A Central California coastal ocean modeling study.
Part I: The forward model and the influence of realistic versus climatological forcing.

M. Veneziani, C. A. Edwards
Ocean Sciences Department, University of California Santa Cruz, USA

J. D. Doyle
Naval Research Laboratory, Monterey, CA, USA

D. Foley
NOAA Southwest Fisheries Science Center, Pacific Grove, CA, USA

M. Veneziani, Ocean Sciences Department, University of California Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA. (milena@ucsc.edu)
Abstract.

We report on a numerical simulation of the California Current circulation using the Regional Ocean Modeling System (ROMS) model, focusing on the region of the northern and central California during the 5-year period from 2000 to 2004. Unlike previous model studies of the California Current System, the present configuration is characterized by both realistic external forcing and a spatial domain covering most of the North America west coast. Specifically, this configuration is driven at the surface by high-resolution meteorological fields from the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) and at the lateral open boundaries by output from the project, Estimating the Circulation and Climate of the Ocean supported by the Global Ocean Data Assimilation Experiment (ECCO-GODAE). The simulation is evaluated favorably through quantitative comparisons with the California Cooperative Fisheries Investigations (CalCOFI) data set, satellite derived sea surface temperature, and surface drifters derived eddy kinetic energy. The impact of adopting realistic versus climatological surface forcing is demonstrated by comparing mean and mesoscale circulation characteristics. Realistic surface forcing qualitatively alters the seasonal cycle of the mean alongshore jet and better reproduces the summer spatial structure and intensity of the eddy kinetic energy field along the central California coast.
1. Introduction

The California Current is a typical eastern boundary current whose coastal dynamics are directly tied to the atmospheric wind forcing and highly influenced by the steep bathymetry, narrow continental shelf, and shape of the coastline. Its circulation has been widely studied through observational efforts [e.g., Rosenfeld et al., 1994; Swenson and Niiler, 1996; Ramp et al., 1997; Barth et al., 2000; Strub and James, 2000] and numerical modeling [e.g., McCreary et al., 1987; Batteen, 1997; Gan and Allen, 2002a, b; Marchesiello et al., 2003]. The California Current System (CCS) is comprised of the wind-driven, broad, weak equatorward flow found offshore, and a coastal flow whose spatial and temporal characteristics are subject to the strong seasonal cycle induced by changes in the atmospheric pressure field (excellent reviews of the CCS can be found in Hickey [1979, 1998]). In winter, the Aleutian low pressure system is well established over the Gulf of Alaska, producing predominantly west-southwesterly winds along the Washington and Oregon coast, inshore Ekman transport, and consequent downwelling conditions. To the south, the North Pacific high pressure system generally occupies a vast area over most of the North Pacific Ocean, causing northwesterly winds along the California and Mexico coast south of Cape Mendocino (key geographical locations are indicated in Fig. 1), and upwelling conditions year-round. In winter, however, the strengthening of the Aleutian low occurs, while the North Pacific high shifts to the south, thus weakening considerably the central California coastal northwesterly winds and associated upwelling circulation. During the so-called ‘spring transition’ [Lynn et al., 2003], the Aleutian low retreats northward, the North Pacific high strengthens and northwesterly winds extend uninterruptedly...
along the North America west coast south of Washington. These events mark the start
of the upwelling season in the ocean with the formation of a strong, surface intensified,
coastal equatorward jet. As the season progresses, the coastal jet evolves from a nar-
row feature tightly hugging the coastline to a highly meandering structure, with standing
meanders extending several hundred kilometers offshore in correspondence of the major
coastal promontories (from north to south: Cape Blanco, Cape Mendocino, Point Arena,
Point Sur, Point Conception). Internal instabilities of the meandering jet cause the for-
mation of eddies and filaments during the summer and early fall season [e.g., Chereskin
et al., 2000; Strub and James, 2000; Marchesiello et al., 2003]. Finally, in the fall, when
the Aleutian low pressure system strengthens and the winds along the California coast
weaken, coastal upwelling is reduced considerably and the equatorward jet is replaced by
a coastal poleward flow, often called the Davidson Current.

While this broad picture of the CCS circulation is well established, several open ques-
tions remain about the details of its variability and forcing, particularly on the extent of lo-
cal versus remote driving mechanisms [Davis and Bogden, 1989; Hickey et al., 2003, 2006],
and on the physics and variability of the subsurface and deep circulation on the conti-
nental shelf and slope [Werner and Hickey, 1983; Collins et al., 2000; Noble and Ramp,
2000; Pierce et al., 2000]. In this and a companion paper [Veneziani et al., 2008, hereafter
referred to as PartII], we address some of these questions by investigating the sensitiv-
ity of the central California coastal circulation to the local external forcing and internal
dynamics versus the large-scale and remote forcing mechanisms. Our methodology is to
perform a high-resolution modeling study of the CCS using the Regional Ocean Model-
ing System (ROMS) model. In PartII, we carry out sensitivity studies using the adjoint
model approach by taking advantage of the powerful tangent-linear and adjoint modules recently developed for ROMS [Moore et al., 2004]. In the present paper, the objective is twofold. First, we intend to present the results of the ROMS forward simulation\(^1\), which differs from other model studies of the California Current region in the application of realistic forcing over a spatial domain covering most of the U.S. west coast. Indeed, former investigations are either realistic but local [e.g., Gan and Allen, 2002b; Shulman et al., 2002; Di Lorenzo, 2003; Cervantes and Allen, 2006; Shulman et al., 2007] or extend over a large domain but adopt climatological external forcing data [e.g., Marchesiello et al., 2003]. Second, we aim at assessing the importance of adopting realistic external forcing versus climatological fields to determine the structure of the CCS circulation. At this scope, we perform traditional sensitivity analyses by changing the type of product used as surface and lateral boundary conditions (bc’s), and by observing the impact on metrics representative of both the mean and mesoscale circulation. The results are quite revealing for they show that the realistic surface forcing better reproduces not only key features of the mean alongshore jet along the U.S. west coast, but also the intensity of its mesoscale structures in proximity of the main coastal promontories.

