Numerical Model Simulations of Continental Shelf Flows off Northern California

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Abstract

The three-dimensional circulation on the continental shelf off northern California in the WEST (Wind Events and Shelf Transport) experiment region during summer 2001 is studied using the primitive equation Regional Ocean Modeling System (ROMS). The simulations are performed with realistic topography and initial stratification in a limited-area domain with a high-resolution grid. Forcing consists of measured wind stress and heat flux values obtained from a WEST surface buoy. The general response shows a southward coastal upwelling jet of up to 1 m s\(^{-1}\) and a weakening or reversal of currents inshore of the jet when upwelling winds relax. Model results are compared to WEST moored velocity and temperature measurements at five locations, to CODAR surface current observations between Pt. Reyes and Bodega Bay, and to hydrographic measurements along shipboard survey lines. The model performs reasonably well, with the highest depth-averaged velocity correlation (0.81) at the inshore mooring (40 m water depth) and lowest correlation (0.68) at the mid-depth mooring (90 m depth). The model shows generally stronger velocities than those observed, especially at the inshore moorings, and a lack in complete reversal of southward velocities observed when upwelling winds relax. The comparison of surface

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velocities with CODAR measurements shows good agreement of the mean and the dominant mode of variability. The hydrography compares closely at the southern and northern edges of the survey region (correlation coefficients between 0.90-0.97), with weaker correlations at the three interior survey lines (correlation coefficients between 0.44-0.76). Mean model fields over the summer upwelling period show slight coastal jet separation off Pt. Arena and significant separation off Pt. Reyes. The cape regions also experience relatively strong bottom velocities and nonlinearity in the surface flow. Across-shelf velocity sections examined along the shelf reveal a double jet structure that appears just north of Bodega Bay and shows the offshore jet strengthening to the south. We examine the dynamics during an upwelling and subsequent relaxation event in May 2001 in which the WEST measurements show evidence of a strong flow response. The alongshelf variability in the upwelling and relaxation response introduced by Pt. Reyes is evident. Analysis of term balances from both the three-dimensional and depth-averaged momentum equations helps to clarify the event dynamics in different regions over the shelf. A clear pattern in the nonlinear advection term is due to the spatial acceleration of the southward jet around the capes of Pt. Arena and Pt. Reyes during upwelling. Results from a three-dimensional Lagrangian analysis of water parcel displacement show the source of upwelled water near the coast south of Pt. Reyes is local, as compared to that north of Pt. Reyes, which has a signature of deeper water from farther north.

**Keywords:** Coastal oceanography, wind-driven circulation, upwelling, numerical models; USA, northern California; 36°N – 40°N, 126°W – 121°W.

1. **Introduction**

As part of the Coastal Ocean Processes (CoOP) program, the Wind Events and Shelf Transport (WEST) project has the overall goal of understanding the role that wind-driven
transport plays in biological productivity over the northern California shelf. The region of interest for WEST extends from just south of Pt. Reyes to about 50 km north of Bodega Bay (Figure 1). This is an area that has been studied previously by large observational programs, such as the Coastal Ocean Dynamics Experiment (CODE) (Beardsley and Lentz, 1987) and the Shelf Mixed Layer Experiment (SMILE) (Alessi et al., 1991), and results of those experiments have been used for guidance in design of the WEST field measurements. Moorings deployed at five locations from May 2001–2003 by the WEST project collected measurements of current velocity, temperature, conductivity, pressure, wind, chlorophyll fluorescence, and optical transmissivity (Dever et al., 2004). Additionally, surface heat flux parameters were measured at the central D090 mooring and fluxes were calculated using the algorithms specified in Beardsley et al. (1998) (E. Dever, personal communication). Land-based coastal radar (CODAR) systems were in operation during May 2001–September 2003 to measure surface currents over the region from Pt. Reyes to Bodega Bay. Ship surveys were also conducted during three summer upwelling periods and two winter downwelling periods between June 2000 and November 2002. These surveys were comprised of both vertical profiles and underway tow-yo sampling of water properties and current velocity (Largier, 2004).

In this study, we utilize the Regional Ocean Modeling System (ROMS) to model the circulation over the continental shelf and upper slope in the WEST region during May – June 2001. During this period, the winds are generally upwelling favorable at the central D090 mooring with a mean wind stress magnitude of 0.074 N m\(^{-2}\) directed toward 120 T. The magnitude and direction of maximum standard deviation in wind stress are similar to the mean for this period, i.e. 0.052 N m\(^{-2}\) and 116 T. This wind stress forces an upwelling circulation that persists throughout the summer with the exception of intermittent 1-3 day periods during which the alongshelf winds relax or reverse. The modeled velocity and
hydrographic fields are first compared quantitatively with the WEST data sets. Following the model-data comparisons, we discuss the time mean response, which is dominated over the shelf by an upwelling circulation, and then proceed to focus on the dynamics of a specific upwelling and subsequent relaxation wind event that occurs from May 17 – 23, 2001.

The numerical model description and setup are presented in section 2. Comparisons of the model with the datasets described above are provided in section 3. General characteristics of the flow field in response to summer upwelling-favorable winds are discussed in section 4. A detailed dynamical analysis of an upwelling and relaxation event is presented in section 5 and a summary is provided in section 6.

2. Model Formulation

The Regional Ocean Modeling System (ROMS) is a hydrostatic primitive equation model with terrain-following vertical coordinates. ROMS is based on the S-Coordinate Rutgers University Model (SCRUM) described by Song and Haidvogel (1994), but has been rewritten to include, for example, high-order advection schemes, accurate pressure-gradient algorithms, and several subgrid-scale parameterizations (Shchepetkin and McWilliams, 2004). We use the embedded Mellor-Yamada 2.5 level turbulence closure scheme (Mellor and Yamada, 1982) as modified in Galperin et al. (1988) and the third-order upstream bias advection scheme for momentum and tracers (Shchepetkin and McWilliams, 1998). The pressure-gradient scheme is a splines density Jacobian, one of three methods developed by Shchepetkin and McWilliams (2003) to minimize the errors associated with computing horizontal pressure gradients with terrain-following coordinates.

The model domain and bathymetry is shown in Figure 2. The model bathymetry is a spatially-filtered version of that obtained from the National Geophysical Data Center.
GEODAS dataset with 3-second resolution. It is smoothed such that the maximum local slope factor, defined as $|\delta h/h|$ (Mellor et al., 1994), is no greater than 0.2. This value has been shown to limit the errors associated with the pressure gradient calculation (Barnier et al., 1998; Beckmann and Haidvogel, 1993).

Periodic boundary conditions are used on the northern and southern boundaries and the model bathymetry is adjusted to be equal at these boundaries. The alongshelf length of the domain is 400 km and the across-shelf length is approximately 135 km. The Cartesian $(x,y)$ grid has a resolution of 1.7 km in the alongshelf $y$ direction and between 0.8–1.8 km in the across-shelf $x$ direction with the highest resolution near the coast. In the vertical, we use 40 $s$-levels with spacing such that there is higher resolution in the surface and bottom layers.

At the coastal boundary, conditions of zero normal velocity and of half slip for the tangential velocity component are applied. At the offshore boundary, we use a condition of zero normal depth-integrated velocity ($U = 0$) and free slip for the tangential depth-integrated velocity ($V_x = 0$). The free surface satisfies an implicit gravity wave radiation condition (GWI as described in Chapman, 1985), the depth-dependent velocities satisfy a radiation condition, and the tracers and turbulence quantities satisfy a no gradient condition ($T_x = S_x = q^2_x = 0$). The initial temperature and salinity profiles in Figure 3 are horizontally uniform and are taken from the spatial average of the summer 2001 mean central D line CTD survey data. The temperature profile is very similar to that calculated as the mean of April 1981-82 values from the CODE experiment central line. However, the salinity profile from the WEST measurements is less stratified than that from the CODE measurements, which has a value of approximately 33.3 psu near the surface and increases to 33.9 psu at 140 m depth (Huyer, 1984).

The model simulation occurs over 57 days during April 25 – June 20, 2001. We
regard the first ten days (April 25 – May 4), during which the WEST measurements are unavailable for model-data comparisons, as a spinup period. Therefore, we calculate time mean fields presented in section 4 over 47 days from May 5 – June 20, 2001. The wind stress and heat flux time series used to force the model (Figure 4) are calculated from measurements at the central D090 mooring, then low-pass filtered and applied uniformly in space. The assumption of no spatial variability in the wind field is not accurate, as has been previously shown by wind measurements in the CODE and WEST regions (Beardsley et al., 1987; Dorman and Winant, 1995). However, generally favorable model-data comparisons in section 3 show that forcing with spatially-uniform winds results in a successful representation of a substantial component of the observed shelf flow that is strongly influenced by interactions with topography. Future modeling studies utilizing wind stress fields obtained from a high-resolution regional mesoscale atmospheric model after these become available following analysis and model-data comparisons (D. Koracin and C. Dorman, personal communication) are planned that will address specifically the effects of spatially-variable wind stress in this region.

