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The impact of the ocean observing system on estimates of the California current circulation spanning three decades

Andrew M. Moore [a,*], Michael G. Jacox [b,c], William J. Crawford [a], Bruce Laughlin [a], Christopher A. Edwards [a], Jérôme Fiechter [a]

[a] Department of Ocean Sciences, 1156 High Street, University of California, Santa Cruz, CA 95062, United States
[b] Institute or Marine Sciences, 1156 High Street, University of California, Santa Cruz, CA 95062, United States
[c] Environmental Research Division, Southwest Fisheries Science Center, NOAA, Monterey, CA, United States

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ABSTRACT

Data assimilation is now used routinely in oceanography on both regional and global scales for computing ocean circulation estimates and for making ocean forecasts. Regional ocean observing systems are also expanding rapidly, and observations from a wide array of different platforms and sensor types are now available. Evaluation of the impact of the observing system on ocean circulation estimates (and forecasts) is therefore of considerable interest to the oceanographic community. In this paper, we quantify the impact of different observing platforms on estimates of the California Current System (CCS) spanning a three decade period (1980–2010). Specifically, we focus attention on several dynamically related aspects of the circulation (coastal upwelling, the transport of the California Current and the California Undercurrent, thermocline depth and eddy kinetic energy) which in many ways describe defining characteristics of the CCS. The circulation estimates were computed using a 4-dimensional variational (4D-Var) data assimilation system, and our analyses also focus on the impact of the different elements of the control vector (*i.e.* the initial conditions, surface forcing, and open boundary conditions) on the circulation. While the influence of each component of the control vector varies between different metrics of the circulation, the impact of each observing system across metrics is very robust. In addition, the mean amplitude of the circulation increments (*i.e.* the difference between the analysis and background) remains relatively stable throughout the three decade period despite the addition of new observing platforms whose impact is redistributed according to the relative uncertainty of observations from each platform. We also consider the impact of each observing platform on CCS circulation variability associated with low-frequency climate variability. The low-frequency nature of the dominant climate modes in this region allows us to track through time the impact of each observation on the circulation, and illustrates how observations from some platforms can influence the circulation up to a decade into the future.

1. Introduction

The California Current System (CCS) along the west coast of North America forms the equatorward branch of the North Pacific subtropical gyre (see Fig. 1). It comprises a dynamicaly rich and highly variable circulation which has been the subject of many previous studies (see Hickey (1998) and Checkley and Barth (2009) for some excellent in-depth reviews). A dominant feature of the CCS circulation is the presence of a pronounced seasonal cycle in coastal upwelling. During the spring and summer, the winds between Washington and Baja California are equatorward and upwelling favorable. This results in cold, nutrient rich waters at the ocean surface which in turn enhance ocean primary productivity. The associated offshore Ekman transport also sets up an offshore pressure gradient that drives an equatorward coastal jet. During the fall and winter, the North Pacific high pressure system gives way to the Aleutian low and the winds north of ~40N become poleward which promotes downwelling along the coast of Northern California, Oregon and Washington. A poleward flow at depth is also often present, the so-called California Undercurrent (CUC), located over the continental shelf between 100 m and 300 m, with a velocity $\sim 0.1–0.3\ ms^{-1}$ (Hickey, 1998). The CUC is relatively poorly observed, although it has been observed along the entire west coast of the U.S. (Pierce et al., 2000). While a poleward current is to be expected on the grounds of mass

* Corresponding author.
E-mail address: ammoore@ucsc.edu (A.M. Moore).

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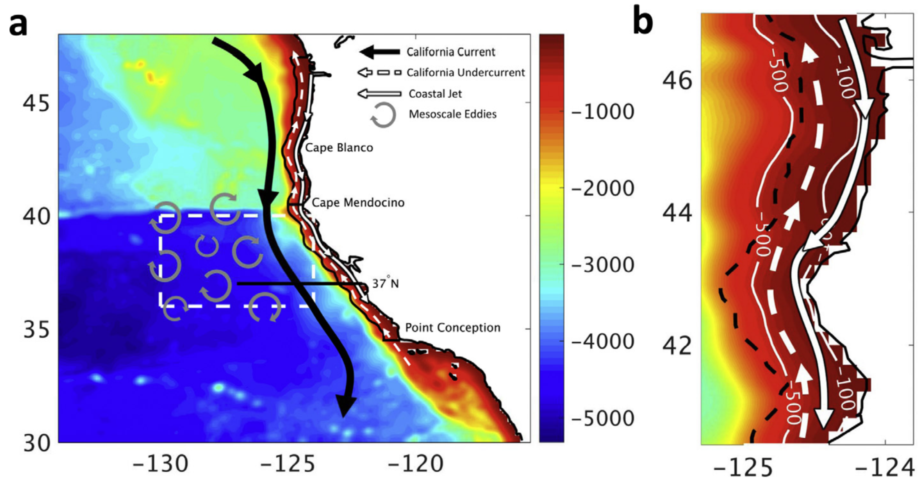

