Observing and Modeling the California Current System

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The California Current System (CCS) is one of the best sampled ocean regions, yet it remains obscurely understood and inadequately sampled. Technological advances in ocean modeling and observational techniques can now change this situation. Enhanced understanding of the features and dynamics of the CCS can aid fisheries and wildlife management, prediction and abatement of pollution and toxic phytoplankton blooms, atmospheric and climate change forecasts, and shipping and military operations.

The CCS extends up to 1000 km offshore from Oregon to Baja California and encompasses a southward meandering surface current, a poleward undercurrent and surface countercurrents. It exhibits high biological productivity, diverse regional characteristics, and intricate eddy motions that have puzzled oceanographers for decades. CCS phenomena must be observed with better temporal and spatial resolution to understand and predict physical and biological processes for various applications.

An example of the practical importance of the CCS is that the U.S. Navy uses it as a testbed for developing coupled ocean-atmosphere models for operationally relevant analysis and prediction. The environmental quantities of interest include sea-surface and air temperature; atmospheric humidity; location and structure of upper ocean fronts and eddies; biogeochemical distributions; sea-surface roughness; and near-shore waves and currents.

Many of these quantities are also important for resource and environmental management. Depending on the application, the time scales of interest range from days (such as when spills and blooms occur) to decades (such as when considering fisheries management or studying climate change).

Trying to understand and predict these environmental quantities raises fundamental questions about the physical and ecological processes in the CCS. A recent workshop focused on CCS models and observations and where they should lead. Highlights are discussed here. Ultimately CCS modeling may lead to a community CCS model (or models), which could be used for nowcasting and forecasting purposes as well as for basic scientific investigations.

Rich Eddy Activity

The CCS was once thought of as a sluggish eastern boundary current driven by coastal upwelling and characterized by broad, weak equatorward flow. But satellite SST images and in situ and remote measurements of currents, temperature, salinity, and sea level have changed that view during the last quarter century [Hickey, 1998].

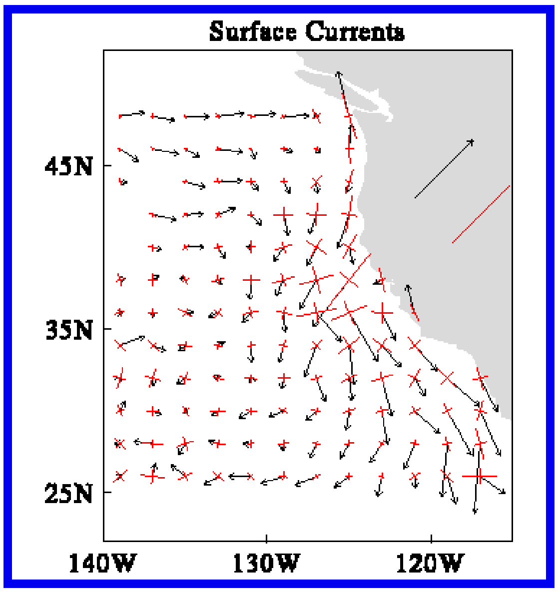

Figure 1. Mean 15-m velocity (black arrows, 15 cm/s) and its variance (red crosses, 500 cm^2/s^{-2})in the California Current System (CCS) and eastern Pacific from available surface drifters (National Oceanic and Atmospheric Administration Global Drifter Center, www.aoml.noaa.gov/phod/dac/gdc.html) during the period 1985-1998. Symbols are plotted at the center points of a 2° grid.

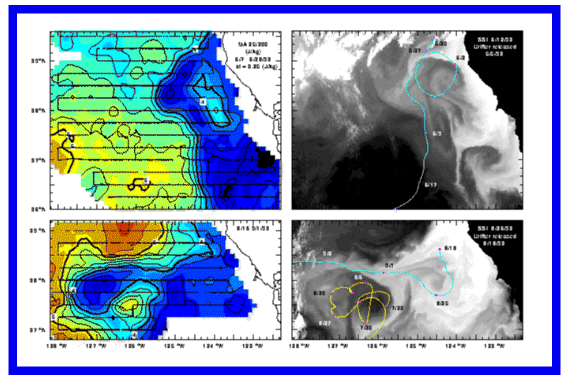

Figure 2. Geopotential anomaly at 25 m relative to 200 m from June (upper left) and August (lower left) 1993 [Huyer et al., 1998]. Satellite sea surface temperature (SST) images from June 1, 1993 (upper right), and August 26, 1993 (lower right). Superimposed are drifter tracks (courtesy of M. Abbott and R. M. Letelier) flowing through the region at approximately the same date; bullets are located at weekly time intervals. The dynamic height field and SST images show the continuity and evolution (offshore propagation and development of eddies) of the equatorward jet in the CCS.