3. Model-Data Comparisons

3.1. Moored velocity and temperature observations

In order to verify the model’s ability to represent the wind-driven shelf flow in this region, we conduct model-data comparisons with the available WEST observations. The first such comparison is with the moored velocity and temperature time series. Figure 5 shows depth-averaged velocities from the observations and the model at the D Line moorings. The depth-averaged velocities are computed over the depths of the mooring instruments. The wind stress vectors used to force the model are also plotted at the top. The time period shown is the entire duration of the model simulation (April 25 – June 20,
2001), including the spinup. However, because the moored time series are not available until May 5, correlations between the model and mooring observations are computed over May 5 – June 20. The complex correlation is highest at the inshore mooring (0.81), however the phase angle shows a fairly significant counterclockwise rotation of the modeled currents as compared to the observed D040 currents (23.44°). The correlation is lowest at the central D090 mooring (0.68), but the phase angle is very small (1.07°), indicating that the model does get the direction of the velocity fluctuations correct at this location. Correlations at the other 90-m moorings, C090 and E090 (not shown) are 0.64 with 7.73° phase angle and 0.57 with 6° phase angle, respectively. The correlation and phase angle at D130 (0.74 and 12.34°) lie between those at D040 and D090, and the root mean square error (rmse) at this location is significantly smaller in the alongshelf direction than at the other two moorings. The discrepancies between the model and observed time series are evidently due to the larger model velocity magnitudes during upwelling forcing (especially at D040 and D090) and the lack of a significant reversal in the modeled velocities when upwelling winds relax (especially at D090 and D130). The model performs well at depth at the two offshore moorings due to decreased model velocities that match the observations more closely than at the surface (not shown).

We also compare the near-surface temperature time series at the D Line moorings for the same time period (Figure 6). The modeled temperature at the D040 and D090 moorings is 1-4 degrees cooler than the observations, with this difference a maximum during wind relaxation events when the observed temperature increases by 1-2 degrees. Thus, the model temperature has a weaker relaxation response than the observed temperature as expected from the weaker velocity relaxation response. The connection between observed northward velocities during relaxation and observed warming at the D line is likely the northward advection of warm, fresh water from San Francisco Bay, an input that is neglected in this
modeling study.

Time mean depth-averaged velocity vectors from the observations and the model at the WEST mooring locations show the mean modeled velocities are larger than the mean observed velocities at all mooring locations except D130 (Figure 7). The first mode EOF, which explains 86% of the variance in both the model and observations, shows the model does better at matching the magnitude of the variability in the observations. The time series of the EOFs have a correlation of 0.88. The observed amplitude is consistently higher than the model, with the biggest difference when the sign is positive. This corresponds to the observed reversal of velocities when upwelling winds relax, a response that the model does not represent completely as discussed earlier.

Further comparison between the moored velocity observations and the model is made by computing space-lagged correlation coefficients between model velocity components and between observed velocity components at the mooring locations (Table 1). The observed and modeled depth-averaged velocities (averaged over the measurement depths) are rotated to their respective principal axes calculated from the depth-averaged currents to objectively determine local values of the alongshelf and across-shelf velocity components. The observed correlations are shown in bold. For both the model and the observations, alongshelf correlations are computed for C090, D090, and E090 and across-shelf correlations for D040, D090, and D130. The modeled and observed velocities have generally higher correlations alongshelf between the 90-m moorings than across-shelf on the D line. Alongshelf velocity correlations for \( v \) are high for both the model and observations at the 90-m moorings. The modeled response shows a lower \( u \) correlation for D090 – E090 (0.44) and C090 – E090 (0.08) than for C090 – D090 (0.73), whereas the observed correlations are relatively uniform (0.51 – 0.61) between these pairs. Observed \( u \) correlations between D040 and the offshore D moorings are small and negative. The model correlations, however, are larger (0.54 –
0.66) for all three D mooring pairs. This result illustrates a complexity in the observed flow at the inshore mooring location that is not captured by the model.

3.2. CODAR surface velocity observations

Daily-averaged surface velocities in the CODAR region (see Figure 1) are available from May 4 – June 20, 2001. We compare the modeled surface velocities over the same region in Figure 8. Shown are the complex correlation and phase, the time mean surface velocities, and the mode 1 EOFs from the CODAR observations and the model. Note the 100-m and 200-m isobaths are plotted for reference. The correlations are between 0.6 – 0.8 over much of the coverage area, with the exception of a few patchy areas at the north and south and near Cordell Bank, the topographic feature offshore of Pt. Reyes where the 100-m contour is closed. Phase angles are small in the middle of the CODAR region, with higher values around the edges. The mean velocities are very similar offshore of the 100-m isobath, but near the coast, the modeled velocities are stronger. This pattern is consistent with the discussion of Figures 5 and 7 in which the depth-averaged velocity magnitudes at D130 are comparable, but the modeled velocities at the inshore moorings are stronger than the observed velocities. The root mean square errors between the observed and modeled mean surface velocities are 0.06 m s\(^{-1}\) and 0.11 m s\(^{-1}\) for the east/west and north/south components, respectively. The structure of the observed and modeled mode 1 EOFs is similar over the entire CODAR region.

The modal amplitudes (bottom) are highly correlated, with a correlation of 0.79. To attempt to determine if the mode 1 EOF represents the wind-driven mode, we compute cross-correlations between the wind stress components and the observed and modeled mode 1 time series. Significant agreement is found between \(\tau_y\) and the mode 1 amplitudes, with zero-lag correlations of 0.88 and 0.63 for the observed and modeled modes, respectively.
With the mode 1 amplitude lagging $\tau_y^*$ by one day, the model correlation increases to 0.66. Cross-correlations of $\tau_x^*$ with the mode 1 amplitudes are small at all time lags. We conclude that the mode 1 EOFs represent the dominant coherent wind-driven variability.

3.3. Shipboard hydrographic observations

Shipboard surveys following the large scale and small scale survey plans shown in Figure 1 allow an opportunity for model-data comparisons. The large scale survey encompasses WEST lines A, D, and F, while the small scale survey covers lines B, C, D, and E. In Figure 9, we compare two lines from a single CTD survey to the modeled potential density $\sigma_\theta$ during the event period we will discuss later in section 5. The modeled and observed $\sigma_\theta$ fields show similar characteristics. At the D line, upwelled isopycnals are found near the surface from the coast to 30 km offshore in both the model and observations. The sections at the F line also compare well qualitatively, with the exception of an observed bulge of low density water extending from the surface to almost 100 m depth between 15 – 30 km offshore. This feature is possibly related to an output of warm, fresh water from San Francisco Bay that enters the study region when upwelling winds relax to near zero on May 20.

A quantitative comparison (Figure 9) is given by scatter plots of all the observations available for each of these survey lines (five surveys in May/June on the D line and one survey on the F line) versus corresponding model values. The correlation is very high on the F line (0.97) and the regression line has a slope near one (0.91). The correlation is lower on the D line (0.76) and more scatter is found, however the rmse values are similar at the two sites. The results for comparisons along lines A, C, and E (not shown), computed for one survey on lines A and E and two surveys on line C, have a high correlation (0.9) on the A line, while the C and E lines are much lower (0.51 and 0.44, respectively). A
similar comparison between the modeled potential density and that observed with the tow-yo instrument, which encompasses the large scale survey lines A, D, and F, yields a high correlation on the F line (0.93) and lower correlations on the A and D lines (0.54 and 0.53, respectively). The model clearly captures the density structure well at the northern end of the study region where the flow is relatively simple compared to that just north of Pt. Reyes and Cordell Bank, where the three interior survey lines are located. Somewhat surprising, perhaps, is the high correlation on the A line, where the model flow is quite complicated as we will illustrate.