The paper is organized as follows. The model configuration is described in Section 2, while the simulated circulation and a comparison with observations are presented in Section 3. The results of the sensitivity studies to the type of external forcing are described in Section 4, and a discussion of the conclusions of this paper is included in Section 5.

2. The Regional Ocean Modeling System (ROMS)

ROMS is a primitive equation, hydrostatic, free-surface ocean general circulation model [Shchepetkin and McWilliams, 2005], which has been widely used for regional and coastal
ocean applications [e.g., Di Lorenzo, 2003; Capet et al., 2004; Cervantes and Allen, 2006; Doglioli et al., 2006; Wilkin and Zhang, 2007] as well as large-scale studies [e.g., Marchesiello et al., 2003; Wang and Chao, 2004; Curchitser et al., 2005; Gruber et al., 2006]. Its terrain-following s-coordinate scheme is designed to provide higher vertical resolution near the ocean surface and bottom, where small scale, turbulent dynamics occur and the influence of topographic features is greatest [Song and Haidvogel, 1994; Haidvogel et al., 2000; Shchepetkin and McWilliams, 2005].

The ROMS configuration chosen for the present study (Fig. 1) covers a large domain extending zonally from 134°W to 115.5°W and meridionally from Washington State (48°N) to northern Baja California (30°N). It features a 1/10° horizontal resolution and 42 s-levels. The vertical resolution varies spatially and is equal to ∼0.3-8 m over the continental shelf, while ranging offshore between 7 m at the surface and 300 m in the deep ocean. The model topography is obtained by bicubic interpolation of the ETOPO2 analysis [NGDC, 2001] and by using a Shapiro filter to smooth depth gradients such that |δh|/2h < 0.35 (where h =depth). This is a common practice used in terrain-following coordinate models to avoid large errors in the pressure gradient computation [Haney, 1991].

The data used to constrain the circulation at the three open boundaries of the domain is provided by the Estimating the Circulation and Climate of the Ocean project [Heimbach et al., 2006; Wunsch et al., 2007], which has been developed in the framework of the Global Ocean Data Assimilation Experiment, and is therefore commonly referred to as ECCO-GODAE. It is based on the global, z-level, primitive-equation Massachusetts Institute of Technology General Circulation Model (MITgcm, Marshall et al. [1997a, b]), featuring a 1° horizontal resolution and 23 vertical levels. ECCO-GODAE employs an adjoint-
based assimilation technique to assimilate a variety of global observations, such as WOCE
hydrography, satellite altimetry data, and ARGO floats.

In order to build the necessary ROMS boundary conditions, the ECCO-GODAE prod-
uct is interpolated from z- to s-level coordinates: a bilinear interpolation is used for
free-surface, $\eta$, temperature, $T$, and salinity, $S$, while a bicubic scheme is adopted for the
horizontal velocity field, $u,v$. The vertically integrated (barotropic) velocity, $u_{\text{bar}}, v_{\text{bar}}$,
is computed by enforcing volume conservation across the boundaries. A combination of
radiation and clamped conditions is employed to nest the interior ROMS solution to the
ECCO-GODAE data. In particular, radiation conditions are imposed on the free-surface
and barotropic velocity following Chapman [1985] and Flather [1976], respectively. A 1.5°
wide sponge layer is also applied at the boundaries to avoid the formation of spurious
eddy-like structures at the north- and south-western corners of the domain. Finally, tem-
perature and salinity are slowly nudged towards their ECCO-GODAE boundary values
within a 1.5° wide nudging layer in order to reduce inconsistencies between the interior and
boundary area circulation. Due to the lower resolution of the ECCO-GODAE data with
respect to our ROMS configuration and the differences between the two model setups,
we expect these inconsistencies to still be present. Nevertheless, results from a sensitivity
study using higher temporal and spatial resolution ECCO bc’s were not as satisfactory as
in our control run, as is discussed more extensively in Section 5.