Fig. 1. (a) The ROMS CCS model domain and bathymetry. Also shown is a schematic representation of some important dynamical features of the circulation in the region. The central and northern CCS target regions for upwelling and thermocline depth referred to in the main text are shown (black lines), as well as the target region for eddy kinetic energy (white dashed line) and the 37°N section. (b) A zoom of the northern CCS region showing the 100 m and 500 m isobaths used to define the target region for the undercurrent transport.

conservation in the presence of coastal upwelling (e.g. Gill, 1982), the dynamics of the CUC are not well understood, although a recent study by Connolly et al. (2014) suggests that the CUC may be associated with an alongshore pressure gradient. At some times of the year, a surface poleward return flow is also observed along the coast, the so-called Davidson Current, which some have attributed to a surfacing of the CUC, although there is no census of opinion on this (Hickey, 1979).

The circulation is dominated by the first baroclinic mode, with the result that as the sea surface goes down in response to offshore transport during the upwelling seasons, the pycnocline shoals making nutrient rich sub-thermocline waters more accessible. Poleward of Cape Mendocino, the California Current (CC) and coastal jet form fairly coherent circulation features (Fig. 1). At Cape Mendocino, inertia carries the CC farther offshore where it becomes baroclinically unstable contributing to a field of energetic mesoscale and sub-mesoscale eddies, leading to a region of elevated eddy kinetic energy offshore (Kelly et al., 1998).

The CCS is also influenced by several known modes of climate variability that include the El Niño Southern Oscillation (ENSO), the North Pacific Gyre Oscillation (NPGO), and the Pacific Decadal Oscillation (PDO). Through a combination of changes in the local atmospheric circulation and remotely generated coastally trapped waves, ENSO exerts a significant influence on the physical and biogeochemical conditions in the CCS (Jacox et al., 2015; Frischknecht et al., 2015; Jacox et al., 2016). For example, thermocline depth, upwelling intensity, and the depth of the upwelling source waters can be dramatically different during El Niño years, leading to warmer than normal ocean temperatures and depleted nutrients along much of the California coast. Similarly, changes in the large scale atmospheric circulation over the NE Pacific associated with the PDO and NPGO have been linked to low frequency variability in the CCS (e.g. Di Lorenzo et al., 2008; Di Lorenzo et al., 2009; Johnstone and Mantua, 2014).

Recently, Neveu et al. (2016, hereafter N16) have computed a sequence of historical circulation estimates of the CCS spanning the period 1980–2010. Using the Regional Ocean Modeling System (ROMS) and a state-of-the-art 4-dimensional variational (4D-Var) data assimilation system, these analyses combine model circulation estimates with all available quality controlled ocean observations in the region to yield analyses of the ocean circulation environment that are more reliable than either the model or the observations considered in isolation. The focus of the present study is to explore the extent to which the different observing platforms constrain different aspects of the circulation that characterize the CCS (e.g. upwelling, alongshore transport, the CUC, eddy kinetic energy, etc), and changes in the circulation associated with the dominant low frequency modes of climate variability identified above.

Observation impact studies are now routine at many numerical weather centers (e.g. Langland and Baker, 2004; Errico, 2007; Zhu and Gelaro, 2008; Gelaro and Zhu, 2009; Lupu et al., 2011, 2012; Jung et al., 2013; Tyndall and Horel, 2013; Lorenc and Marriott, 2014). There have been some efforts in oceanography also to quantify the impact of the observing system on ocean analyses using Observing System Experiments (OSEs; e.g. Balmaseda et al., 2007; Oke and Schiller, 2007; Smith and Haines, 2009), spectral analysis of the representer matrix (Le Hénaff et al., 2009), quantification of the degrees of freedom of the observing system (Moore et al., 2011a), assessment of observation footprints (Oke and Sakov, 2012), and ensemble methods (Storto et al., 2013). A more extensive review of these efforts can be found in Oke et al. (2015a,b). In the present study we use an adjoint-based method developed by Langland and Baker (2004), that is commonly used by the meteorological community to quantify the impact of individual observations on different aspect of an analysis-forecast system.

This study is unique in that it quantifies the impact of an ocean observing system during a period spanning three decades starting from an initial period served only by in situ hydrographic data through to the present day where multiple satellite observing systems and in situ assets are in place. Section 2 outlines the ocean model, data assimilation system, and circulation analyses that form the foundation of this study. The methodology used to quantify the observation impacts is described in Section 3, along with several metrics that quantify important aspects of the CCS circulation. The impact of the control vector components and observations on each metric are presented in Sections 4 and 5 respectively. These calculations are extended in Section 6 to include climate variability. A summary and conclusions are presented in Section 7.