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Modeling the effects of coastal wind- and wind–stress curl-driven upwellings on plankton dynamics in the Southern California current system

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ABSTRACT

We use a Nitrogen-Phytoplankton-Zooplankton-Detritus (NPZD) biogeochemical model implemented in a time-dependent box model scheme to simulate the temporal dynamics of the pelagic ecosystem in the Southern California Current System (SCCS). The model was forced by winds, sea surface temperature and light. Nutrient inputs to the modeled box were driven by coastal upwelling or upwelling due to wind-stress curl in order to assess the importance of each process in the temporal dynamics of the SCCS ecosystem. Model results were compared to the CalCOFI dataset, both in terms of climatological annual cycles and actual values. This comparison led to modifications of the basic model structure to better represent the coastal ecosystem, particularly phytoplankton growth and zooplankton mortality terms. Wind-stress curl-induced upwelling was found to be significant only in the offshore regions while coastal upwelling better represented the dynamics of the inshore areas. The two upwelling mechanisms work in synchrony, however, to bring nutrients to surface waters during the same time periods. Finally, the effect of low-frequency perturbations, such as those associated with the ENSO and NPGO, were assessed by comparing model results and data. Since the NPGO cycle largely impacts the SCCS through modifications of upwelling-favorable winds, its effects were well represented in the model results. In contrast, ENSO responses were poorly captured in the simulations because such perturbations alter the system by changing surface water mass distributions via mechanisms that were not included in the model forcing.

1. Introduction

The California Current System (CCS) comprising the eastern boundary current of the North Pacific Gyre extends more than 15° of latitude over a range of temporally and spatially variable environments with subpolar to subtropical influences. Eastern boundary currents are among the most productive marine coastal environments in the world (Carr, 2002), providing the base for food webs that support some of the most economically important fisheries. The high biological productivity in the CCS is primarily fueled by the supply of nutrients from wind-driven upwelling as a result of the prevailing equatorward winds that push the near-surface waters offshore through Ekman transport, causing nutrient-rich waters from mid-depths to upwell to the surface (e.g. Murphree et al., 2003; Wooster and Reid, 1963).

In the northern CCS, along the relatively straight and north–south oriented coastline of Washington and Oregon, strong seasonal reversals in winds drive dramatic annual cycles in onshore and offshore currents, hydrographic properties and productivity (Hickey, 1979; Lynn and Simpson, 1987). Seasonal and interannual variabilities in productivity are closely tied to wind-driven coastal upwelling, with the offshore density front and equatorward jet responding rapidly to fluctuations in the strength of upwelling-favorable (southward) winds (Huyer and Smith, 1985; Strub and James, 2000). However, upwelling is not a spatially uniform process. Certain regions are more conducive to upwelling (Schwing and Mendelssohn, 1997), and local characteristics (topography, bathymetry, hydrography) can strongly modify the seasonal production patterns expected from the annual wind cycle on a regional scale (e.g. Henson and Thomas, 2007; Hickey and Banas, 2008). It is also known that several climatic phenomena influence the CCS on interannual scales, such as the strength and position of the Aleutian Low atmospheric pressure system (Rebstock, 2003) represented by the magnitude of the Pacific Decadal Oscillation index (PDO) (Mantua et al., 1997). Especially in the northern CCS, the phase and magnitude of the PDO index has been found to be correlated with fluctuations in standing stocks of phytoplankton (Thomas et al., 2009), zooplankton (Mackas et al., 2006), and fishes (Mantua et al., 1997).

In contrast to the northern CCS, the mechanisms connecting physical forcings and biological productivity are less clear in the southern sector of the California Current System (SCCS). Bathymetry and topography are complex in the area south of Point Conception (ca. 35°N) down to Baja California. Notably, the sharp eastward bend in the coastline at Point Conception (which creates the Southern California Bight (SCB)) establishes a wind gradient with an offshore maximum when southerly upwelling-favorable winds blow down the coast. Also, local wind stress

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at the coastline is generally weaker and without the pronounced seasonal directional changes of the northern region. Temporal physical dynamics of the SCCS are further complicated by currents that vary with the local surface winds (Allen, 1980).

Plankton dynamics in the SCCS have been well documented (Allen, 1941; Hayward and Venrick, 1998) but are still not well understood. One of the main points of debate is the extent to which coastal upwelling is responsible for the annual plankton cycle (as it is in the northern CCS) since regular coastal upwelling is limited to a small region around Pt. Conception (Fig. 1) (Hickey, 1979; Lynn and Simpson, 1987). Di Lorenzo (2003) has noted, however, that isopycnals generally tilt upward along the coast during the upwelling season, forced by winds in the SCB. While upwelling-favorable winds relax close to shore during summer, they are still strong offshore near the continental slope. This positive gradient generates wind-stress curl and offshore upwelling. The relative contributions of the two upwelling processes to plankton production in the SCCS are poorly known. Recent estimates suggest, however, that wind-stress curl, though of lesser intensity than coastal upwelling, could provide half or more of the upwelling transport within the CCS because it affects a much larger surface area (Pickett and Paduan, 2003; Rykaczewski and Checkley, 2008).