The external surface forcing data is provided by the atmospheric component of the Cou-
pled Ocean-Atmosphere Mesoscale Prediction System (COAMPS) model [Hodur, 1997;
Hodur et al., 2002]. The COAMPS configuration consists of four nested grids centered
around Monterey Bay with horizontal resolution ranging from 3 to 81 km (inner to outer
grid, respectively). Only the data from the three inner COAMPS grids are necessary to cover the ROMS horizontal domain. The resulting surface forcing data set has high resolution (3-9 km) along the California and Oregon coast, allowing the representation of complex wind structures typical of this region [Doyle et al., 2008]. The actual ROMS surface fluxes are computed internally using an ocean-atmosphere boundary layer routine [Liu et al., 1979; Fairall et al., 1996a, b], and the following atmospheric fields: wind velocities at 10 m, air temperature and relative humidity at 2 m, sea level pressure, precipitation rate (hourly accumulation), surface net shortwave and longwave radiation.

The parameterization of turbulent phenomena is accomplished using a Generic Length Scale (GLS) mixing scheme in the vertical direction [Umlauf and Burchard, 2003; Warner et al., 2005], while the horizontal mixing of momentum, temperature, and salinity is performed along s-surfaces.

The circulation is spun up from an arbitrary initial condition (obtained by using a 1992 snapshot of the ECCO-GODAE model solution) for a period of 7 years using Levitus [Conkright et al., 1998] and COADS [Conkright et al., 2002]) climatological fields as boundary conditions and external forcing, respectively. The result provides initialization fields for our control run, which is the base for both the present and PartII study: a 6-year simulation spanning the time period 1999–2004, using the monthly averaged ECCO-GODAE output² as bc’s and the daily averaged COAMPS product as surface forcing.

Four additional experiments are also carried out to perform the sensitivity analysis of Section 4. They feature unchanged horizontal resolution and the following choices for surface forcing/lateral bc’s (run properties are also summarized in Table 1): COADS/Levitus for an additional 6 years following the spinup period (RUN2); COADS/ECCO-GODAE
(RUN3); daily COAMPS/Levitus (RUN4); and monthly COAMPS climatology/ECCO-GODAE (RUN5, where the COAMPS climatology is computed by averaging the daily fields over the 1999-2004 period). Hereafter, we will refer to the last 5 years (2000–2004) of the daily COAMPS/ECCO-GODAE simulation as the ‘realistic’ run, and to the last 5 years of RUN2 as the ‘COADS climatological’ run.

3. Modeled circulation and comparison with observations

In this section, we present the main results of the realistic run in terms of mean circulation features and mesoscale dynamics, and compare them with observational products when available. In Section 4, we show how these results are affected by changes in the external forcing.

3.1. Surface fields: mean SST and SSH

We first compare the annual cycle of the model Sea Surface Temperature (SST) field with a blended satellite product. The latter is developed at the CoastWatch/NOAA-Fisheries in Pacific Grove, CA [its error statistics is described in Powell et al., 2008], and combines the high-resolution but cloud-obscured infrared measurements of the NOAA and NASA geostationary and polar-orbiting satellites (GOES Imager, AVHRR, and MODIS on Aqua and Terra spacecraft), with the lower-resolution but cloud-penetrating data of the Advanced Microwave Scanning Radiometer (AMSR-E, on the Aqua spacecraft). The end product is a 5-day averaged data set with horizontal resolution of 0.1°, covering most of our model spatial domain and the time period Sep 2002–Dec 2004 (late 2002 is when the Microwave Radiometer sensor became operative). The SST field from the ROMS realistic run, monthly averaged over the same time period, is shown in Figs. 2a–d (for
January, April, June, and September), and compared with the corresponding monthly satellite data (Figs. 2e–h). The spatial distribution of the difference between model and satellite SST is also displayed in Figs. 2i–l.

Generally, the model SST has a cold bias of $\approx 1^\circ C$ over the whole domain in January and April, with slightly warmer temperature than the data at the coast south of Point Arena in April. The situation is different during the second part of the year, when the model-data difference alternates sign in various part of the domain and reaches a local maximum of $\approx \pm 2.5^\circ C$ offshore Washington, Cape Blanco, and Cape Mendocino in September. The overall spatial structure of the model SST field is nevertheless very similar to the satellite product, especially between the northern Oregon coast and Point Conception. We are able to reproduce the onset of the upwelling season near the California coast in April-May, and the meandering structure and upwelling centers downstream of Cape Blanco, Cape Mendocino, Point Arena, and Point Sur (see also the results in terms of stratification in Section 3.2). Higher amplitude model-data SST differences in summer are most likely due to the higher eddy activity and to the difficulty in reproducing the jet meandering and filament formation at exactly the same time and location as in the observations.

