Modeling observed California Current mesoscale eddies and the ecosystem response

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Abstract. Satellite and in situ observations are used to test model dynamics for the California Current System (CCS). The model and data are combined to reconstruct the mesoscale ocean structure during a given three-week period. The resulting physical flow field is used to drive a 3D ecosystem model to interpret SeaWiFS and in situ chlorophyll-a (Chl-a) variations. With this approach we obtain a more complete and consistent picture of the physical and ecosystem processes of the CCS, and provide the basis for addressing fundamental questions about dynamics and predictability of the coastal ocean.

1. Introduction

Many studies on the dynamics of the California Current System (CCS) have been conducted using observations (Hickey 1998) and numerical models (Haidvogel et al. 1991). This region is characterized by intense mesoscale activity, with generation and evolution of complex meanders, eddies and filaments along the coast. The processes responsible for the underling dynamics of many of these features are not well understood (Strub et al. 1991), leaving us with an incomplete view of the controlling mechanism of large-scale and mesoscale variations of the physical properties.

The rich variety of dynamics along the California coast is also of primary influence in the evolution of the oceanic ecosystem (e.g., Hayward and Venrick 1998). Identifying the specific mechanisms of the physical forcing can aid biological population dynamics studies and fisheries management applications.

Combining data from various sources (including satellite and in situ measurements) with numerical models of physics and biology can provide a means for addressing questions about the physical and ecosystem processes. It also enables us to gain more insight on the extent to which satellite surface data and limited subsurface data describe the complete 3D ocean for nowcasting and forecasting purposes.

We present here the results of fusing different data sources with a 3D dynamical ocean circulation model to develop a more complete picture of the evolving flow field observed during February 1998 in the Southern California Bight (SCB) coastal ocean. The inverse procedure used to combine the observations with the physical model, often referred to as a "fit", minimizes the model-data mismatch and allows the model to evolve consistently with its own dynamics. The flow field resulting from the fit is used to drive a seven-component ecosystem model that provides a 3D view of the evolving biology.

Fits such as these can be used to diagnose the model dynamical balances and assess the importance of mesoscale instabilities, topographic control, remote oceanic forcing and wind forcing in eddy evolution in the SCB and to examine properties of the biological dynamics. Predictive timescales can also be assessed in various flow regions by integrating the model forward in time into periods where independent data is available.

We here mainly focus on results of testing the assimilation method in fitting the physics of the SCB for a specific time period and testing the qualitative behavior of the spatial and temporal evolution of the ecosystem response. A brief dynamical interpretation of the results from the fit is provided. Detail analysis of the dynamical balances of the physics and biology, and predictive skill of the California coastal ocean will be addressed in later publications.

2. Data Sources

The data used in this study include: TOPEX/POSEIDON (T/P) altimetry measurements of sea level height; daily satellite-derived estimates of near-surface Chl-a obtained from the NASA SeaWiFS data archive; and in situ measurements of temperature, salinity, nitrate, and Chl-a from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) hydrography (http://www-mlrg.ucsd.edu/calcofi.html) from 23 Jan to 14 Feb 1998. The model uses the NCEP ocean analysis fields for lateral boundary conditions, COADS as surface forcing and ETOPO5 as bottom topography.

3. Physical and Ecosystem Model

The eddy-resolving primitive equation ocean model used here is called the Regional Ocean Modeling System (ROMS), a descendent of SCRUM (Song and Haidvogel 1994) that has improved physics and parallel architecture (Marchesiello et al. 2002). The model uses a generalized sigma-coordinate system in the vertical and a curvilinear horizontal grid (9 km resolution) that extends approximately 1200 km along the coast from northern Baja to north of the San Francisco Bay area with roughly 800 km offshore extent normal to the coast. In this domain, Di Lorenzo (2003) has shown that the model is able to capture the dynamics of the observed seasonal circulation when forced with realistic atmospheric forcing.

The physical model drives a seven-component NPZD ecosystem model that includes nitrate, phytoplankton, zooplankton, two (large and small) detritus pools, ammonia, and Chl-a. The biological quantities are modeled with an advection-diffusion equation and non-linear source/sink coupling terms (Moisan and Hoffman 1996) computed following the Fasham et al. (1990) formalism.