4. Characteristics of Upwelling Season Response

We are interested in the mean wind-driven response of the shelf flow over the model simulation period. The winds are dominantly upwelling-favorable (Figure 4), however several relaxation events lasting 1–3 days occur during May and June 2001. The modeled shelf response at the surface can be seen in the region from Pt. Reyes to Pt. Arena in Figure 10. Clearly, the fields demonstrate that the upwelling response dominates the time mean. The surface velocity vectors show the location of the coastal upwelling jet, which separates slightly from the coast off Pt. Arena and significantly off Pt. Reyes, approximately following the 100-m isobath in both cases. Separation of the coastal upwelling jet from Pt. Reyes is a feature that has been previously discussed in the numerical model results of Gan and Allen (2002a). The largest variability in the velocity amplitude is off the capes and along the 200-m isobath. The variability is high off Pt. Arena and Pt. Reyes because the flows are complicated due to interactions with the variable coastline and bathymetry. Gan and Allen (2002a,b) found that, due to these interactions, the coastal capes in this area play a dominant role in the alongshelf variability of upwelling.

Another region of significant southward velocities at the surface offshore of the 200-m
isobath is also apparent south of Pt. Reyes. This corresponds to a bifurcation in the separated coastal jet with an inshore portion of the jet following the 100-m isobath and another portion turning offshore, crossing isobaths, and returning southward about 60 km offshore. This double jet structure will be discussed in further detail later in this section.

The mean surface temperature field displays an upwelling response with the coldest water near the coast and increasing temperature offshore. An area of relatively cold water is also found on the shelf south of Pt. Reyes. The standard deviation of temperature shows high variability offshore and south of Pt. Reyes due to the relatively large signal observed during upwelling relaxation in this region.

The coastal jet location is more obvious in the mean depth-averaged velocity than at the surface because velocities at depth decrease significantly offshore of the 200-m isobath (Figure 11). Overlaid on the depth-averaged velocity vectors are transport streamfunction contours, illustrating how the flow follows the coastline north of Pt. Reyes, where it veers offshore following the 100-m isobath. The transport is greatly decreased inshore of the 100-m isobath south of Pt. Reyes and a cyclonic recirculation area is found 50 km south of Cordell Bank between the regions of southward velocities associated with the bifurcated jet.

Bottom velocities have an onshore component under the coastal jet due to the bottom Ekman flow. Purely onshore bottom flow is found just south of Pt. Reyes. Consistent with the distribution of large bottom velocity, the bottom stress and bottom turbulent kinetic energy values are highest off Pt. Reyes and Pt. Arena. The turbulent kinetic energy variable (tke) is computed using the Mellor-Yamada level 2.5 closure scheme \( tke = \frac{1}{2} q^2 \). Nonlinearity in the surface flow is indicated off Pt. Reyes and Pt. Arena by the relatively large magnitudes of the surface relative vorticity divided by the Coriolis parameter \( f \), which gives a measure of the local Rossby number. These results all point to the high spatial variability and complexity associated with the coastal jet separation. Mean potential
density $\sigma_\theta$ at the bottom shows the isopycnals are approximately aligned with bathymetry contours with somewhat lower values inshore of the 100-m isobath south of Pt. Reyes.

Sections of time mean alongshelf velocity $v$ and potential density $\sigma_\theta$ at the locations shown in Figure 2 illustrate the significant variability in structure due to the flow response to the variable shelf geometry and coastline shape at different alongshelf locations (Figure 12). North of the F line (line 166), a coastal jet with a defined core extends about 200 m deep and 30 km offshore, with slightly northward velocities inshore. Along the F line (line 148), the jet widens and shallows to about 100 m depth. Continuing south to the E line (line 130), the existence of two separate jet structures begins to develop, with stronger velocities in the inshore jet. Evidence in Figures 10 and 11 of weaker surface and depth-averaged velocities between the 100-m and 200-m isobaths at this location was discussed previously. The double jet feature, however, is better defined and more visible in the sections than in the horizontal velocity fields. The double jet can be seen in Figure 12 at each subsequent section south of line 130, with southward velocity increasing in the offshore jet and becoming larger than that inshore at Pt. Reyes and along the A line (lines 112 and 104). The jets move offshore between lines 112 and 104 due to separation off Pt. Reyes as shown in Figure 11. Areas with zero or slightly northward velocity are found along the continental slope between the two jets at all sites. A region of northward velocity from 5–20 km offshore at the A line reflects the relaxation response that is strongest south of Pt. Reyes. The relaxation contribution to the time mean also causes slightly northward velocities near the coast just south of Pt. Arena (line 166), where a relaxation response is present, but much weaker than that south of Pt. Reyes.

The E line (line 130) is located about 10 km north of Cordell Bank, so it is possible that upstream influence of the bank causes this double jet velocity structure, which strengthens to the south as the isobaths are modified significantly by the presence of the bank (see
Figure 2). Other indications of upstream influence of Cordell Bank will be discussed later in connection with Lagrangian calculations presented in section 5.2. The identification in the model results of this double jet structure is new. Attempts to find evidence of a similar jet structure in the observations, both from WEST and from other northern California programs such as CODE, did not lead to any conclusive results. It is unclear, however, whether an appropriate comparison could be made from these observations due to their limited coverage areas. The southernmost CODE survey line is just north of the E line, and the WEST CODAR region does not extend offshore of the 200-m isobath around Cordell Bank and Pt. Reyes. WEST shipboard ADCP surveys during May 2001 (M. Roughan, personal communication) are available at the A, D, and F lines, but only for a few days. The ADCP measurements do not always extend far enough onshore or offshore to capture the necessary range for a comparison. However, one ADCP survey on May 26 that extends offshore along the D line (line 124) shows negative $v$ velocity on the shelf, a region of near zero $v$ just offshore at the shelf break (30 km from the coast), and surface-intensified negative $v$ from about 32 – 50 km from the coast. The model $v$, sampled in the same manner as the observations, has a similar across-shelf structure. This is clearly a qualitative comparison, but one which shows that relevant available observations are not inconsistent with the model results.

Time mean density fields do not exhibit as noticeable a transformation between alongshelf locations, although the region of upwelled isopycnals extends farther offshore as the location progresses south from line 166 to line 104. This difference between sections is largest at the A line (line 104), where the 26.3 kg m$^{-3}$ isopycnal surfaces approximately 40 km offshore, as compared to 15–25 km offshore at lines 166–112. The contrast in across-shelf density front location illustrates that more dense water is upwelled at the surface over a larger expanse of the shelf south of Pt. Reyes, where the alongshelf coastal jet is displaced
offshore relative to its location north of Pt. Reyes.

5. Dynamical Analysis of Upwelling and Relaxation Wind Event

5.1. Eulerian Analysis

We now focus our discussion on a specific wind event from May 17 – 23, 2001 during which the wind stress begins as upwelling-favorable and greater than 0.1 N m$^{-2}$ until May 19, at which time it decreases to near zero on May 20. Both components of the wind stress remain near zero until May 23 (see Figure 4). The modeled upwelling and relaxation response during this event is representative of those throughout the summer simulation period. This analysis also allows a contrast between upwelling and relaxation conditions over a typical event time scale. Shown in Figure 13 are surface velocity vectors, surface temperature, and surface elevation $\eta$ fields on May 18, 20, and 22. The wind stress during the event is provided at the top for reference. The location of the core of the alongshelf coastal upwelling jet on May 18 is between the 100-m and 200-m isobaths north of Pt. Arena and approximately along the 100-m isobath south of Pt. Arena. The jet separates from the coast south of Pt. Arena and to a greater extent south of Pt. Reyes. Surface temperatures are coldest and surface elevations are lowest near the coast due to upwelling, with the coldest water north of Bodega Bay and a large region of cold water with low $\eta$ found south of Pt. Reyes from the coast to the 100-m isobath.

On May 20, surface velocities decrease everywhere except in the coastal jet region. Surface temperatures decrease between Pt. Reyes and Bodega Bay due to the southward advection of cold water from north of Bodega Bay. Surface elevations decrease near the coast by 2-3 cm. May 22 shows the flow response to wind relaxation with a decrease in surface velocities everywhere, a warming of surface temperatures near the coast, and an increase in surface elevation near the coast.
In order to examine the dynamics of this event in more detail, we study fields of the depth-averaged velocity and alongshelf momentum term balance in Figures 14 and 15. We write the momentum equation for the depth-averaged alongshelf flow in the $y$ direction as

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} - G^y - F^y + fU + \frac{1}{\rho_0} \frac{\partial p}{\partial y} - \frac{1}{\rho_0 D} \tau^y_s + \frac{1}{\rho_0 D} \tau^y_b = 0,$$

where $(U, V)$ are the depth-averaged currents in the $(x, y)$ directions, $\tau^y_s$ and $\tau^y_b$ are the $y$ components of the surface and bottom stress, respectively, $G^y$ is the dispersion term, $F^y$ is the horizontal diffusion term, $f$ is the Coriolis parameter, and $D$ is the water depth. We refer to the terms $\frac{\partial V}{\partial t}$ as acceleration, $U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} - G^y - F^y$ as advection, $fU + \frac{1}{\rho_0} \frac{\partial p}{\partial y}$ as the ageostrophic pressure gradient, $\frac{1}{\rho_0 D} \tau^y_s$ as wind stress, and $\frac{1}{\rho_0 D} \tau^y_b$ as bottom stress.