This scenario is also evident in Fig. 3, which shows the 15-day averaged model-data difference, $\Delta T$ (Fig. 3a), the difference standard deviation, $\text{std}(\Delta T)$ (Fig. 3b), and the ratio between the model and data SST variances, $C = \sigma_m/\sigma_d$ (Fig. 3c). The statistics are computed by spatially averaging over the following three coastal subregions (their contours are displayed in Figs. 2i–l): the Southern California Bight (SCB, box 1); the central and northern California coast (box 2); and the northern U.S. west coast (box 3). While $\Delta T$ (Fig. 3a) does not show a definite seasonal variability at all locations, $\text{std}(\Delta T)$
(Fig. 3b) is always higher during late summer-early fall, when the eddy activity of the coastal jet is strongest. However, the averaged $\overline{\Delta T}$ (std($\Delta T$)) ranges between $-0.17^\circ$ and $-0.68^\circ$C (0.76$^\circ$ and 0.93$^\circ$C) in the three regions, which is either below or slightly above the typical satellite data uncertainty, estimated at $\pm 0.5^\circ$C. Furthermore, the ratio $C$ between the model and data SST variances (Fig. 3c) is always rather close to 1 (except for a single event in box 1 in mid-June 2003), which suggests that our model solution contains very similar SST spatial structures as the observations. The averaged value of $C$ is 0.97 in the central California region (box 2), which corresponds to the area where the highest resolution COAMPS external forcing is available.

The model annual mean sea level $\eta$ computed over the 2000–2004 period is presented in Fig. 4, and can be compared with the unbiased surface velocity field obtained from satellite-tracked drifters by Centurioni et al. [2008, their Fig. 12]. The comparison shows a very good agreement with the data-derived geostrophic velocities. In particular, the modeled mean $\eta$ exhibits all of the four standing meanders whose axis are found in correspondence of Cape Mendocino, San Francisco Bay, north of Point Conception, and south of the Channel Islands, respectively. Furthermore, narrower $\eta$ isolines coincide with regions of intensification of the unbiased drifter flow, offshore of Cape Mendocino and Point Arena, and south of the Channel Islands. We also computed the annual cycle of the mean $\eta$ by averaging the January-March, April-June, July-September, and October-December fields for the 2000–2004 period (Fig. 5). These results compare quite well with the Sea Surface Height (SSH) maps derived from satellite altimetry and coastal tide gauge data in Strub and James [2000, their Figs. 4 and 10]. Spring (Fig. 5b) is characterized by a sharp decrease of mean sea level in a narrow coastal band from the northern U.S. west...
coast to the SCB. This is consistent with the onset and subsequent strengthening of the
upwelling season from April through June, and corresponds to the period of minimum
SST at the coast and maximum values of stratification and equatorward surface current
(see Section 3.2). Weak meandering of the jet appears offshore of Cape Mendocino, Point
Reyes, and Point Sur. Meanders become more convoluted in summer and fall (Figs. 5c,d)
south of Cape Blanco, as observed from altimetry and ADCP data [Strub and James,
2000; Barth et al., 2000], producing local, enclosed circulation patterns between the equa-
torward jet and the main coastal promontories (such as the Point Arena anticyclone in
June-July [Lagerloef, 1992]).

3.2. Stratification: hydrography and alongshore currents

We first consider the model results in terms of vertical profiles of potential temperature
and salinity in the SCB region, which can be directly compared with the four-monthly
hydrographic cruise data from the California Cooperative Oceanic Fisheries Investigations
(CalCOFI) program. We then complete the description of the mean modeled circulation
by presenting vertical cross-shore sections of alongshore currents at key locations, which
are compared to previous observational studies.

Since 1949, the CalCOFI field program has provided an invaluable source of physical,
chemical, and biological property information for the southern California region. Cruises
are typically conducted quarterly following six transect lines orthogonal to the SCB coast³.
We interpolated the model potential temperature and salinity onto the position and depth
of the cruise stations, and compared their profile to the corresponding CalCOFI data. An
example of $T/S$ section along CalCOFI Line 90 for January and July 2002 is presented in
Fig. 6. The figure also illustrates the remarkable difference in stratification characteristics
between the winter and summer seasons, and the ability of the model to reproduce it, especially in terms of temperature stratification. Given the large number of total CalCOFI sections (6 lines for each of the 20 cruises in 2000–2004), we synthesize the model-data comparison by computing vertical profiles of model-data differences and std values. The statistics are obtained by averaging over the total number of stations and over the two periods January-February and June-July 2000–2004. The results are presented in Fig. 7, together with the vertical profiles of the standard deviations of the model and data fields alone (red and green line, respectively). In agreement with the SST results, the model potential temperature over the SCB (black lines in Figs. 7a,c) displays a cold (warm) bias of up to 0.5°C (1°C) in the upper 50 m of the water column in winter (summer). The deeper model-data $T$ differences tend to be lower (less than 0.5°C) in both winter and summer. This is also exemplified by the temperature sections in Fig. 6 (left panels).

