major eastern boundary currents in the global ocean characterized by a pronounced seasonal cycle of coastal upwelling. Primary productivity in the California Current System (CCS) supports an important and diverse complex of marine ecosystems that are vulnerable to climate variability and climate change. The CCS circulation is characterized by variability on space- and time-scales ranging from the relatively short, sub-seasonal variability of the sub-mesoscale circulation, through to seasonal, inter-annual, and decadal time-scales. The CCS is arguably one of the best observed regions of the world ocean. Nevertheless, despite the plethora of ocean observations along the U.S. west coast, the *in situ* observations are fairly sparse in space and time, and large swaths of the ocean surface are often obscured by an extensive layer of marine stratus, preventing infrared sensors aboard earth orbiting satellites from observing the surface temperature. Data assimilation is therefore an important tool for blending discontinuous ocean observations with state-of-the-art ocean models to yield reliable space-time estimates of the circulation. Neveu et al. (2017) hereafter N16 describe in detail a sequence of ocean circulation estimates for the CCS that span the last three decades, and that are based on an advanced 4-dimensional variational (4D-Var) data assimilation system. The circulation estimates described in N16 are available as a community resource, and in this paper they are used to quantify the variability in the CCS circulation associated with the Pacific Decadal Oscillation (PDO), the North Pacific Gyre Oscillation (NPGO), and, to a lesser degree, ENSO.

The NPGO is the oceanic complement of the atmospheric North Pacific Oscillation and is characterized by a spin-up and spin-down of the subtropical and subpolar gyre circulations on decadal time-scales (Di Lorenzo et al., 2008). The NPGO index is defined as the Principal Component (PC) time series of the second EOF of SSH in the North Pacific (http://www.o3d.org/npgo). Since the CCS forms part of the equatorward branch of the North Pacific subtropical gyre, the NPGO can significantly influence the coastal circulation along the U.S. west coast. The positive phase of the NPGO manifests itself physically as a strengthening of the North Pacific Current characterized by an increase in the meridional sea surface height (SSH) gradient, downwelling favorable conditions in the subtropical gyre and along the Alaskan coast, and upwelling favorable conditions in the Alaskan gyre and in the CCS

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equatorward of 38 °N (Di Lorenzo et al., 2008).

Within the CCS region, the NPGO has been shown to correlate with variability in sea surface salinity (SSS), nutrients, chlorophyll-a, and alongshore upwelling winds (Di Lorenzo et al., 2009; Chhak et al., 2009a, 2009b). Combes et al. (2013) confirmed the connection between the NPGO and upwelling winds by correlating the surface concentration of a modeled passive tracer along the central and southern California coast (following a sub-surface release) with the NPGO index. Additionally, Chenillat et al. (2012) have shown that the phase of the NPGO can affect the timing of the onset of the upwelling season (i.e. the spring transition), with the positive (negative) phase initiating an earlier (delayed) onset. The timing of the spring transition has been shown to have significant ecological effects with an early onset of upwelling typically leading to a more productive ecosystem (McClatchie et al., 2009).

The PDO is another important basin-wide mode of variability, with a structure similar to the El Niño Southern Oscillation (ENSO) in the tropical central and eastern Pacific (Mantua et al., 1997). Similar to ENSO, the PDO drives variability through adjustments to the atmospheric pressure over the North Pacific and is defined as the first PC time series of SST in the North Pacific between 20° N and 65°N (http://jisao.washington.edu/pdo). During the positive phase of the PDO, anomalously low pressure in the North Pacific is associated with cyclonic winds along the west coast of North America. Poleward alongshore wind anomalies drive anomalous onshore transport of surface water creating anomalously high sea surface temperature (SST) and SSH. Schneider and Cornuelle (2005) have shown that the PDO can be viewed as the combined response of ocean forcing by ENSO and the Aleutian Low, and modulation of zonal advection by the Kuroshio-Oyashio extension by oceanic Rossby waves, lending weight to the idea that the PDO is not associated with a single dynamical mode of the ocean-atmosphere system.

The influence of the low-frequency component of the PDO on the CCS is commonly discussed in terms of regime shifts. A shift in phase (or polarity) of the PDO often leads to a shift in the long-term average (>10 years) of the ocean state that is generally accompanied by a shift in ecological communities. Such a regime shift occurred in 1977 when the PDO transitioned from a negative to positive phase accompanied by anomalously low sea level pressure leading to weakened alongshore winds, warm SST anomalies and anomalously high SSH in the CCS (Miller et al., 1994; King, 2005). Bograd and Lynn (2003) document a warming in the upper 200–400 m of the water column, an increase in stratification, and shifts in the position of the dominant large-scale currents in the CCS due to changes in the depth and slope of isopycnal surfaces. The PDO has also been linked with the source depth of coastally upwelled waters, with the positive phase leading to a reduction in source depth (Chhak and Di Lorenzo, 2007). This reduction in the supply of deep, nutrient rich waters during the positive phase of the PDO is coherent with changes in marine ecosystem communities during the 1977 regime shift (McGowan et al., 2003; Chavez et al., 2003).

