Flow-topography interactions in the northern California Current System observed from geostationary satellite data

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[1] Data from Geostationary Operational Environmental Satellites are used to study the seasonal evolution of temperature fronts in the northern California Current System (CCS), focusing on the interactions with topographic features. Fronts first appear close to the coast in response to upwelling winds, moving offshore with the continuous input of energy to the system. Late in the upwelling season (after July), the upwelling front is persistently found over deeper waters south of Heceta Bank, Oregon, than north of it, suggesting that the equatorward jet separates from the shelf at Heceta Bank. Inshore of the upwelling front, weak gradients are found on the Bank. The interaction of the equatorward flow with Heceta Bank and Cape Blanco, Oregon, farther south, substantially increases the mesoscale activity and oceanic frontal habitat downstream to the south in the CCS, where fronts are persistently found greater than 100 km from the coast. **Citation:** Castelao, R. M., J. A. Barth, and T. P. Mavor (2005), Flow-topography interactions in the northern California Current System observed from geostationary satellite data, *Geophys. Res. Lett.*, *32*, L24612, doi:10.1029/2005GL024401.

1. Introduction

[2] The majority of shelf circulation studies off Oregon have been in regions of simple topography, to the north of Newport (44.65°N). Recently, however, interest in regions with alongshore bathymetric variations has increased, as indirect observations (e.g. high chlorophyll concentration in satellite images, fishing success) suggest that production is enhanced in the vicinity of topographic features. Despite the intense field efforts conducted near Heceta Bank (HB) and Cape Blanco (CB) in the last decade [e.g., *Barth et al.*, 2000; *Barth and Wheeler*, 2005], observations are generally restricted to small areas or have short temporal coverage. The high spatial and temporal resolution of satellite measurements makes them ideal for observing the evolution of sea surface temperature (SST) fronts, complementing the less extensive, but depth-resolving field data. Field data off Oregon during the upwelling season often show a coastal jet flowing along a sharp gradient in SST. We make use of Geostationary Operational Environmental Satellites (GOES) data to describe the mesoscale structure of the SST fronts and its seasonal evolution, focusing on the influence of HB and CB on circulation in the northern California Current System (CCS).

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2. Data and Methods

[3] SST fields were derived from GOES hourly data collected during 2001. After cloud screening [*Wu et al.*, 1999], a daily-averaged SST field was calculated with 5 km resolution. The daily images were processed by an edge-detection algorithm [*Canny*, 1986] to identify SST fronts. The frontal data were aggregated over each month, and a probability of detecting a front (PDF) was formed by dividing the number of times a pixel was occupied by a front by the number of times the pixel was clear during that time period [*Ullman and Cornillon*, 1999]. A Sobel gradient operator (3x3 pixel window) was used to estimate the magnitude of the SST gradient vectors. A detailed description of the data processing is given by *Breaker et al.* [2005]. Using data from a geostationary satellite (24 images per day) increases the possibility of inferring cloud-free SST at least once each day compared with polar-orbiting satellite data (generally 4 images available per day), an important advantage as the region of interest tends to be cloudy during all seasons.

3. Spatial and Temporal Variability of the Fronts

[4] The frontal patterns in the CCS, including the region off Oregon, show strong seasonal variability [*Strub and James*, 2000]. During 2001, the PDF off Oregon is very low from January to April (Figure 1). The wind direction (Figure 2) during these months was characterized by frequent reversals, with a weakly downwelling favorable (northward) cumulative effect. Although mesoscale activity may be significant, fronts during the downwelling season are bottom intensified, making them undetectable by satellite observations. No coherent region with high probabilities is found. Scattered high values, primarily in the offshore region, represent background values consisting, in part, from mesoscale activity generated the previous upwelling season. A strong upwelling favorable (southward) wind event in the beginning of May marks the beginning of the upwelling season in the HB region (Figure 2), and the cumulative wind stress decreases until mid October. South of CB, frequent upwelling favorable winds begin in mid March (not shown), and the cumulative wind stress is significantly upwelling favorable in May. Consistent with the forcing, a large increase in the PDF is observed in May south of CB, with a much weaker increase in the HB region (Figure 1).