Furthermore, while the std difference (blue lines in Figs. 7a,c) reaches higher values in the subsurface between 50 and 150 m, the ROMS and CalCOFI $T$ std values (red and green lines in Figs. 7a,c) present a very similar profile, suggesting that the model captures well the variability of the sections temperature at all depths. The situation is different for the salinity profiles (Figs. 7b,d) in the upper 250 m of the water column: the model displays a fresh (salty) water bias between 150 and 300 m (the surface and $\approx 75$ m) of up to 0.2 psu (0.1 psu) in the SCB region during both winter and summer. The std differences are slightly higher. Furthermore, the difference between the model and data salinity std values ranges between 0.1 and 0.2 psu in the upper 200 m depth. This behavior is also illustrated by the salinity sections of Fig. 6 (right panels), which additionally indicate that a less sharp halocline in the model may be responsible for the subsurface fresh water
bias. In the upper ocean, salinity is usually difficult to reproduce in ocean models because
of the high uncertainty associated with the external surface fresh water fluxes [Ebert et al.,
2003]. In particular, rainfall is a challenging parameter to predict for atmospheric models
[Doyle, 1997]; our surface salinity results can be considered quite satisfactory if compared
with those obtained using climatological forcing (not shown, surface $\Delta S \approx 0.15$ psu versus
the $\approx 0.1$ value in Fig. 7c,d). Further investigation is needed to assess the model-data
discrepancy in the 150-300 m depth range (Fig. 7c,d). Indeed, the subsurface bias is not
affected by either a change in surface forcing or lateral boundary conditions (the results
of RUN2–4 are not shown but are similar to those in Fig. 7c,d), and may also be related
to the particular choice of vertical mixing scheme.

In order to gain a better understanding of the model performance in terms of actual
mean circulation, vertical sections of alongshore velocity (velocity vector rotated of 33°
angle clockwise with respect to the positive x axis) are computed at key coastal locations
as monthly averages over the 2000–2004 period. Results for the sections at 40.1°N (Cape
Mendocino), 36.8°N (mid Monterey Bay), and 35.8°N (south of Point Sur) are presented
in Fig. 8 for the months of January and June (section locations are also indicated by
the thick black lines in Fig. 1). Poleward, slightly subsurface intensified flow, ranging
between 2 cm/s (Monterey Bay) and 8 cm/s (south of Point Sur), prevails in January at
all locations (Figs. 8a,c,e), becoming weakly equatorward at the surface in mid Monterey
Bay. The flow reverses to the weak equatorward California Current $\approx 100$ km from the
coast at Cape Mendocino, much further offshore near Monterey Bay, and again $\approx 80$ km
from the coast south of Point Sur. In June (Figs. 8b,d,f), the coastal equatorward
jet associated with the summer upwelling conditions is already well established at all
locations, featuring a core velocity of up to 35 cm/s (strongest south of Point Sur) and extending down to depths of $\approx 100$ m. A poleward California Undercurrent is also visible near the continental slope, with velocities of up to 8 cm/s. As also seen from observations [Ramp et al., 1997; Noble and Ramp, 2000; Pierce et al., 2000], the Undercurrent weakens considerably near Monterey Bay.

These results are consistent with the surface signals in SST and $\eta$, and are remarkably similar to the seasonal cycle of alongshore currents in Hickey [1979, her Fig. 8]. Pierce et al. [2000] analyzes ADCP data collected in July-August 1995 along the entire U.S. west coast to investigate the continuity of the California Undercurrent. Two of the vertical cross-sections of alongshore velocity in their Fig. 2 can be compared with our results at Cape Mendocino and Point Sur (Fig. 8b,f, respectively). The vertical extension and velocity structure of the modeled equatorward jet is similar to the ADCP results; an even stronger (and thus more consistent with the data) jet is present at Cape Mendocino in July and August (not shown) when the observations were collected. The model Undercurrent is weaker than in Pierce et al. [2000], especially south of Point Sur, while its core tends to be less pronounced and to encompass a larger range of depths ($\approx 50 - 400$ m versus the observed $100 - 250$ m).

3.3. Mesoscale dynamics: Eddy Kinetic Energy

We conclude this section by showing the performance of the model simulation in terms of mesoscale eddy variability. Typically, the California Current System exhibits higher eddy activity east of 130°W during the summer season, due to the meandering of the coastal jet south of Cape Blanco and the formation of filaments and vortices in correspondence of the main coastal promontories [e.g., Chereskin et al., 2000; Strub and James, 2000;
Marchesiello et al., 2003]. We evaluate the eddy variability by computing a surface Eddy
Kinetic Energy (EKE) field with respect to the seasonal mean flow. The latter is calculated
by averaging the model velocities over trimester periods between 2000 and 2004. The
results are presented in Fig. 9a for the summer season, and compared with those obtained
from surface satellite-tracked drifters⁴ (Fig. 9b). The drifters span the time period 1992–
2006 and mainly sample the offshore part of the CCS (the upwelling coastal area being
a region of strong flow divergence). Drifters’ EKE is computed from the Lagrangian
velocities along the drifter trajectories, with respect to the 0.5° × 0.5° binned mean flow.
The latter is in turn calculated by separating the Lagrangian velocities according to their
season, and by averaging all values that fall in 0.5° squared boxes (this is the most
common methodology for computing pseudo-Eulerian fields from Lagrangian data; see
e.g., Fratantoni [2001]; Veneziani et al. [2004]). No error bias, possibly resulting from
inhomogeneities in the drifter concentration and/or Lagrangian diffusivity tensor [Freeland
et al., 1975; Davis, 1991] are considered in the computation of the drifter statistics. Only
bins with a number of independent measurements⁵ higher than 5 are shown in Fig. 9b.