Observations reveal many energetic, seasonally dependent flow regimes with diverse characteristics. Coastal upwelling along irregular coastlines and over strongly sloping topography generates a rich eddy field. High eddy kinetic energy (EKE) obscures the measurement of mean flows. But recent surface-current observations from satellite-tracked drifters [Swenson and Niiler, 1996] now show clearly the large-scale mean equatorward surface flow and concomitant surface eddy field (Figure 1).

The zero line in the annual mean wind-stress curl (marking the boundary of the subtropical and subpolar North Pacific gyres) turns southward and parallel to the coast and passes through the center of the CCS off northern California. The wind-stress curl has a strong annual cycle about its zero line, which produces seasonally reversing SSH and current patterns. The associated horizontal divergences within about 200 km of the coast may cause the observed extension of the "coastal upwelling" region well beyond the continental shelf off northern California.

Observations also reveal that high upper-ocean EKE extends about 500 km offshore. The maximum occurs near the coast during early summer upwelling, then moves westward over a broad offshore region in late summer and fall [Kelly et al., 1998; Strub and James, 1999]. However, the region of high EKE is not apparent west of about 130°W, indicating that some, as yet undetermined, process arrests, diverts, or dampens the signal.

Maps of surface currents and SST reveal narrow energetic squirts and jets and larger-scale eddies near particular topographic features, which subsequently transport materials far from the coast (Figure 2). The energetic summertime mesoscale circulation is associated with wind-driven upwelling and an upwelling front. Upwelling centers are typically located south of coastal headlands, where wind-stress curl is enhanced by orographic effects and where the longshore coastal upwelling jet often turns offshore with 1 m/s peak velocities. Cape Blanco (43°N) is the northernmost point where the equatorward upwelling jet recurringly separates from the coast; there it veers offshore across the continental shelf, while deepening, gaining transport and then interacting with the eddy field to the south [Barth et al., 1999].

A Productive Current

Because of the resupply of nutrients by coastal upwelling, the CCS has high biological productivity. Measurements from satellites, moorings and hydrographic surveys reveal tremendous heterogeneity in the distributions of chlorophyll and plankton, which impact the development of fish, birds, and mammals. Upwelled water is stirred by eddies, and biological fields reflect these transport influences with additional intrinsic variability from ecosystem population dynamics.

A poleward undercurrent flows continuously along the shelf break from 33°N-51°N at an average depth of 200 m and speeds of 15 cm/s [Pierce et al., 1999]. A surface countercurrent (the Davidson Current) also flows northward, is associated with seasonal wind changes, and sometimes merges with the undercurrent. These new observations suggest a strong dynamical link between deep water flows and current regimes over the continental shelf and slope.

Vigorous debates continue on the dynamical balances of mean and eddy fields, especially the importance of topography; the instability of mean currents and its geographical variation; and influences from local and remote atmospheric forcing, where remote influences are mainly through poleward propagating waves from the tropics. Eddy production by baroclinic instability appears to be dominant because of the prevalence of eddy energy around mean fronts and the lack of a direct relationship between eddies and wind anomalies.

Physical and Biological Models

The CCS physical models used today are generally primitive equation models that embody advective nonlinearity, baroclinicity, steep topography, and seasonality. Widely used models include the Princeton Ocean Model, a sigma coordinate formulation; the S-Coordinate Rutgers University Model and its descendent, the Regional Ocean Modeling System, with improved parallel performance, algorithms, and subgrid-scale parameterizations; the z-coordinate DieCAST model, using a blend of collocated and staggered grids with fourth-order differencing; and the Rutgers Spectral Element Ocean Model, a promising method for multiscale circulations.