The depth-averaged velocity is southward with magnitudes of 0.2–0.3 m s$^{-1}$ in the coastal jet, which is shown to separate off Pt. Arena and Pt. Reyes. Weaker velocities are found in the lee of the capes. The bifurcation of the jet, as apparently caused by upstream influence of Cordell Bank, is also shown with weak velocities directly over and north of the bank. Velocities increase near the capes on May 20, then decrease everywhere on May 22 following two days of near zero winds. On May 18, wind stress values are relatively large everywhere on the shelf due to the spatial uniformity of the wind forcing. Bottom stress values are high near the coast due to forcing of appreciable currents in the shallower water depths and off Pt. Reyes and Pt. Arena because bottom velocities are relatively large near the capes. As the winds decrease on May 20, bottom stress values decrease near the coast and the wind stress is near zero everywhere. Bottom stress weakens further on May 22 while wind stress values increase slightly near the coast.

In Figure 15, large negative acceleration on May 18 is due to the continued strengthening of the southward coastal jet caused by upwelling wind stress forcing. In the advection term, we see a spatial pattern of negative advection values offshore and north of Pt. Arena and Pt. Reyes and positive advection values to the south. This corresponds
to southward spatial acceleration of the southward coastal jet off the capes and southward spatial deceleration south of the capes. The advection terms are balanced primarily by the opposite-signed ageostrophic pressure gradient term. Note the characteristic spatial variation of the advection and ageostrophic pressure gradient terms around Pt. Reyes and Pt. Arena also occurs on a smaller scale off Bodega Head, the small cape at the northern end of Bodega Bay in the center of the WEST study area.

As the winds decrease, the acceleration term switches sign on May 20 over the shelf and the alongshelf velocity field decelerates. The regions of large advection and ageostrophic pressure gradient off the capes increase in area and magnitude on May 20. All three terms in Figure 15 then weaken on May 22.

The characteristics of the alongshelf pressure gradient pattern are of interest because the alongshelf topographic and coastline variability associated with Pt. Reyes and Pt. Arena are important factors in the dynamics of the shelf flow response. Gan and Allen (2002a) found a similar alongshelf pressure gradient distribution during upwelling-favorable winds in numerical modeling studies of this region. They explain the pattern as a response to decreased surface elevation south of the capes, which is related to increased velocities around the capes. In addition to a geostrophic balance in the across-shelf direction, which leads to lower surface elevation in regions of increased alongshelf velocities, nonlinear advection contributes significantly near Pt. Reyes and Pt. Arena. This leads to a gradient wind-like balance with a nonlinear centrifugal force term $V^2/R$ that is important due to increased $V$ and decreased radius of curvature $R$ around the capes. Thus, the surface elevation response is tied to the alongshelf velocity through the across-shelf momentum balance, and the modified surface elevation field serves to intensify the alongshelf pressure gradient. In this study, we find similar results in daily plots of surface elevation $\eta$ (Figure 13) and in the ageostrophic pressure gradient and nonlinear advection terms from
the across-shelf momentum balance (not shown). The surface elevation is low near the coast and south of Pt. Reyes and an across-shelf ageostrophic pressure gradient balances a relatively large nonlinear advection term near Pt. Reyes and also near Pt. Arena. Throughout the event, surface elevation is a minimum in the region south of Pt. Reyes on May 20, and correspondingly, depth-averaged velocity vectors are largest just off Pt. Reyes and Pt. Arena on May 20 (Figure 15). In support of the previous argument, the change in $\eta$ and the depth-averaged velocities from May 18 – 20 are consistent with the strengthening of the alongshelf nonlinear advection and ageostrophic pressure gradient terms.

Time series of the modeled depth-averaged alongshelf momentum terms at the locations of the D line moorings and at 90 m depth on the A and F lines allow us to investigate further the dynamics as they develop in response to the variable winds and the differences as a function of shelf location (Figure 16). Several upwelling events occur during the period shown, including the event that is the focus of this discussion. At all five moorings, the characteristics during upwelling forcing include a positive surface stress term that forces a negative acceleration of the upwelling jet followed by development of a negative bottom stress. The relative magnitude of the bottom stress decreases as the depth increases from D040 to D130. The major qualitative difference between the dynamics at D040 and the offshore moorings is the sign of the ageostrophic pressure gradient and advection terms. At D040, the advection is negative, and is balanced by a positive ageostrophic pressure gradient, presumably reflecting a southward spatial acceleration of the nearshore alongshelf current around Bodega Head, similar to the more intense behavior found off Pt. Reyes and Pt. Arena (Figure 15) during upwelling wind forcing. In contrast, generally positive advection terms are found at the other four moorings, illustrating the southward spatial deceleration of the coastal jet as it moves offshore to adjust to the presence of Pt. Reyes. The ageostrophic pressure gradient is generally negative, balancing positive wind stress and
advection and also positive acceleration when it occurs during wind relaxation events. The ageostrophic pressure gradient term has the highest zero-lag correlation with the advection term (correlation coefficients of 0.51–0.9) at all five moorings, with the exception of F090, which has a very low correlation between these terms.

Alongshelf variability is illustrated by the different responses at A090, F090, and D090. To the north, F090 shows similar wind stress and acceleration magnitudes, but smaller ageostrophic pressure gradient and advection terms, reflecting smaller effects of alongshelf topographic variability. The lack in correlation between the pressure gradient and advection time series also points to a significantly different response than that in the regions of influence of capes, as represented by the other time series. To the south, the terms at A090 show considerably larger ageostrophic pressure gradient and nonlinear advection terms. These terms are dominant in this region because of the influence of Pt. Reyes on the alongshelf advection processes and on the alongshelf pressure gradient field, as discussed previously. Acceleration, surface stress and bottom stress play a smaller role in the balance. The bottom slope is very small in this portion of the shelf at the A line, so that a wide range of sites, all with depths of 85 – 90 m, produce quantitatively different alongshelf momentum balances, but with the common characteristic that the dominant balance is between the nonlinear advection term and the ageostrophic pressure gradient. The A line dynamics therefore cannot be identified by approximate water depth, but rather across-shelf location must also be considered in interpreting the momentum balance time series.

Also of interest is the variability of the flow response (Figure 17) and the dynamical balances (Figure 18) across sections at the A, D, and F lines. The structure of the alongshelf velocity and density during the event is quite different at these locations, as expected from the time mean fields discussed in Figure 12. At the F line (line 148), the coastal jet
weakens from May 20 to May 22 with near-zero velocities inshore on May 22. The upwelled isopycnals also retreat slightly toward the coast following the relaxation of upwelling winds. The jet region is characterized (Figure 18) by positive advection, reflecting southward spatial deceleration in the slightly onshore-directed coastal jet (Figure 15). Nonlinear advection is balanced by a negative ageostrophic pressure gradient which also, through the Coriolis force, balances vertical diffusion in the surface and bottom boundary layers. The acceleration term (not shown) is about one half the magnitude of the other terms and has a spatial pattern similar to the nonlinear advection term with opposite sign. This corresponds to increasing southward velocities when the jet strengthens on May 18.

At the D line (line 124), the velocity structure is more complex due to the strong inshore jet and weaker offshore jet with northward velocities at depth in between. The momentum term balance shows a pattern of negative advection corresponding to southward spatial acceleration (balanced by a positive pressure gradient) on the offshore side of the weaker offshore jet, and positive advection corresponding to southward spatial deceleration (balanced by a negative pressure gradient) on the inshore side. In contrast, the dynamical structure of the stronger inshore jet is similar to that at the F line. This result leads to the conclusion that the inshore portion of the bifurcated jet matches the signature of the coastal upwelling jet north of Pt. Reyes, whereas the offshore portion of the bifurcated jet exhibits different dynamics and a generally weaker dynamical response in the momentum balance fields.

