HINDCASTING AND NOWCASTING THE PHYSICAL AND BIOLOGICAL STATE OF THE CALIFORNIA CURRENT SYSTEM

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Assessing the past or present state of the ocean and predicting its future state are challenging enterprises. Observing activities are expensive, and as a result the ocean is woefully undersampled relative to important scales of variability spanning several orders of magnitude (from meters to hundreds of kilometers) in space and hours to decades in time. Numerical ocean models offer a relatively inexpensive alternative to observational sampling, and provide fully 4-dimensional representation of ocean fields and governing processes to better understand field distributions and changes. Yet numerical ocean models offer imperfect representations of nature for many unavoidable reasons, including errors in model initial conditions, forcing fields, model parameterizations, and discretization of the model on a finite grid. In ocean state estimation modelers use methods of data assimilation to rigorously adjust control variables (e.g., model initial conditions or forcing fields) to reduce discrepancies between model fields and observations (Edwards et al. 2015).

The widely-used Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams 2005) includes an advanced 4-dimensional variational data assimilation capability (Moore et al. 2011a) that has been applied in various California Current system configurations. The UC Santa Cruz Ocean Modeling Group implementation consists of a domain extending from 30˚N to 48˚N (Baja California, Mexico, to near Puget Sound, Washington) and offshore to 134˚W, resolved at 1/10 degree, with 42 terrain-following levels spanning the water column (Broquet et al. 2010, Moore et al. 2011b, 2013). Experience assimilating a variety of physical data types has shown that the system produces ocean state estimates with reduced root-mean-square error of both assimilated and unassimilated observations relative to unconstrained model output (Broquet et al. 2009). Forecast-like calculations in which the final state of one assimilation cycle is used as an initial state for an unconstrained forecast indicate that model skill is sustained beyond the period of assimilation alone.

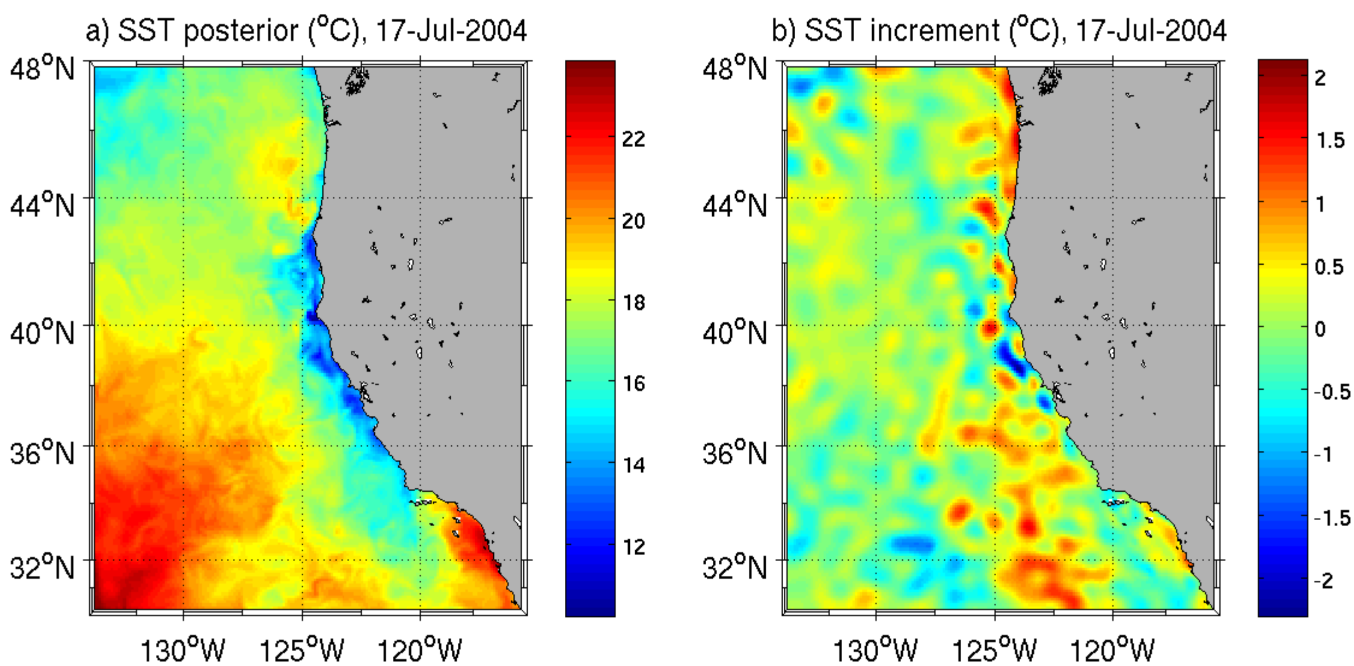

Figure 1. (a) Reanalysis sea surface temperature (SST) on July 17, 2004. (b) Corrections to the prior estimate of SST that were calculated through data assimilation and resulted in the field shown in (a).