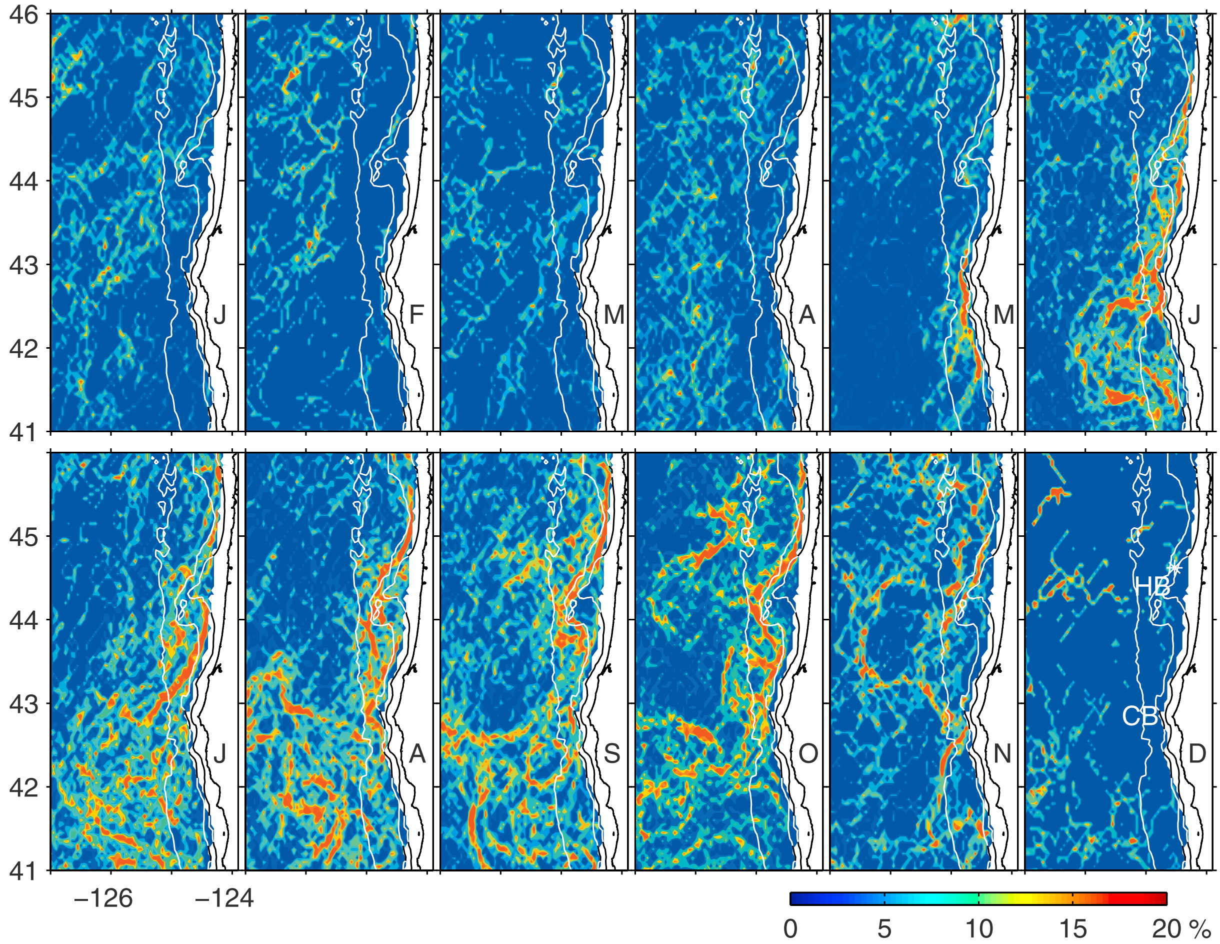

Figure 1. Probability of detecting a SST front (%) off Oregon during 2001. Probabilities larger than 20% are shown in dark red in order to reveal as much of the horizontal structure as possible. The 100-, 200- and 1500-m isobaths are shown. The white asterisk in the December map shows the location of the wind buoy. HB: Heceta Bank; CB: Cape Blanco. J: January; F: February; and so on.

[5] The cumulative input of energy from the wind leads to a significant increase in the PDF during late spring to early fall. During June, a thin band of high values is found close to the coast north of 43°N, inshore of HB. In July, high probabilities span a larger area. *Castelao and Barth* [2005a], using in situ observations, showed that the coastal jet and the upwelling front over HB moved several kilometers offshore over a period of roughly 7 days during a strong wind event in July. The shift in the position of the front is consistent with high probabilities spread over a wider area. Later in the upwelling season, the SST front is located on the offshore side of the Bank. It is interesting to note that the front frequently follows the 200-m isobath on the upstream half of HB (44–45°N), but occupies much deeper waters south of it, even though the bottom topography profiles upstream and downstream of the Bank are similar. This is most clear in the August probability map. Using a set of idealized numerical simulations, with bottom topography mimicking the 200-m isobath at HB, *Castelao and Barth* [2005b] showed that the small radius of curvature on the downstream part of HB is responsible for substantially increasing the cross-isobath flow toward deeper waters. High PDF close to the coast in the southern part of the Bank (44°N) indicates the spin up of a local coastal jet, a result supported by other observations [*Castelao and Barth*, 2005a; *Kosro*, 2005].