4. Fitting Method

A given three-week model run is sampled with the same temporal and spatial resolution of the actual data in order to compute a model-data misfit (sum of squared differences between observed and modeled variables). The misfit is reduced by adjusting the model ocean initial conditions under the assumption that the model physics and surface forcing are correct. The physical model is first initialized using all the subsurface data to generate a first-guess initial condition. A set of perturbation runs (240 each for temperature and salinity) that represent independent spatial corrections to the initial temperature and salinity are used in an inverse method approach (e.g., Wunsch 1996) to find the optimal correction to the initial state. The inverse method is described in detail by Miller and Cornuelle (1999) and is applied to other observations in the SCB by Miller et al. (2000).

The 3D NPZD ecosystem model is tested for qualitative consistency with observations for the January-February 1998 period, characterized by low productivity and stronger than usual coastal poleward flow in the SCB because of the El Niño conditions. We attempt to model only that part of the biological variability that is driven by physical processes. To initialize the ecosystem model, the physical initial condition (obtained from the fit procedure) is used to force the ecosystem model until the biological variables adjust to the physical forcing. The first day of integration is iterated 15 times, where in each iteration the physics is restarted from its initial condition and the biological variables continue from their end values from the previous 1-day period. This ecosystem initialization procedure was tested successfully with a model twin experiment in this domain. After spinning up the ecosystem we then perform the 21-day fully evolving physics and biology integration covering the period of the fit.

5. Results and discussion

The fitting procedure is successful in reducing by 49% the model-data misfit variance of temperature and salinity during the 23 Jan to 14 Feb 1998 period. The spatial structure of the flow field in the model (represented by the depth of the 26.5 isopycnal) compares well with the observed (figure 1). A narrow coastal current in the SCB moves northward during this time interval, indicative of nearshore warming from the strong El Niño conditions. Offshore a cold, slowly evolving, eddy migrates westward.

An independent estimate of the surface circulation is provided by the T/P sea surface height anomaly (SSHa) analyses (AVVISO, Le Taron et al. 1998) over the period of the fit (figure 2a). The T/P SSHa is defined with respect to the 1993-1996 annual mean. The model SSHa (figure2b) is defined with respect to a 50-year model annual mean because a 1993-1996 model hindcast is not available. In order to reduce the offset between the two different means, we also remove the spatial average SSHa over the CalCOFI data domain for the period of the fit for both T/P and model. Taking into account the errors associated with the model annual mean SSH estimate, the T/P analysis, and the different time averages used to obtain the maps gives us an estimated error of ? 6 cm.

The spatial structure in T/P compares well with the model both inside the CalCOFI data domain as well as north of this area. Spatial differences are noticeable along the coast in the SCB region where the model shows an anomalous narrow poleward flow that T/P is unable to resolve. South of the CalCOFI data domain, the model is too close to its southern open boundary to properly resolve the flow field. Two dipole eddy structures are found in the model and T/P, indicated as E1 and E2 in figure 2a,b. At location E2 the dipole structure is found to migrate westward in the model integration, significantly impacting the ecosystem response as discussed below. Because the dipole lies outside the CalCOFI data domain, where subsurface initial condition cannot be constrained by the data fit, its evolution in the model differs from that seen in T/P. At location E1 the T/P analysis shows a cyclonic eddy that is stronger and larger than the eddy seen in the model. However, the T/P track locations reveal that this eddy was not directly sampled by T/P and can therefore be attributed to the AVVISO analysis procedure. In between the T/P tracks, the density structure of the model is very close to and consistent with the in situ CalCOFI data.

A more quantitative comparison between T/P and model can be obtained by computing the misfit of the space-time alongtrack SSHa between T/P and model inside the CalCOFI domain. The misfit (figure 2f) shows that the differences generally lie within the estimated errorbars suggesting that the in situ measurements are sufficient to constrain the flow field when sampled at this spatial and temporal resolution.

These results demonstrate that the physical model fit is largely consistent with the mesoscale dynamics in the SCB region of the CCS. In future applications of the fitting procedure, the T/P data will be included in the pool of fit data. This will provide a stronger constraint for the physical fields outside the SCB domain where the only available information here comes from poorly resolved NCEP ocean analyses. Moreover, the spatial resolution of the correction to the initial conditions needs to be increased by including higher horizontal and vertical wave number perturbation members in the ensemble. Preliminary tests of the sensitivity of the model suggest that adjustments to surface forcing and boundary conditions are less important than initial condition adjustments for this three-week fitting interval.

