Observing and Modeling the California Current System

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 nearshore 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 sea surface temperature (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]. 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 [Suomi and Niler, 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 windstress 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 windstress 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 extents about 500 km offshore. The maximum occurs near the coast during early summer upwelling. Then it moves westward over a broad offshore region in late summer and fall [Kelly et al., 1998; Stab and Hill, 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 largescale 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 windstress 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 recurves 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 topographic 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 dominated 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 advection 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 descendant, 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 pre-
What are the contributions from locally and remotely forced variability?

The accuracy of CCS models depends on resolving oceanic fronts, topographic features, finescale 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 mismatch 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 1999 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 near-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 costsharing among 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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References