At the southernmost A line (line 104), the complexity increases as velocities in the offshore jet are as strong as those in the inshore jet. Both jets are displaced offshore relative to their D line locations due to separation off Pt. Reyes, and a region of significant northward velocities is found inshore. The density front is 30 km offshore and relatively dense water covers the broad shallow shelf inshore, illustrating the effectiveness of the
upwelling shelf circulation at the A line. The bottom boundary layer under the inshore jet, indicated by the negative vertical diffusion term, is also displaced offshore at the A line relative to the D and F lines (Figure 18). On May 20 and 22, large negative vertical diffusion is found in the water column above the bottom boundary layer on the inshore side of the southward coastal jet, about 20–25 km offshore. Inshore, below the region of northward velocities near the coast, positive vertical diffusion corresponds to offshore flow in the bottom Ekman layer. Hence, convergence in the bottom boundary layer could lead to positive vertical advection and increased vertical diffusion values that extend upwards into the water column at the boundary between the southward and northward velocities (Kurapov et al., 2005). The advection and ageostrophic pressure gradient fields on the shelf, which have maximum values on May 20, show significant vertical and horizontal structure. This includes large positive advection in the region of strong northward velocities within about 20 km of the coast (corresponding to northward spatial acceleration), which is balanced by a negative (northward) pressure gradient force. The advection and pressure gradient terms switch sign progressing offshore into the region of the nearshore coastal jet, then once again between the two jets where alongshelf velocities are near zero, and a final time in the region of the offshore jet. This pattern reflects the spatial acceleration and deceleration associated with the complex velocity structure on the shelf and slope just south of Pt. Reyes. The magnitude of these terms in the offshore jet region is weaker than that inshore, as discussed previously along the D line.

5.2. Lagrangian Analysis

Lagrangian fluid motion is calculated using two different techniques. The first approach involves computing parcel trajectories by solving the differential equations

\[
\frac{dx}{dt} = u, \quad \frac{dy}{dt} = v.
\]
Parcels are indexed by their initial positions at every \((x, y)\) grid point. In the vertical, parcels are initialized at the center of the grid cell next to the surface and remain at this depth throughout the simulation. Numerical solutions to (2) are calculated utilizing a fourth-order Milne Predictor Hamming Corrector scheme. The time step used for the Predictor-Corrector scheme is the model internal time step. The updated positions obtained from the solutions to (2) are recorded daily for each initial parcel position.

In addition to tracking individual water parcels, we utilize a second technique that provides Lagrangian trajectories for a continuous field of parcels. This approach involves the definition of three Lagrangian label fields that are advected by the model velocities (Kuebel Cervantes et al., 2003). The Lagrangian labels, \(X(x, y, z, t)\), \(Y(x, y, z, t)\), and \(Z(x, y, z, t)\), satisfy the following equations:

\[
\frac{DX}{Dt} = 0, \quad \frac{DY}{Dt} = 0, \quad \frac{DZ}{Dt} = 0,
\]

(3)

where \(\frac{D}{Dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z}\). The initial conditions are

\[
X(x, y, z, t = 0) = x, \quad Y(x, y, z, t = 0) = y, \quad Z(x, y, z, t = 0) = z.
\]

(4)

For calculations without errors, i.e., those performed in the limit of vanishing spatial grid sizes and time steps, the Lagrangian parcel trajectories obtained from both techniques would be equivalent.

In this application of the Lagrangian labels, the initial \(Y\) and \(Z\) labels are a function of their initial alongshelf and vertical location, respectively, as in (4). To aid in the physical interpretation, however, the \(X\) label is initialized as the water depth \(h\),

\[
X(x, y, z, t = 0) = h(x, y).
\]

(5)

This allows a ready assessment of across-isobath displacement of water parcels, which we refer to as onshore/offshore displacement in the following discussion. The labels \(X\), \(Y\), and
are calculated as fields on the model grid with the third-order upstream bias advection scheme. Since the model also includes a parameterization of small-scale turbulence, these Lagrangian parcel trajectories comprise only the resolved part of the full fluid motion represented in the model.

Examination of the time evolution of the label fields helps to provide insight into the Lagrangian characteristics of the flow. Surface distributions of the \( Y \) label and of the Lagrangian parcels, both initialized on May 17, are shown in Figure 19. The colorbar indicates values from 100 – 400 km, measured as distance from the southern boundary of the model domain. The alongshelf locations of the surface parcels (bottom) have been color-coded to allow a comparison of the evolution of the surface \( Y \) label (top) and the parcels. A striking feature in Figure 19 is the significant southward advection in the region of the coastal jet, with parcels being advected up to 100 km southward by May 22. The structure shows a well-defined split in the trajectories that occurs near Cordell Bank, with significant southward advection both offshore of the bank and inshore along the 100-m isobath. In regions inshore of the 100-m isobath, on Cordell Bank, and south of Pt. Reyes, the southward surface advection is decreased. Just off Pt. Reyes, a cyclonic recirculation region is apparent due to the interaction of northward flow south of the cape and the southward coastal jet. This cyclonic recirculation is also evident in velocity and temperature fields in Figure 13. This feature is located inshore of the recirculation region found in the mean depth-averaged velocity field (Figure 11).

The evolution throughout the event is shown most clearly in the \( Y \) label fields, but the parcel tracking shows a very similar response. Spatial correlations between the \( Y \) label and the parcels computed at the parcel locations range from 0.99 on May 18 to 0.95 on May 22. The comparison in Figure 19 is evidence that the two techniques perform consistently and provides a quantitative check on the ability of the Lagrangian methods.
Depth-averaged values of the $\Delta X$ and $\Delta Y$ Lagrangian label displacements and surface values of $\Delta Z$ are shown in Figure 20 during the event. The label displacements are calculated as $\Delta X(x, y, z, t) = X(x, y, z, t = 0) - X(x, y, z, t)$, $\Delta Y(x, y, z, t) = Y(x, y, z, t = 0) - Y(x, y, z, t)$, and $\Delta Z(x, y, z, t) = Z(x, y, z, t) - Z(x, y, z, t = 0)$ where the time of initialization $t = 0$ corresponds to May 17. Recall that the $X$ Lagrangian label is initialized as water depth so that positive values of $\Delta X$, $\Delta Y$, and $\Delta Z$ denote onshore, southward, and upward displacements, respectively. On May 18, the $\Delta Y$ displacement is relatively small, but by May 20, areas of southward advection are found in the region of the coastal jet. $\Delta Y$ values are small south of Pt. Reyes, due to the coastal jet separation, and are small inshore of the jet near the coast. Southward $\Delta Y$ displacements increase significantly from May 20 to May 22, however the pattern remains much the same. A large region of onshore displacement (positive $\Delta X$) just offshore of the 200-m isobath is apparent near the F line on May 18, with offshore displacement (negative $\Delta X$) to the north and south. Velocity fields on May 16 and 17 (not shown) indicate evidence for a cyclonic eddy-like circulation south of Pt. Arena that weakens as the southward alongshelf currents intensify on May 18. Velocities along the F line are onshore at the southern edge of this eddy, apparently leading to the onshore displacement seen in $\Delta X$ at this location. The negative regions just off the shelf break are caused by offshore velocities due to the coastal jet separation off Pt. Reyes and Pt. Arena. The positive $\Delta X$ patch is advected southward and distorted on May 20 – 22. Inshore of the 100-m isobath between Pt. Reyes and Pt. Arena, the $\Delta X$ values are generally positive, reflecting net onshore displacement.

Surface $\Delta Z$ shows upwelling of water from about 40 m depth in a few locations near the coast on May 18. Significantly more water from depth is found on May 20 and May 22, with initial depths greater than 60 m from the coast to about 10 km offshore everywhere north of Pt. Reyes. The response south of Pt. Reyes shows that the spatial pattern of
upwelling is complex and extends offshore in response to the separated coastal jet, rather than being contained in a cohesive region near the coast, and that water upwells to the surface from shallower depths there than north of Pt. Reyes. Note the effects of the cyclonic recirculation south of Pt. Reyes discussed previously with reference to Figure 19. This feature is associated with upwelling of water from the north and offshore transport of water parcels (positive $\Delta Y$ and $\Delta Z$ and negative $\Delta X$).

A Lagrangian investigation corresponding to the discussion of Figures 17 and 18 in section 5.1 is presented with sections of all three Lagrangian label displacement fields along the A, D, and F lines during the upwelling and relaxation event (Figure 21). The $\Delta Y$ Lagrangian label displacement shows a structure very similar to the alongshelf velocity, with the largest southward displacement corresponding to the jet location at all three sections. Upwelling of parcels occurs across the shelf, with upward displacements of up to 60 m in $\Delta Z$. Offshore displacements indicated by negative $\Delta X$ occur in the region of the upwelling jet, with the largest values at the surface due to the surface Ekman flow, and decreasing values with depth. Large patches of onshore displacement are found on the shelf at the F line (148) on May 18 and at the D line (124) on May 22, corresponding to the feature discussed in Figure 20. At the A line (104), the region of offshore displacements is a striking feature that is clearly centered over the offshore upwelling jet core. The $\Delta X$ response at the A line is caused by the coastal jet separation off Pt. Reyes, so that water in the jet is advected southward and offshore. Because the depth rapidly increases offshore of 100 m at the A line, the $\Delta X$ values are large just off the shelf break, although the actual offshore advection distance is 20 km or less. On the shelf at the A line, values of the label displacements are smaller than those at the D and F lines. A conclusion of the analysis of Figure 21 is that the source of upwelled water near the coast at the D and F lines is farther north and deeper than that at the A line, given the larger values of $\Delta Y$ and $\Delta Z$. Hence,
water that is upwelled on the shelf just south of Pt. Reyes is from a more local source because the presence of the cape significantly impacts the upwelling dynamics through jet separation. As shown in Figure 17, the upwelling circulation that occurs at the A line is effective at bringing more dense water to the surface across the entire shelf.