The lower model EKE levels with respect to the observations, and the fact that the
energy pattern does not extend as far offshore as in the drifters EKE distribution, may be a
result of the model resolution. Indeed, since the formation of the CCS mesoscale eddy field
is mainly through internal baroclinic instabilities [e.g., Pares-Sierra et al., 1993; Tisch and
Ramp, 1997; Marchesiello et al., 2003], and considering that the baroclinic Rossby radius
can be smaller than 10 km at the coast, the 1/10° model resolution may be insufficient
to capture all of the region eddy variability. Other model-data discrepancies are found
within two model grid-points of the western boundary, where the model EKE values are
unrealistically high. This result may reflect the presence of spurious perturbations at the open boundary, but does not seem to impact the interior EKE distribution. In fact, our model configuration is able to reproduce the most important structural characteristics of the EKE field, which are the high energy bands extending offshore of the main capes: Cape Blanco, Cape Mendocino, Point Arena, and north- and south-westward of Monterey Bay (around 124.5°W, 36.5°N and 123°W, 35°N, respectively). In particular, Point Arena exhibits the highest EKE values as in the observations. Between capes, EKE is low near the coast, as also seen from altimetry data and other model studies. Eddy activity is weak in the interior west of 128 – 130°W, for what is believed to be a geostrophic turbulence ‘barotropization’ process [Rhines, 1979], i.e. a transformation of energy from the baroclinic eddy field towards the barotropic large-scale flow [Haney et al., 2001].

4. Sensitivity to external forcing data

In this section, we investigate the impact of the realistic COAMPS versus the climatological COADS surface forcing by looking at the solution of the COADS climatological run (RUN2), in terms of mean sea level seasonal cycle (Fig. 10), vertical profile of the mean alongshore current at the same locations considered in Fig. 8 (Fig. 11), and surface EKE for the summer period (Fig. 12). We also discuss whether the impact of the COAMPS forcing is due to its high-resolution spatial structure or its temporal variability by considering the results of a model simulation forced by monthly COAMPS climatological fields (RUN5; all other model features are as in RUN1).

The deepening of η at the coast in spring (Fig. 10b) is much more pronounced in the COADS climatological run than in the realistic run (Fig. 5b). This behavior persists during the summer and fall seasons (Fig. 10c,d), with a marked decrease in the mean-
dering structure of the coastal jet with respect to the realistic run (Fig. 5c,d). RUN3
(with COADS surface forcing and ECCO bc’s) presents very similar results (not shown),
suggesting that the climatological surface forcing is responsible for the reduction of the
SSH meandering structure in summer and fall. In particular, its lower spatial resolution
(compared to COAMPS) may be a key factor in the simulation of the SSH distribution.
This is indicated by the results of RUN5 (not shown), which reveal a similar η seasonal
cycle as in the realistic run.

The strong SSH deepening at the coast in the COADS climatological run is consistent
with a much stronger coastal jet than that simulated in the realistic run in June (compare
Fig. 11b,d,f with 8b,d,f). Even more importantly, the equatorward jet is also present at
all locations in January (Fig. 11a,c,e), instead of the poleward Davidson current that is
reproduced in the realistic run (Fig. 8a,c,e). RUN3 produces very similar results to the
climatological run, whereas RUN4 (with daily COAMPS surface forcing and Levitus b.c.’s)
as well as the run with COAMPS climatology are able to simulate a Davidson current
south of Point Sur in January (not shown). This confirms that the surface forcing, and
in particular its spatial distribution, is mainly responsible for the differences between
the COADS climatological and realistic run in the structure and seasonal cycle of the
mean upper-ocean circulation. The characteristics of the California Undercurrent are
less affected by the change in surface forcing, with higher discrepancies found at Cape
Mendocino (Fig. 11a,b), but generally similar vertical structures found in the realistic
and climatological runs near Monterey Bay and Point Sur (Fig. 8c-f and 11c-f).

The impact of the COAMPS surface forcing is also evident in the surface EKE field
(compare Figs. 9b and 12). In the COADS climatological run, the EKE levels east of
126W are on average almost half as much as those in the realistic run. Moreover, the EKE spatial structure in Fig. 12 less faithfully reproduces that observed from in-situ drifters (Fig. 9b), exhibiting less developed bands near Cape Mendocino and Point Arena, no energy offshore of Cape Blanco, and only one energetic band extending offshore of Point Reyes and Monterey Bay. These results are in agreement with the reduced meandering structure of the mean sea level field (Fig. 10), suggesting that the climatological surface forcing in our simulation inhibits the development of a convoluted equatorward jet during the summer and fall seasons, and in the end produces a less energetic coastal California circulation. Inspection of the summer EKE from RUN5 (not shown) reveals a similar spatial structure as in the realistic run, but generally lower values of EKE. This indicates that the temporal variability of the atmospheric forcing, as well as its spatial distribution, contribute to the overall energy structure of the CCS.