Coupled physical-biological models are needed to understand the CCS ecology. Of these, the most conventional type is the nitrogen-phytoplankton-zooplankton (NPZ) class, where these fundamental ecosystem components are advected and diffused by the circulation. NPZ ecosystem models are generally successful in reproducing phytoplankton blooms in the upwelling regions (Figure. 4).

Another type is a Lagrangian individual-based model of zooplankton that describes populations as ensembles of individuals advected by the physical system. This approach can incorporate complex biological processes, such as migratory behavior, feeding history, and variability within a population, but it is less efficient than an NPZ model. A final type assimilates satellite data of surface properties (such as SST and chlorophyll levels) and predicts new or total primary production for the euphotic zone [Kudela and Chavez, 1999]. Although limited by the satellite data, it could be expanded to include higher trophic levels.

New Interpretations

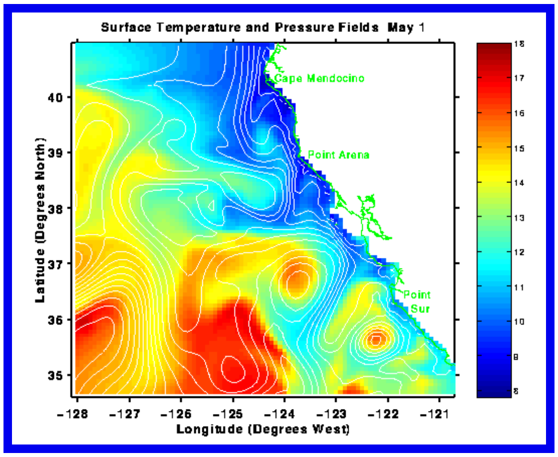

Figure 3. SST (color in °C) and sea level height (2 cm contour interval) on a typical May 1 from the DieCAST CCS model showing the types of upwelling filaments, eddy structure, and equatorward jet typical of modern CCS models.

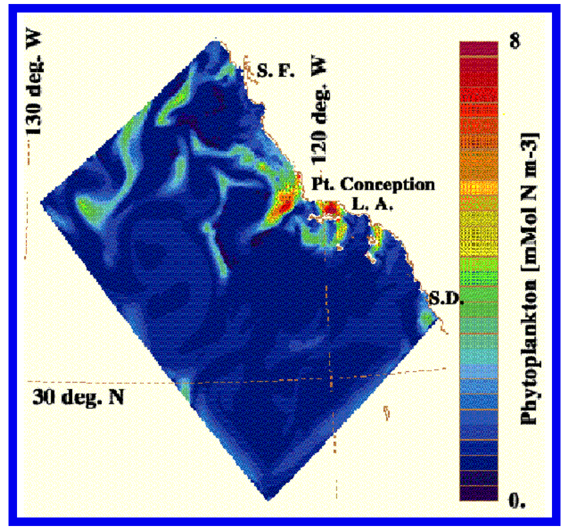

Figure 4. Summertime surface phytoplankton distribution from the Regional Ocean Modeling System showing a typical pattern of phytoplankton blooms off Point Conception and patches of open ocean phytoplankton populations. These locations and patterns are also evident in Sea-viewing Wide Field-of-view Sensor's ocean color estimates of observed surface chlorophyll.

Successful simulations often give rise to new interpretations of observed phenomena. A good example of this is an explanation for the westward decrease of surface EKE from its primary source near the coast. Recent model solutions simulate the observed seasonal evolution of the EKE and suggest that it decreases westward from the coast because of its vertical redistribution to the deep ocean. Rather than being dissipated as it moves offshore, it simply spreads downward in the water column, resulting in diminished surface signatures. This vertical spreading is accomplished by baroclinic energy conversion from high to low vertical wave numbers [Allen et al., 1991].

CCS models allow a detailed description of the dynamical balances of the mean and eddy flows. A prominent result from seasonal cycle models, wherein eddies develop intrinsically, is the dominance of baroclinic energy conversion from the mean flow to eddies. Figure 3 shows typical model SST and SSH fields during the upwelling season during which the eddies are energized. The modeled coastal upwelling jet meanders and produces narrow cold water filaments extending several hundred kilometers seaward as observed (Figure 2).

Hindcasts using observed winds and heat fluxes allow the identification of locally or remotely forced response components. For example, a current was observed with surface drifters in and around the Santa Barbara Channel flowing northward during December 1997 and reversing during April 1998. This behavior has been simulated in a CCS model during the mature stage of the El Niño with important influences from both anomalous local winds and coastal waves arriving from the tropics [Oey, 1999].