Another important feature of the annual production cycle in the SCCS is its response to remote forcing by climatic patterns, one of the most significant on interannual scales being the El Niño-Southern Oscillation (ENSO) (Bograd and Lynn, 2001). Decreased biological productivity is observed in the SCCS during El Niño events, generally with an opposite response during La Niña conditions (Chavez et al., 1998). An additional potentially influential climatic oscillation in the region is the North Pacific Gyre Oscillation (NPGO) described by Di Lorenzo et al. (2008). This climatic pattern emerges as the 2nd dominant mode of sea surface height variability in the Northeast Pacific and is well correlated with upwelling intensity and primary production along the California coast.

With >60 years of time-series sampling in the SCCS, the California Cooperative Oceanic Fisheries Investigations (CalCOFI) provide a rich data set for understanding seasonal patterns and long-term trends in the region (Bograd et al., 2003; Lavaniegos and Ohman, 2007). Here, we attempt to synthesize the data using a coupled physical-biological model (c.f., Riley, 1941). Simulating the small spatial scales, rapid time-varying processes and strong mesoscale features of coastal systems (e.g., Moisan et al., 2004) has progressed rapidly in the last decade with the increase in computer technologies, improved methods for computational fluid dynamics, improved knowledge of ocean circulation and biogeochemical dynamics, and large increase in availability of remotely sensed data for model forcing and validation (Moore et al., 2004).

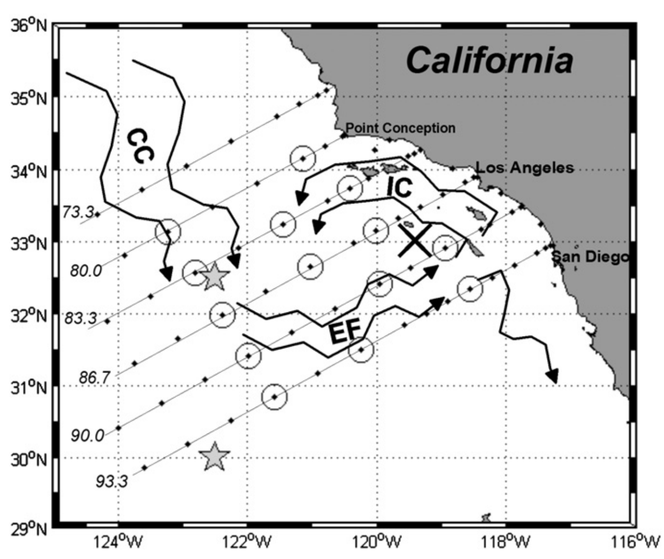

Fig. 1. The Southern California Current System. Black dots are the CalCOFI grid stations. Encircled stations are used for climatological comparison. Black cross show the location of the coastal upwelling index (CUI) estimate, and gray stars are the positions where wind-stress curl was calculated. The main circulation features are also shown schematically: the California Current (CC), the Ensenada Front (EF) and the Inshore Countercurrent (IC).

Our approach to simulating these highly dynamic areas is to reduce complexity to minimum levels by using integrative representations. Thus, in the present work we simulate ecosystem dynamics of the SCCS with a NPZD model using a time-dependent box model framework of the surface ocean. Nutrient input to the modeled box is forced by either coastal or wind-stress curl-driven upwelling. This box-model physical framework has been applied successfully to simulate coastal upwelling systems in previous studies (e.g., Ianson and Allen, 2002; Olivieri and Chavez, 2000). Its simplicity greatly reduces the computational cost, allowing a more thorough analysis of the simulation results and more extensive comparison with observational data.

The biogeochemical model is based on Fasham et al. (1990), which was initially developed to simulate the seasonal cycle of nutrients and primary production at Station S off Bermuda and includes a simplified microbial loop represented by heterotrophic bacteria. This general formulation has been used in many local, regional and basin-scale applications with considerable success (e.g., Fasham, 1995; Sarmiento et al., 1993; Toggweiler and Carson, 1995).

In the present study, results of the model are compared to climatological and actual values from the CalCOFI grid to evaluate (i) the relative importance of upwelling processes (coastal versus wind-stress curl) and (ii) the potential of this simple approach to predict the conditions of the SCB under different climate scenarios, including ENSO cycles and NPGO variations.

2. Material and methods

Our model is only time dependent, with a “virtual box” represented by mean parameter values of the upper 50 m water in the SCB. The horizontal dimension of the box is approximately equal to the internal Rossby radius of deformation in the area, calculated to be around 10 km (e.g., Franks, 1992).

Two different sets of simulations are performed, one using coastal upwelling forced by Ekman pumping and the other using wind-stress curl-induced upwelling as the main external forcing to the model (see detailed description below). Each simulation represents 42 year period, from 1967 to 2008, the length of the available upwelling time-series. Each simulation was initiated after a spin-up run of 10 years i.e., the model was run during the first 10 years of the available upwelling forcing using as initial values the mean of all model constituents for the region available in the literature. The ecosystem final state after these 10 years run was used as the initial condition for the 42-year run. Model equations were solved using the *ode45* function in Matlab®, which adjusts the time step to ensure that the maximum difference between consecutive integrations is of order 10^{-6}. The output was collected and stored for each 14.4 minutes of simulation, essentially breaking each day into 100 time steps.

We assume that the water input to the modeled box (computed as described below) only contains nitrate, with the concentrations of all other constituents of the ecosystem being zero. The upwelled water with associated nutrients is considered to be immediately mixed and homogeneously distributed throughout the entire box neglecting any spatial heterogeneity. To conserve volume, an equal amount of water to that introduced by upwelling leaves the modeled box at each time step. This outflowing water has the characteristics of the box waters, with identical concentrations of all constituents of the ecosystem, both living and nonliving.