5. Discussion

In this paper, we perform a high-resolution ROMS simulation of the CCS, with an emphasis on the circulation of the northern and central California region, using a realistic model data product as external forcing for both the ocean surface (COAMPS) and the lateral open boundaries (ECCO-GODAE). By comparing the model results with available observations and previous modeling efforts, we find that the present model solution well represents the mean features and seasonal cycle of the California coastal circulation. We also perform a sensitivity analysis to specifically study the effect of realistic versus climatological forcing on the large-scale and mesoscale dynamics of the CCS.

We concentrate on this type of forcing comparison - time-dependent, high-resolution forcing versus climatology - mainly because previous regional model investigations of the
CCS [e.g., Marchesiello et al., 2003; Batteen et al., 2003; Batteen, 1997] adopt climatological forcing for both the surface and lateral boundary conditions. Our focus here is on the impact that realistic atmospheric forcing has on the annual cycle of the CCS. Studies of interannual variability would obviously also require the use of time-dependent realistic surface forcing. This is, for instance, addressed by Curchitser et al. [2005], who carried out multi-scale model simulations of the North Pacific - downscaling from a basin-wide, climatologically-forced setup to a regional, realistically-forced configuration - with the objective of studying the effects of interannual and climate processes on the physical and ecosystem dynamics of the northeast Pacific. Another atmospheric product commonly used to drive oceanic models is the NCEP/NCAR reanalysis product, which has the advantage of covering a long period of time between the 1950’s to the present, but is characterized by a lower horizontal resolution (≈ 2.5°) than that of COADS/Levitus. Our own experience using NCEP/NCAR for the present high-resolution CCS study indicate that the resulting circulation is not as well reproduced as when using the climatological forcing. In particular, the mesoscale eddy energy is very weak south of Cape Blanco and the energetic bands off the main promontories are almost absent.

While the use of a realistic, high-resolution forcing data product such as COAMPS versus the use of a climatological forcing is generally not considered fundamental for reproducing the mesoscale internal variability of an oceanic system, this is possibly not true for a complex system like the CCS. It is reasonable to think, for example, that a highly resolved spatial wind structure in a coastal upwelling region (COAMPS resolution is 3–9 km along the California coast while COADS resolution is 1° everywhere) leads to a better representation of the upper ocean stratification and associated cross-shore
and alongshore circulation structure. Furthermore, a high-resolution wind field is able to reproduce the locally intensified wind stress curl that occurs within 50–100 km from the coast, and which is now recognized to contribute substantially to coastal upwelling through the Ekman pumping mechanism [Enriquez and Friehe, 1995; Pickett and Paduan, 2003; Koracin et al., 2004]. Di Lorenzo [2003] also finds that spatially well resolved wind stress and wind stress curl are fundamental in reproducing the seasonal cycle of the mean Southern California Bight circulation and the SCB coastal poleward flow in late summer-fall. Finally, numerical studies by Castelao and Barth [2006] show that both the presence of an irregular coastline geometry (capes) and phenomena of wind intensification in proximity of the coastal promontories are responsible for the separation of an upwelling jet from the coast. Such results suggest that a spatially well resolved wind field would enhance the coastal jet separation at the main capes located along the U.S. west coast south of Cape Blanco, likely intensifying the jet turbulent behavior and consequent eddy activity downstream of these locations.

An important contribution of this paper is indeed to confirm that realistic surface forcing such as COAMPS, and in particular their high-resolution spatial structure, greatly improve not only the simulation of the CCS mean circulation but also of its mesoscale eddy activity. The seasonal cycle of the upper-ocean coastal alongshore jet is better represented, as well as its spatial structure. Moreover, the mesoscale eddy field associated with the jet instabilities is more intense and displays a more realistic spatial distribution than that in the COADS climatological run. The next step of this investigation will be to increase the horizontal resolution of the ROMS model, in order to better resolve the
baroclinic Rossby radius of deformation and provide an even more realistic representation of the coastal jet instability processes.

Although not discussed within this text, we investigate the impact of using different lateral boundary forcing fields on the model solution. Sensitivity studies are conducted to verify whether higher temporal and spatial resolution bc products provide an improvement over using 1° monthly ECCO-GODAE fields. We therefore perform simulations using the 1/8° monthly ECCO2 product, a 1° daily ECCO-GODAE product, and various choices of boundary condition schemes (clamped and radiation). The results show that, while certain improvements are introduced (lower boundary EKE values when using radiation conditions, and a better representation of the geostrophic transport across northern CalCOFI Lines when using ECCO2 bc’s), the overall circulation is not as well represented as in our control RUN1. This is likely because larger inconsistencies exist between the ROMS interior circulation and the considered higher resolution ECCO products, which are more difficult to eliminate by the open boundary condition scheme.