More recently, Johnstone and Mantua (2014) have explored the role of the PDO in the context of the observed long term upward trend in SST in the Northeast Pacific between 1900 and 2012 (Field et al., 2006) and its connection to anthropogenic forcing. They found that even though an upward trend is apparent in sea level pressure and SST, a *possible* reversal of the trend has occurred since 1980.

The CCS response to ENSO is driven by two distinct mechanisms often referred to as *local* and *oceanic* mechanisms. The local forcing of ENSO on the CCS is through atmospheric teleconnections from the tropics which drive changes in the local atmospheric circulation. The oceanic forcing occurs via coastally trapped waves that propagate poleward along the coastal wave guide from the equator. A frequently used index of ENSO activity in the equatorial Pacific is the Multivariate ENSO Index (MEI, http://www.esrl.noaa.gov/psd/enso/mei). The MEI is defined as the principal component (PC) time series of the first EOF of a combination of several measured oceanic and atmospheric variables in the tropical Pacific that include sea-level pressure, SST, zonal and meridional components of the surface wind, surface air temperature and total cloudiness (Wolter and Timlin, 2011).

The PDO and NPGO are essentially statistical constructs and have been identified from EOF analyses of surface fields alone. However, this view of the oceanic and atmospheric circulation is far from complete and may very well represent a very distorted view of the circulation variability in regions such as the CCS. In this paper, we have adopted a different approach to that commonly used, and explore variability in CCS circulation estimates by considering covariability in the full 3-dimensional ocean circulation. The ocean circulation estimates used here span the period 1980–2010 and were computed using the Regional Ocean Modeling System (ROMS) and a 4D-Var data assimilation system. The ROMS-CCS 4D-Var analysis system is briefly reviewed in Section 2. In Section 3, multivariate 3-dimensional principal component analysis is used to explore the dominant spatial modes of variability captured by the 4D-Var analyses. In Section 4, the Principal Oscillation Patterns (POPs) of the CCS circulation are computed using linear inverse modeling methods, and in Section 5 are used to explore the intrinsic low frequency variability of coastal upwelling. Specifically forcing of the leading POPs by the PDO, NPGO and ENSO is explored. A summary of our findings and conclusions is presented in Section 6.

2. The CCS historical analyses

The CCS circulation estimates analyzed here were computed by assimilating available observations for the period 1980–2010 into ROMS using 4D-Var data assimilation. The configuration of the model and ROMS 4D-Var data assimilation system are presented in detail in N16, so only a brief description will be given here.

The ROMS CCS model domain and bathymetry are illustrated in Fig. 1. The model was configured with 1/10° horizontal resolution and 42 terrian following σ-levels in the vertical that vary in thickness between 0.3 m and 8 m over the continental shelf and 7–100 m in the deep ocean. The period 1980–2010 was divided into consecutive 8-day overlapping windows, and all available ocean observations during each window were assimilated into ROMS CCS. Observations assimilated

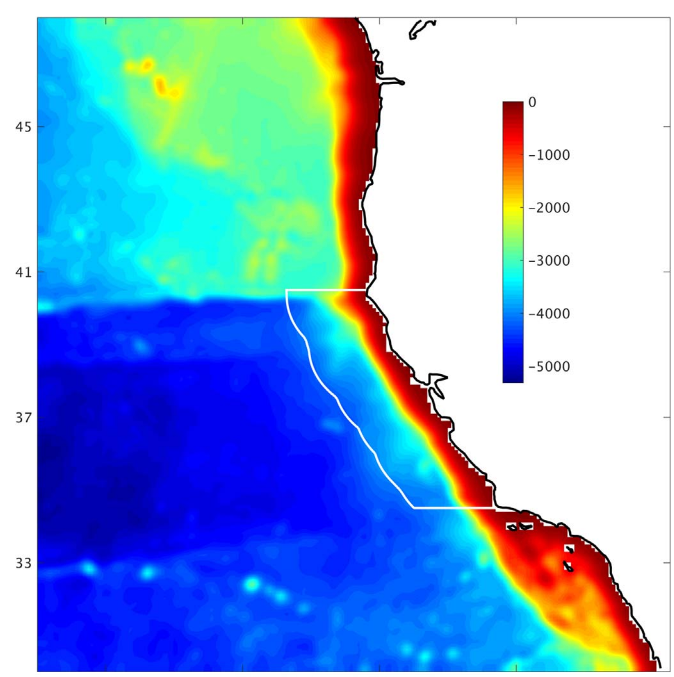

Fig. 1. The ROMS domain and bathymetry (m) used in WCRA31. Also shown is the central California region referred to in the text, which extends offshore 200 km between Cape Mendocino and Point Conception.