In order to further explore the question of how the Lagrangian dynamics vary as a function of across-shelf distance, we plot contours of all three Lagrangian label displacements, as well as $v$ and $\sigma_\theta$, as a function of depth and time during the event at the D line moorings (Figure 22). Significant upwelling of deeper and more dense water from about 40 km to the north occurs at D040. At D090, upwelling of water from about 80 km to the north occurs but the deeper water does not surface as at D040. The appearance of water from offshore is seen in $\Delta X$ at 40 m depth on May 19. This patch of offshore water corresponds to a small positive $\Delta X$ region at the D line on May 20 in Figure 21 and the onshore spreading of the large positive $\Delta X$ region in Figure 20. The water appears to be upwelled, as shown by its location at the upper edge of the upwelled water in $\Delta Z$. With regard to Lagrangian displacements, the upwelling response at D090 is clearly more complex than at D040.

At D130, there are distinct contrasts with the inshore moorings. Noticeable upwelling is not evident in either $\Delta Z$ or $\sigma_\theta$, but further evidence of the onshore patch of water discussed previously is found. $\Delta X$ shows that water from offshore (and 100 km to the north as shown by $\Delta Y$) is advected into the site at 40 m depth on May 21 and displaced downward to 100 m depth by May 23. Because there is no corresponding signal in $\Delta Z$, this water is not upwelled from depth.

A final illustration of the alongshelf variability of the Lagrangian characteristics is provided by time series of $v$, $\sigma_\theta$, $\Delta X$, $\Delta Y$, and $\Delta Z$ at 90 m depth along the A and F lines (Figure 23). The alongshelf velocity $v$ is weaker than at D090, especially at the F line,
where $v$ is near zero below about 20 m over much of the event period. Deeper isopycnals reach the surface at 90 m depth at the F line than at the D line, but upwelling in the isopycnals at the A line is much less evident. The A090 location is on the edge of the density front, just inshore of the signature of Cordell Bank (see Figure 17). The density front is farther offshore at the A line than at the northern lines, as discussed previously. Thus, upwelling occurs over much of the shelf region at the A line (Figures 20 and 21), but the evolution throughout the event is relatively weak at this 90-m location. The structure of the $\Delta Y$ time series is similar at all three locations, especially at the A and D lines. Note that the location of A090 is offshore of the region of locally upwelled water on the A line discussed previously and it shows a significant signal in $\Delta Y$. While $\Delta Y$ displacements are comparable between the A, D, and F lines during the event, the $\Delta X$ and $\Delta Z$ responses are quite different. $\Delta Z$ displacements are generally complex at all three locations. $\Delta Z$ shows that water at depth after May 19 is upwelled from shallower depths on the F line as compared to the A and D lines. As shown in Figure 21, deep water is upwelled at F, however it doesn’t reach as far inshore. $\Delta X$ shows that significantly less across-isobath motion occurs at 90-m depth at the A and F lines than at the D line. The A and F lines do not show evidence at 90 m of the large patch of onshore-displaced water that is prevalent at the D line in Figures 20, 21, and 22.

The main results from the three-dimensional Lagrangian analysis discussed in this section are summarized here. The influence of the double jet structure on the southward displacement of parcels over the shelf is clearly shown to produce greater southward displacement along the 100-m isobath and offshore of Cordell Bank. Directly over the bank and near the coast, southward displacement is decreased. Alongshelf variability in fluid parcel displacement is also introduced by the presence of Pt. Arena and Pt. Reyes. Offshore of these capes, parcels are advected off the shelf due to the offshore-directed velocities
associated with the separation of the coastal upwelling jet. A cyclonic recirculation feature detected south of Pt. Arena prior to the event leads to a large patch of onshore-displaced parcels that first appears near the F line and is displaced southward and distorted in time. This behavior shows directly that eddy-like structures that develop in the coastal jet as a result of flow-topography interactions can have a significant impact on across-shelf transport. South of Pt. Reyes, the upwelling response of the fluid parcels contrasts from that north of Pt. Reyes in that water upwelled near the coast is from a more local source and the spatial pattern of upwelling is variable rather than occurring in a defined region near the coast. Across-shelf variability in the response of water parcels along the D line is also evident, including decreased vertical displacement of upwelled water parcels and increased southward displacement of parcels in the offshore direction.

6. Summary

We have presented a modeling application using the Regional Ocean Modeling System (ROMS) with the objective of studying and understanding the wind-driven flows off Northern California in the region of the Wind Events and Shelf Transport (WEST) project. In this modeling effort, we set out to answer questions about flow variability across and along the shelf, flow complexities introduced by Cordell Bank, and the source of upwelled water in the region. To address these questions, we used both an Eulerian and a Lagrangian approach and focused analysis on an upwelling and relaxation wind event that is representative of those occurring throughout the summer in this region.

Numerous model-data comparisons suggest that the model performs reasonably well in this region, with high correlations between modeled and measured depth-averaged velocities at the mooring locations, surface velocities in the CODAR region, and potential density along survey lines. A weakness of the model is the inability to fully capture the reversal of
southward velocities that is observed following relaxation of upwelling winds.

The mean circulation over the period of May 5 – June 20, 2001 is dominated by an upwelling response, including a southward coastal jet of up to 1 m s$^{-1}$ that separates from the coast off Pt. Arena and Pt. Reyes. The capes are regions of nonlinearity in the surface flow and significant turbulence near the bottom. Sections of alongshelf velocity at several locations reveal significant alongshelf variability and the existence of a distinct double jet structure that develops just north of Bodega Bay. Upstream influence of Cordell Bank is postulated to be the cause for this double jet.

With regard to the time variability of the flow, we have focused attention on a specific upwelling and subsequent relaxation wind event. Flows around Pt. Reyes show a different response north and south due to interactions of the shelf flow with the highly variable coastline shape and shelf geometry. South of Pt. Reyes, the upwelling circulation is effective in bringing relatively cold, dense water to the surface over the entire shelf. Relaxation of upwelling winds causes the development of northward velocities south of Pt. Reyes and near the coast between Pt. Reyes and Pt. Arena. Depth-averaged momentum balance terms illustrate the importance of the alongshelf topographic and coastline variability in causing a negative nonlinear advection offshore of Pt. Reyes and Pt. Arena, balanced by positive ageostrophic pressure gradient. This pattern is due to the spatial acceleration of the velocity around the capes.

Variability in the across-shelf direction is also investigated through time series of the depth-averaged alongshelf momentum balance terms at the D line moorings. The response is similar at 90 m and 130 m, however at 40 m the dynamics are different as shown by the opposite sign of the nonlinear advection and ageostrophic pressure gradient terms resulting from the small cape structure of Bodega Head. Differences in the D090 time series and those at 90-m depth along the A and F lines again point to the importance of variability
of the topography and coastline on the details of the depth-averaged momentum balance. At F090, a region with relatively uniform topography along the shelf, the advection and ageostrophic pressure gradient terms are small compared to the wind stress, while at A090, just south of Pt. Reyes, these terms constitute the dominant balance.

The Lagrangian shelf characteristics and their relationship to the Eulerian fields throughout the wind event are also discussed. We show the upwelling and relaxation response at D040 is strong as compared to the offshore moorings using time series of $v$, $\sigma_\theta$, and Lagrangian label displacements $\Delta X$, $\Delta Y$, and $\Delta Z$. The Lagrangian displacement fields are a useful tool in determining the response of water parcels to upwelling wind forcing. Alongshelf sections and area maps of $\Delta X$, $\Delta Y$, and $\Delta Z$ also show the source of upwelled water near the coast at the A line is local, as compared to that north of Pt. Reyes, which has a signature of deeper water from farther north. This result once again points to a fundamentally different upwelling response north and south of Pt. Reyes, and gives further evidence of the significance of the coastline shape in the behavior of the shelf flow.