The spatial structures and time dependence of model chlorophyll qualitatively compare well with SeaWiFS, showing high values along the coast with maxima exceeding 1.5 micromole N/m^3 (equivalent to mg chl-a/m^3) (figure 2c,d). Further off the coast, horizontal advection and vertical mixing by the eddies contribute to the generation of high values of model surface Chl-a, respectively, at locations E2 and E3 (figure 2d). The signature of these processes in Chl-a is also evident in SeaWiFS although the spatial structures are less coherent because of the non-synoptic sampling and averaging.

Comparing CalCOFI Chl-a variability with SeaWiFS and model maps is difficult because changes in Chl-a over several-week intervals are even higher than those of the physical variables. Mapping the in situ CalCOFI Chl-a over the period of the cruise (figure 2e) introduces substantial spatial and temporal aliasing, especially in the offshore regions dominated by the eddies. Nevertheless some similarities among CalCOFI, model and SeaWIFS Chl-a are visible. A quantitative comparison and a more detailed understanding of the ecosystem processes will be possible after rigorously applying a fitting procedure to the biological data.

This study gives a more complete and consistent picture of the physical and ecosystem processes involved in the SCB than can be obtained by analyzing the data or a model in isolation. In this perspective, it forms a basis for addressing fundamental questions about the underlying physical and biological dynamics, and the predictability of the coastal ocean.

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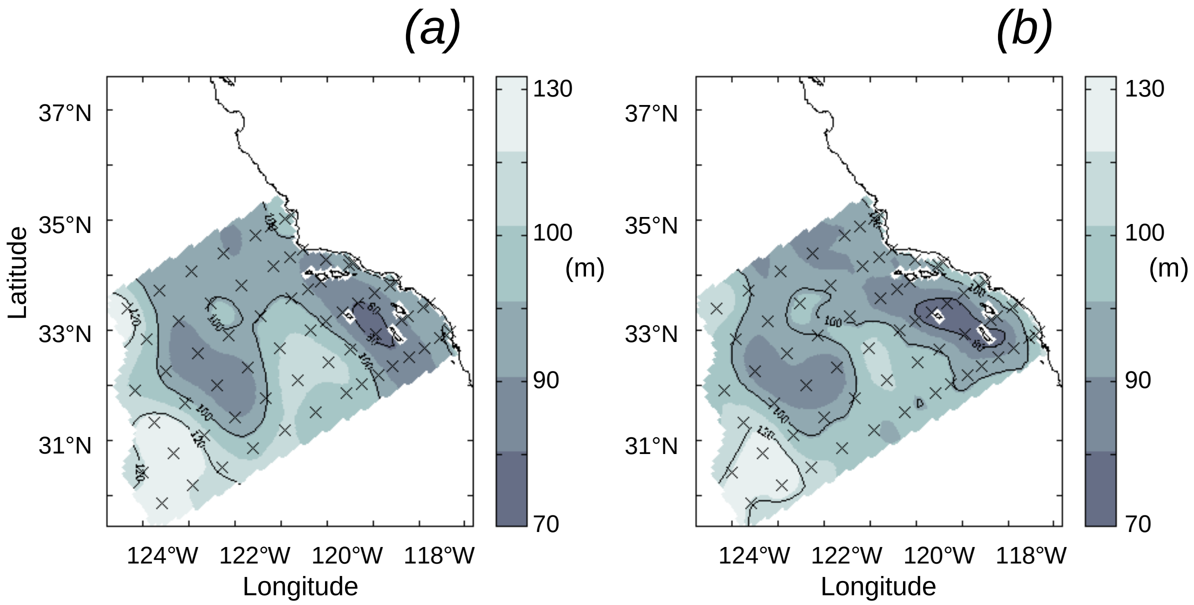
Figure Captions

Figure 1. Comparison of the 26.5 isopycnal for (a) CalCOFI observations and (b) ocean model fit, averaged over the period 23 Jan. 1998 to 14 Feb. 1998. Black crosses indicate locations of CalCOFI hydrographic stations.