A set of data assimilative reanalyses using the UCSC ROMS 4D-Var configuration has been calculated for the CCS (Neveu et al. 2015; Crawford et al. 2015). This product assimilated sea surface temperature (SST) from multiple satellite platforms, satellite-derived sea surface height, and in situ hydrography from various sources in a series of 8-day cycles extending from 1980 to 2010. Lateral boundary conditions were derived from the SODA global ocean state estimate (Carton and Giese 2008). Surface forcing was provided by a combination of CCMP winds (Atlas et al. 2011) and other atmospheric fields from the ERA40 (Källberg et al. 2004) and ERA-Interim (Dee et al. 2011) products. This model output represents a best estimate 31-year, hindcast of the physical state of the California Current, and is served by the UC Ocean Modeling Group for analysis (http://oceanmodeling.ucsc.edu).

Example output from a reanalysis assimilation cycle is shown in Figure 1. SST on this date exhibits cold upwelled water along the central California coast, with warm water bathing the Southern California Bight. Largely mesoscale corrections to a prior estimate, ranging up to about 2 degrees, result in this posterior state estimate.

This set of reanalyses has several applications that may be of interest to the CalCOFI community. It can be used for evaluation of fundamental physical processes. For example, upwelling within the CCS is challenging to observe directly, and in the absence of other information, a coastal upwelling index based on Ekman theory is often used as a proxy (Bakun 1973). The reanalyses reveal that modeled upwelling transport is reasonably approximated by the upwelling index north of about 39˚N, but is poorly represented south of this latitude (fig. 2; Jacox et al. 2014). Actual upwelling transport differs from Ekman transport in regions where cross-shore geostrophic transport encounters the coastal boundary (Marchesiello and Estrade 2010). Reduction of the reanalyses into empirical orthogonal functions reveals anomalous nearshore upwelling transport whose principal component relates to large-scale climate indices such as the NPGO and PDO (Jacox et al. 2014).

Ocean state estimates can also be used to provide context for fisheries studies. Schroeder et al. (2014) evaluated the reanalyses against data collected from the NMFS Rockfish Recruitment and Ecosystem Assessment Surveys. That study identified correlations between biological stocks (juvenile rockfish and krill) and physical variables from the reanalyses such as the depth of the 26.0 kg/m^3 isopycnal surface.

Ocean data assimilation is increasingly becoming a routine activity in global and many regional ocean environments. To date, however, most research has focused on physical data assimilation in which ocean currents, temperature, salinity, and sea surface height are constrained by observations. Exciting developments are underway to extend this capability to biogeochemical variables. The UC Santa Cruz Ocean Modeling Group has implemented a form of 4D-Var that accounts for the differing statistics of ecosystem variables relative to physical variables. Chlorophyll in the ocean has been shown to be better represented by lognormal statistics than by Gaussian distributions (Campbell 1995). The coupled physical-biogeochemical assimilation system incorporates surface chlorophyll, and offers considerable promise for hindcasting and nowcasting the combined physical and lower trophic level biological ocean state (Song et al. in prep.).

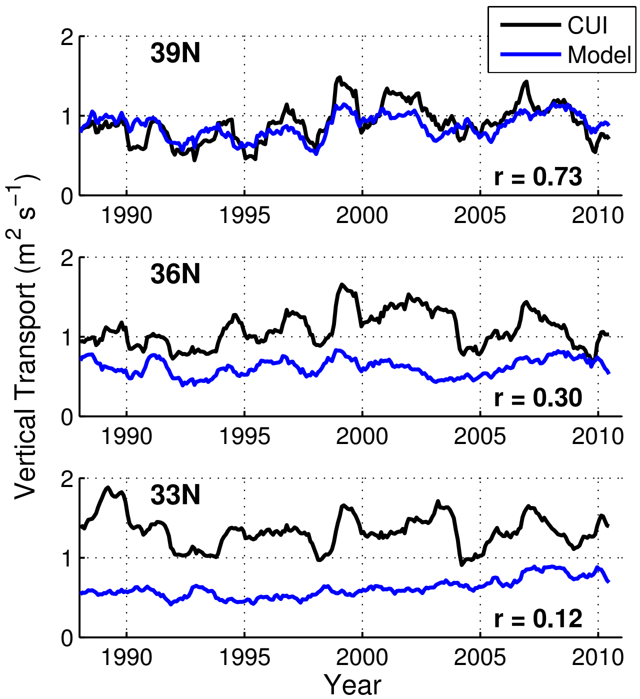

Figure 2. 12-month running means of upwelling estimates from the NOAA Coastal Upwelling Index (CUI, black) and the ROMS-CCS model (blue) of Moore et al. (2013). Model transports are integrated from the coast to 200 km offshore, averaged over 3˚ of latitude for consistency with the CUI, and calculated as transport across a depth level of 40 m. Adapted from Jacox et al. (2014).

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