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References


Figure Captions

Figure 1. Observational layout for Wind Events and Shelf Transport (WEST) project.

Figure 2. ROMS model domain with grid resolution and bathymetry contours. The grid’s
alongshelf axis is aligned along 330 T. The horizontal lines show the locations of across-shelf
sections, numbered according to alongshelf grid number, that are discussed in section 5.
Five of these lines correspond to WEST survey lines A-F as shown on the right side. Note
that the distance from the offshore boundary to the coastal boundary is approximately 135
km at both ends of the model domain, although the distances appear slightly different due
to the map projection. The isobaths shown include 100 m and 200 – 1400 m at intervals
of 200 m. Cordell Bank is the topographic feature just south of the C line denoted by the
closed 100-m isobath.

Figure 3. Initial temperature and salinity profiles.

Figure 4. Across-shelf and alongshelf wind stress and total heat flux time series used to force
the model. The alongshelf component $\tau_s$ has a mean value of -0.064 N m$^{-2}$ and standard
deviation of 0.047 N m$^{-2}$, and the across-shelf component $\tau_x$ has a mean value of 0.035 N
m$^{-2}$ and standard deviation of 0.029 N m$^{-2}$. The total heat flux has a mean value of 80 W
m$^{-2}$ and standard deviation of 56 W m$^{-2}$. The instruments at D090 were not operational
prior to May 5, therefore we used a linear regression of the NDBC 13 buoy winds and a
linear increase in heat flux from near zero to the first measured value. Note that the wind
stress components have been rotated to the model axis, which is aligned along 330 T. Wind
and heat flux measurements from D090 were provided by E. Dever.

Figure 5. Time series of $\tau_s$ (a) and observed and modeled depth-averaged currents (m s$^{-1}$)
at D040 mooring (b-c), D090 mooring (d-e), and D130 mooring (f-g). Major principal axes
(MPA), magnitude of the complex correlation coefficient ($|\rho|^*$), phase angle ($\theta^*$), and root
mean square error for ($u$, $v$) are provided at each location. The highest 95% significance
level for these velocity correlations is 0.51. The depths of the current meters range from 5
m to 33 m, 76 m, and 109 m, respectively, at D040, D090, and D130, with 2 m between
each instrument. Moored velocity measurements were provided by E. Dever.

Figure 6. Time series of $\tau_s$ (a) and observed and modeled near-surface temperatures at
D040 mooring (b), D090 mooring (c), and D130 mooring (d). Correlation coefficients and
root mean square error are provided at each location. The highest 95% significance level for
these temperature correlations is 0.71. The depths of the temperature sensors range from 5
m to 30 m, 70 m, and 50 m, respectively, at D040, D090, and D130, with 5 m between
each instrument. Moored temperature measurements were provided by E. Dever.

Figure 7. Mean (top) and mode 1 EOF (middle) of depth-averaged velocities from the
mooring observations (left) and the model (right). The amplitude time series of the
observed (solid line) and modeled (dashed line) mode 1 EOF is also shown at the bottom
with the correlation coefficient. The 100-m and 200-m isobaths are provided.
Figure 8. Magnitudes of complex correlation coefficients and phase angles (left) between modeled and observed surface currents, time mean surface velocity vectors (middle), and dominant mode 1 EOF (right) of surface currents from the CODAR observations (top) and the model (middle). The percentage of total variance explained by the mode 1 EOF is displayed in the lower left corner of each panel. The amplitude time series of the observed (red) and modeled (blue) EOFs are also shown at the bottom with the correlation coefficient. The 100-m and 200-m isobaths are shown in black. CODAR surface velocities were provided by D. Kaplan.

Figure 9. Potential density sections from CTD observations (top) and model (middle) along the D Line on May 20 (left) and the F Line on May 21 (right). Note the difference in the horizontal scales. At the bottom are scatter plots of all potential density observations compiled from five surveys during May/June for the D Line and one survey for the F Line. Provided below the scatter plots are the slope of the regression line (b), correlation coefficient (r), root mean square error (rmse), and variance from the observations ($\sigma_o$) and the model ($\sigma_m$). Hydrographic data were provided by N. Garfield.

Figure 10. Time mean surface velocity vectors with magnitudes in color (upper left), surface temperature (°C) (upper right), standard deviation of the vector amplitudes (m s$^{-1}$) (lower left), and standard deviation of temperature (lower right) over the region from Pt. Reyes to Pt. Arena. The 100-m and 200-m isobaths are shown in black.

Figure 11. Time mean depth-averaged velocity vectors with magnitudes in color and contours of transport streamfunction in black (upper left), bottom velocity vectors (upper middle), bottom stress vectors $\tau_b$ (upper right), surface relative vorticity $\zeta$ divided by $f$ (lower left), bottom potential density $\sigma_\theta$ in kg m$^{-3}$ (lower middle), and bottom turbulent kinetic energy ($tke$) in $10^{-4}$ m$^2$ s$^{-2}$ (lower right).

Figure 12. Sections of time mean alongshelf velocity $v$ in m s$^{-1}$ (left) and potential density $\sigma_\theta$ in kg m$^{-3}$ (right) plotted as a function of depth (m) and distance offshore (km). The zero $v$ contour is shown in black. The alongshelf grid numbers shown in Figure 2 are in the lower right corner of each $v$ section and corresponding WEST survey lines are in the lower right corner of each $\sigma_\theta$ section.

Figure 13. Daily-averaged surface velocity vectors with magnitudes in color (top), surface temperature (middle), and surface elevation ($\eta$) fields over the region from Pt. Reyes to Pt. Arena on May 18, 20, and 22. The wind stress during the event period is given at the top. Three section locations along the A, D, and F lines that will be detailed in Figures 17, 18, and 21 are shown as black lines.

Figure 14. Depth-averaged velocity vectors and magnitudes in color (top), alongshelf surface stress term (middle) and alongshelf bottom stress term (bottom) from the depth-averaged alongshelf momentum balance over the region from Pt. Reyes to Pt. Arena on May 18, 20, and 22. The terms are on the left-hand side of the equation and oriented along the model $y$-axis. The units for each term are $10^{-6}$ m s$^{-2}$. The locations of the time series shown in Figure 16 are marked with a black × in the middle right panel.
Figure 15. Acceleration term (top), nonlinear advection term (middle), and ageostrophic pressure gradient term (bottom) from the depth-averaged alongshelf momentum balance over the region from Pt. Reyes to Pt. Arena on May 18, 20, and 22. The terms are on the left-hand side of the equation and oriented along the model y-axis. The units for each term are $10^{-6} \text{ m s}^{-2}$.

Figure 16. Time series of depth-averaged alongshelf momentum balance terms ($10^{-5} \text{ m s}^{-2}$) at the D line moorings and at 90 m on the A and F lines from May 17 – June 20. The terms are on the left-hand side of the equation and are rotated to the direction of the time mean depth-averaged velocity at each mooring (337 T at D040, 335 T at D090, 342 T at D130, 354 T at A090, and 306 T at F090). Time series of corresponding depth-averaged velocity vectors (relative to the same direction) from these locations are also shown. The scale for the velocity vectors is given at the bottom. Note the different vertical scale for the time series of terms at D040 and A090.

Figure 17. Sections of alongshelf velocity $v$ (left) and potential density $\sigma_\theta$ (right) along the F (line 148 – top), D (line 124 – middle), and A (line 104 – bottom) lines on May 18, 20, and 22. The zero $v$ contour is shown in black.

Figure 18. Sections of the alongshelf momentum term balance, including the ageostrophic pressure gradient (left), vertical diffusion (middle), and advection (right) on May 18, 20, and 22. The section locations are the same as in Figure 17. Contours of $v$ with a 0.1 m s$^{-1}$ contour interval are shown in black over the pressure gradient contours. The terms are on the left-hand side of the equation and are rotated to the direction of the cross-sectional average of the time mean (over the entire simulation period) depth-averaged velocity (319 T on line 148, 342 T on line 124, and 325 T on line 104). The units for each term are $10^{-6} \text{ m s}^{-2}$.

Figure 19. Surface Y Lagrangian label in km (top) and Lagrangian parcels (bottom) initialized on May 17 and plotted on May 18, 20, and 22. Spatial correlation coefficients between the labels and the parcels are given for each day at the bottom. The colorbar indicates values from 100 – 400 km, measured as distance from the southern boundary of the model domain. The initial Y values at the southern and northern boundaries of the region plotted are 150 km and 320 km, respectively. The locations of the A, D, and F lines are indicated in the right Y panel.