Figure 2. (a) T/P SSHa and (b) model SSHa averaged over the period 23 Jan. 1998 to 14 Feb. 1998. T/P tracks are indicated in black, with the white portions indicating regions where the difference of the model from T/P is beyond the estimated error bars of ?6 cm. The white dots show the location of the CalCOFI sampling grid. (c) SeaWIFS near-surface, (d) model surface, and (e) CalCOFI in situ surface Chl-a for the period 23 Jan. 1998 to 14 Feb. 1998. (f) Alongtrack sea-level misfit between T/P and model fit (black line) and between T/P and model before fit (gray line). The dotted line marks the level at which the differences are significant.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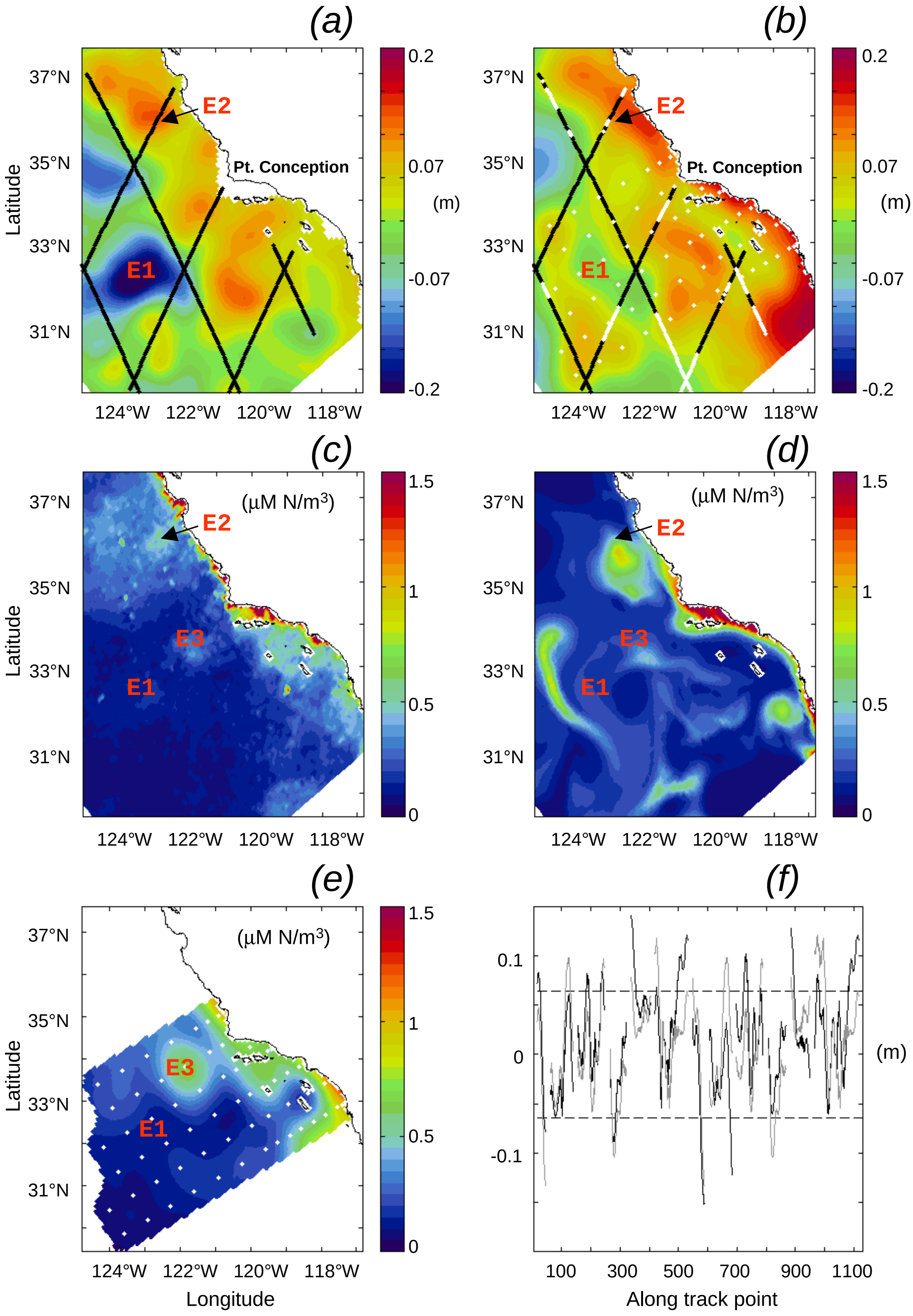
(a)
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Along track point