NPZ models can simulate phytoplankton blooms in characteristic upwelling regions as shown in Figure. 4. IBM studies show important interactions between daily vertical mesozooplankton migration and subsurface onshore flow that can influence their near-shore retention, feeding and growth rates.

Modeling Challenges

Challenging scientific questions need to be addressed by modeling efforts. What are the large-scale effects of baroclinic versus barotropic instability? How do dynamical and biological processes on the continental shelf and slope influence the deep ocean system? How strong is coastal upwelling (via jet evolution) versus open-ocean upwelling (via wind-stress curl forcing)? Why are there preferential locations for upwelling and eddy formation? What dynamics controls seasonal offshore propagation of upper-ocean structures? What are the contributions from locally and remotely forced variability?

The accuracy of CCS models depends on resolving oceanic fronts, topographic features, fine-scale atmospheric forcing and multiscale interactions. Modeling research is needed to explore parameterized effects of unresolved processes; convergence of the solutions with increased resolution; feedbacks between eddies and persistent currents; and influences of the larger Pacific Ocean circulation. The latter issues may require multiple grids, either by nesting or embedding a finer grid within a coarser one (for example, the CCS and a subdomain such as Monterey Bay) or by irregularly distributing the grid cells.

It can be difficult to assess the verisimilitude of CCS model solutions because of limited observations and intrinsic variability of the observed and modeled CCS. Although qualitative verifications are useful, CCS models must be tested quantitatively with observations both for statistical behavior of seasonal cycle simulations and for predictability studies of specific events. Such model testing will require a large observational database to constrain the statistics. Rigorous model fitting techniques can be used to find optimal forcing functions, boundary conditions, and initial conditions to minimize model-data misfit in hindcast scenarios.

Ecosystem models likewise must be tested in seasonal-cycle and hindcast mode. Such activities are planned within the U.S. Global Ocean Ecosystems Dynamics Northeast Pacific Program. The California Cooperative Oceanic Fisheries Investigations surveys are an excellent long-term regional data source for model testing. The Monterey Bay Aquarium Research Institute maintains a high-frequency time series of environmental properties in central California since 1989 that is optimal for comparisons in that region. Satellite SST and ocean color observations, drifters with SST and bio-optical sensors and coarse-resolution Levitus nitrate data can be used in larger areas.

Eventually, CCS models will be expected to make successful real-time forecasts for practical applications in, for example, naval operations, spill containment, toxic blooms or fisheries management. Because some CCS modeling studies will require extremely high resolution, some form of community modeling framework will be needed for cost-sharing among the many interested agencies and groups.

Long-term Observations Required

Sustained observations are crucially needed to establish reliable statistics. Coastal-resource, seafaring, and scientific communities would be best served with a CCS monitoring system akin to the tropical Pacific observing system. Permanent maintained moorings would measure currents, atmospheric fields, temperature, salinity, and biological parameters along key offshore lines, with nominally 2° latitude-longitude spacing. This would provide time series for initialization, verification, and diagnosis of models, as well as real-time observational benefits to the operational needs of many agencies and communities. Scientific progress will be maximized if all observations are easily accessible and available for community use. This could be achieved by the establishment of a CCS observational data center.

Immediate attention should be given to resolving the spatial structure in wind stress and its curl. Present wind analyses are inadequate since the magnitude of wind-stress curl in different analyses can differ by 100%. Although improvements in regional coastal atmospheric models may help relieve this problem, accurate direct estimates of wind stress are needed for a region 500 km offshore with 50 km resolution. Continuing scatterometer measurements can provide this resolution (except within 25 km of the coast), but temporal resolution is limited to a few days.

Accurate measurements of surface heat fluxes (both radiative and turbulent) on scales commensurate with the wind stress measurements are required to distinguish the effects of advection from that of surface heating on SST and surface mixed layer variations.

Models are the key to interpret and guide these observational strategies by diagnosing and synthesizing the data stream. The best chance for scientific breakthroughs and practical successes is for the CCS data center and the CCS community modeling activities to work closely together in addressing the many challenging questions and issues that remain unresolved.

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