Figure 20. Depth-averaged Lagrangian label displacements $\Delta X$ (top) and $\Delta Y$ (middle), and surface $\Delta Z$ (bottom) over the region from Pt. Reyes to Pt. Arena on May 18, 20, and 22. The differences $\Delta X$, $\Delta Y$, and $\Delta Z$ are calculated as defined in the text so that positive values denote onshore, southward, and upward displacements, respectively. The locations of the A, D, and F lines are indicated in the right panels and the locations of the time series shown in Figures 22 and 23 are marked with a black $\times$ in the middle left panel.
Figure 21. Sections of Lagrangian label displacements $\Delta X$ (left), $\Delta Y$ (middle), and $\Delta Z$ (right) on May 18, 20, and 22. The differences $\Delta X$, $\Delta Y$, and $\Delta Z$ are calculated as defined in the text so that positive values denote onshore, southward, and upward displacements, respectively. The section locations are the same as in Figure 17. The zero $\Delta Y$ contour is shown in black. The locations of the D040, D090, and D130 time series plotted in Figure 22 and the A090 and F090 time series plotted in Figure 23 are shown as black lines in the far right column.

Figure 22. Time series of $v$ (row 1), $\sigma_\theta$ (row 2), Lagrangian label displacements $\Delta X$ (row 3), $\Delta Y$ (row 4), and $\Delta Z$ (row 5) at the D line moorings from May 17 – 23. Zero contours are shown in black.

Figure 23. Time series of $v$ (row 1), $\sigma_\theta$ (row 2), Lagrangian label displacements $\Delta X$ (row 3), $\Delta Y$ (row 4), and $\Delta Z$ (row 5) at 90 m depth along the A line (left) and the F line (right) from May 17 – 23. Zero contours are shown in black.
Table 1. Summary of space-lagged correlation coefficients for observed (bold text) and modeled depth-averaged alongshelf velocity ($v$) and across-shelf velocity ($u$) at the mooring locations. The alongshelf and across-shelf velocities are determined by rotating to the principal axes of the depth-averaged currents. The time period over which the correlations are computed is the same as for the model-data comparisons presented in Figures 5, 6, and 7, May 5 – June 20, 2001. The highest 95% significance level for the correlations shown below is 0.51.

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Figure 1. Observational layout for Wind Events and Shelf Transport (WEST) project.
Figure 2. ROMS model domain with grid resolution and bathymetry contours. The grid’s alongshelf axis is aligned along 330 T. The horizontal lines show the locations of across-shelf sections, numbered according to alongshelf grid number, that are discussed in section 5. Five of these lines correspond to WEST survey lines A-F as shown on the right side. Note that the distance from the offshore boundary to the coastal boundary is approximately 135 km at both ends of the model domain, although the distances appear slightly different due to the map projection. The isobaths shown include 100 m and 200 – 1400 m at intervals of 200 m. Cordell Bank is the topographic feature just south of the C line denoted by the closed 100-m isobath.
Figure 3. Initial temperature and salinity profiles.
Figure 4. Across-shelf and alongshelf wind stress and total heat flux time series used to force the model. The alongshelf component $\tau_y^s$ has a mean value of -0.064 N m$^{-2}$ and standard deviation of 0.047 N m$^{-2}$, and the across-shelf component $\tau_x^s$ has a mean value of 0.035 N m$^{-2}$ and standard deviation of 0.029 N m$^{-2}$. The total heat flux has a mean value of 80 W m$^{-2}$ and standard deviation of 56 W m$^{-2}$. The instruments at D090 were not operational prior to May 5, therefore we used a linear regression of the NDBC 13 buoy winds and a linear increase in heat flux from near zero to the first measured value. Note that the wind stress components have been rotated to the model axis, which is aligned along 330 T. Wind and heat flux measurements from D090 were provided by E. Dever.
Figure 5. Time series of $\tau^*$ (a) and observed and modeled depth-averaged currents (m $s^{-1}$) at D040 mooring (b-c), D090 mooring (d-e), and D130 mooring (f-g). Major principal axes (MPA), magnitude of the complex correlation coefficient ($\rho^*$), phase angle ($\theta^*$), and root mean square error for ($u$, $v$) are provided at each location. The highest 95% significance level for these velocity correlations is 0.51. The depths of the current meters range from 5 m to 33 m, 76 m, and 109 m, respectively, at D040, D090, and D130, with 2 m between each instrument. Moored velocity measurements were provided by E. Dever.
Figure 6. Time series of $\tau^s$ (a) and observed and modeled near-surface temperatures at D040 mooring (b), D090 mooring (c), and D130 mooring (d). Correlation coefficients and root mean square error are provided at each location. The highest 95% significance level for these temperature correlations is 0.71. The depths of the temperature sensors range from 5 m to 30 m, 70 m, and 50 m, respectively, at D040, D090, and D130, with 5 m between each instrument. Moored temperature measurements were provided by E. Dever.
Figure 7. Mean (top) and mode 1 EOF (middle) of depth-averaged velocities from the mooring observations (left) and the model (right). The amplitude time series of the observed (solid line) and modeled (dashed line) mode 1 EOF is also shown at the bottom with the correlation coefficient. The 100-m and 200-m isobaths are provided.
Figure 8. Magnitudes of complex correlation coefficients and phase angles (left) between modeled and observed surface currents, time mean surface velocity vectors (middle), and dominant mode 1 EOF (right) of surface currents from the CODAR observations (top) and the model (middle). The percentage of total variance explained by the mode 1 EOF is displayed in the lower left corner of each panel. The amplitude time series of the observed (red) and modeled (blue) EOFs are also shown at the bottom with the correlation coefficient. The 100-m and 200-m isobaths are shown in black. CODAR surface velocities were provided by D. Kaplan.
Figure 9. Potential density sections from CTD observations (top) and model (middle) along the D Line on May 20 (left) and the F Line on May 21 (right). Note the difference in the horizontal scales. At the bottom are scatter plots of all potential density observations compiled from five surveys during May/June for the D Line and one survey for the F Line. Provided below the scatter plots are the slope of the regression line (b), correlation coefficient (r), root mean square error (rmse), and variance from the observations ($\sigma_o$) and the model ($\sigma_m$). Hydrographic data were provided by N. Garfield.
Figure 10. Time mean surface velocity vectors with magnitudes in color (upper left), surface temperature ($^\circ$C) (upper right), standard deviation of the vector amplitudes (m s$^{-1}$) (lower left), and standard deviation of temperature (lower right) over the region from Pt. Reyes to Pt. Arena. The 100-m and 200-m isobaths are shown in black.
Figure 11. Time mean depth-averaged velocity vectors with magnitudes in color and contours of transport streamfunction in black (upper left), bottom velocity vectors (upper middle), bottom stress vectors $\tau_b$ (upper right), surface relative vorticity $\zeta$ divided by $f$ (lower left), bottom potential density $\sigma_\theta$ in kg m$^{-3}$ (lower middle), and bottom turbulent kinetic energy (tke) in $10^{-4}$ m$^2$ s$^{-2}$ (lower right).
Figure 12. Sections of time mean alongshelf velocity $v$ in m s$^{-1}$ (left) and potential density $\sigma_\theta$ in kg m$^{-3}$ (right) plotted as a function of depth (m) and distance offshore (km). The zero $v$ contour is shown in black. The alongshelf grid numbers shown in Figure 2 are in the lower right corner of each $v$ section and corresponding WEST survey lines are in the lower right corner of each $\sigma_\theta$ section.
Figure 13. Daily-averaged surface velocity vectors with magnitudes in color (top), surface temperature (middle), and surface elevation ($\eta$) fields over the region from Pt. Reyes to Pt. Arena on May 18, 20, and 22. The wind stress during the event period is given at the top. Three section locations along the A, D, and F lines that will be detailed in Figures 17, 18, and 21 are shown as black lines.
Figure 14. Depth-averaged velocity vectors and magnitudes in color (top), alongshelf surface stress term (middle) and alongshelf bottom stress term (bottom) from the depth-averaged alongshelf momentum balance over the region from Pt. Reyes to Pt. Arena on May 18, 20, and 22. The terms are on the left-hand side of the equation and oriented along the model y-axis. The units for each term are $10^{-6}$ m s$^{-2}$. The locations of the time series shown in Figure 16 are marked with a black $\times$ in the middle right panel.
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Figure 22. Time series of $v$ (row 1), $\sigma_\theta$ (row 2), Lagrangian label displacements $\Delta X$ (row 3), $\Delta Y$ (row 4), and $\Delta Z$ (row 5) at the D line moorings from May 17 – 23. Zero contours are shown in black.
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