Finally, we investigate the difference between using realistic (ECCO-GODAE) and climatological (Levitus) lateral boundary forcing fields. Though we find quantitative changes to our measures characterizing the circulation, our results are not conclusive as some metrics improve with realistic boundary conditions and others with climatological fields. For instance, the subsurface salinity bias in the CalCOFI region is slightly improved with realistic lateral forcing, whereas the surface bias is slightly worsened. An example of geostrophic velocity derived from the CalCOFI temperature and salinity sections for RUN1 and RUN4 is presented in Fig. 13, for Line 77 in January 2002 (Fig. 13a–c) and Line 83 in July 2004 (Fig. 13d–f). As exemplified in the figure, while the realistic bound-
ary forcing produces much better results in some cases, a different scenario may occur at different times and/or locations. Furthermore, the qualitative structure of meridional velocity within the previously considered cross-shore sections (not shown) is not substantially altered when using the realistic versus the climatological bc’s, nor is there a significant change to the EKE structure. Future studies (and additional in-situ data sets available for model evaluation) may further identify the impact of the specific choice of lateral boundary forcing, particularly on subsurface features, but our initial investigation indicates that surface forcing plays a more dominant role on chosen CCS metrics than do lateral boundary fields. This outcome leads naturally to PartII, where we quantitatively investigate the sensitivities of the California coastal circulation to large-scale external forcing mechanisms and to internal dynamics by adopting an adjoint model approach.

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Notes
1. We refer to ‘forward’ simulation when describing the full non-linear ROMS model results, whereas ‘adjoint’ refers to the backward in time adjoint model simulation.

2. ECCO-GODAE Iteration 199.


5. The number of independent data is calculated as \( n_{\text{obs}} \Delta t/T_L \), where \( n_{\text{obs}} \) is the total number of observations, \( \Delta t = 6 \) h is the drifters sampling interval, and \( T_L \approx 2 \) days is the Lagrangian decorrelation time scale.


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Table 1. Main properties of the different runs discussed in this paper.

<table>
<thead>
<tr>
<th>Run name</th>
<th>Surface forcing</th>
<th>Lateral bc’s</th>
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<tbody>
<tr>
<td>RUN1 ('realistic')</td>
<td>daily COAMPS</td>
<td>ECCO-GODAE</td>
</tr>
<tr>
<td>RUN2 ('COADS climatological')</td>
<td>COADS</td>
<td>Levitus</td>
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<tr>
<td>RUN3</td>
<td>COADS</td>
<td>ECCO-GODAE</td>
</tr>
<tr>
<td>RUN4</td>
<td>daily COAMPS</td>
<td>Levitus</td>
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<tr>
<td>RUN5</td>
<td>monthly COAMPS climatology</td>
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Figure 1. Spatial domain and topography of the present ROMS configuration. Contour lines are every 500 m depth. Thick black lines indicate the three cross-shore sections for which vertical profiles of alongshore currents are considered (see Section 3.2 and Figs. 8, 11).

Figure 2. Model SST for (a) January, (b) April, (c) June, and (d) September; satellite SST product for the same months (e–h); and difference between model and data results (i–l). Monthly averages are computed over the period Sep 2002–Dec 2004 when satellite data is available. Also shown are the contours of the three coastal regions where a quantitative model-data comparison is performed (see Section 3.1 and Fig. 3).

Figure 3. (a) Mean and (b) std value of the difference between model and satellite SST; (c) ratio between the model and data SST variances, $C = \sigma_m/\sigma_d$. The statistics are computed spatially over the three box regions outlined in Fig. 2 (blue line for box 1, red for box 2, and green for box 3).

Figure 4. Annual mean $\eta$ computed by averaging the 2000–2004 model results.

Figure 5. Seasonal cycle of $\eta$ computed by averaging the 2000–2004 model results for: a) winter (January–March); b) spring (April–June); c) summer (July–September); and d) fall (October–December).

Figure 6. Potential temperature and salinity sections along CalCOFI Line 90 (see insert for transect location) for the January and July 2002 CalCOFI cruises. Model (data) sections are plotted in the upper (lower) two panels in each set.
Figure 7. Synthesis of comparison between model and CalCOFI hydrographic data. Black (blue) lines represent the vertical profiles of the mean (std) model-data difference for a,b) potential temperature and c,d) salinity. Units are degree Celsius for temperature and psu for salinity. Also shown are the std values of the model and data fields alone (red and green line, respectively). The statistics are computed by averaging over the total number of stations and over the two periods January-February and June-July 2000–2004.

Figure 8. Vertical profile of alongshore velocity from the realistic run at the three cross-shore sections depicted in Fig. 1 for the months of January (left panels) and June (right panels): a,b) Cape Mendocino (40.1°N); c,d) mid Monterey Bay (36.8°N); and e,f) south of Point Sur (35.8°N). Positive values indicate northward flow.

Figure 9. Surface EKE field for the summer period, obtained from (a) the realistic model run and (b) from 0.5° × 0.5° binned in-situ drifter velocities.

Figure 10. Same as Fig. 5, but for the COADS climatological run.

Figure 11. Same as Fig. 8, but for the COADS climatological run.

Figure 12. Same as Fig. 9a, but for the COADS climatological run.

Figure 13. Geostrophic velocity along a–c) CalCOFI Line 77 in January 2002 and d–f) CalCOFI Line 83 in July 2004. Results are from a,d) CalCOFI data; b,e) the realistic model simulation (RUN1); and c,f) model RUN4 (with daily COAMPS forcing and Levitus bcs). Contour interval is 0.05 m/s (heavy black contours represent zero velocity).
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