[6] South of CB, the seasonal evolution during 2001 is marked by a gradual offshore movement of the fronts. The area with high PDF increases considerably south of CB during the upwelling season, consistent with the observation that the upwelling jet frequently separates from the coast in the vicinity of the Cape [e.g., *Barth et al.*, 2000]. During July, high values are found in a scattered region extending for about 160 km from the coast. This is presumably due to

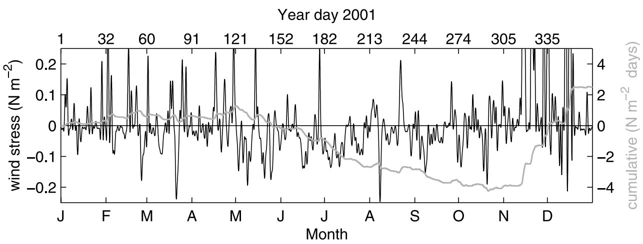

Figure 2. Alongshore component of wind stress from NOAA NDBC Buoy 46050 offshore of Newport, OR (see Figure 1 for location), during 2001. Gray curve is cumulative wind stress starting at 01 January.

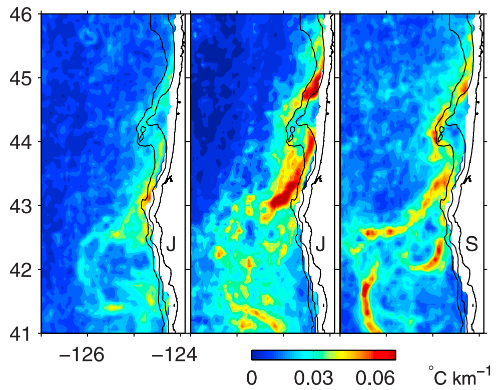

Figure 3. SST gradient magnitude (°C km^{-1}) off Oregon during June, July, and September 2001.

interactions of the flow with the topography, in addition to baroclinic instabilities, which contribute to create finite-amplitude meanders and transfer energy from the mean flow to the eddy fields [*Barth et al.*, 2005]. There is a tendency, however, for higher values to be found in more coherent patterns offshore later in the year (August–September). A similar seasonal evolution is observed in the magnitude of the SST gradients (Figure 3), which are proportional to the flow speed along the front. Strong gradients are found during summer, close to the coast north of CB, but farther offshore downstream of the Cape.

[7] Much lower PDF is found in the whole region during November and December (Figure 1). This is consistent with the wind forcing, which was predominantly downwelling favorable during these months (Figure 2), i.e., SST fronts are destroyed as they are swept shoreward by onshore Ekman transport.

4. Front-Topography Interaction

[8] The effects of flow-topography interactions in the HB region are illustrated by looking at the monthly evolution of the PDF as a function of water depth along transects located in the vicinity of the Bank (Figure 4). All transects show a clear seasonal cycle, with very low values during winter, and larger values from late spring to fall. At the upstream transects (44.65 and 45°N), high values are persistently found inshore of the 200-m isobath. At and south of the Bank, high values are found not only in the inshore region (∼100–200 m), but also over deeper waters. At 43.75°N, for example, jet separation at the Bank region leads to high PDF for over 4 months reaching waters as deep as 1000 m. Also evident is a band of high probabilities inshore of the 200-m isobath, the region where the local upwelling jet is spun up.

[9] To further address the importance of flow-topography interactions, the weighted averaged depth (D^*) occupied by the fronts during May–June, July–August and September–October,

$$D^* = \frac{\Sigma G_i D_i}{\Sigma G_i} \tag{1}$$

was computed. In order to increase the robustness of the calculation, and to estimate inter-annual variability, data from 2002 and 2003 were also used. In (1), G is the gradient magnitude, D is the local water depth, the index i runs along a constant latitude, and only gradient magnitudes >0.025°C km^{-1} and located inshore of the 1500-m isobath are used. Estimates of D^* are larger than the depth where maximum gradients are found due to the influence of background noise. The latitudinal variation of D^* is seasonally dependent (Figure 5). In May–June, D^* varies only slightly over HB, and the maximum increase is observed just upstream of CB. In July–August, on the other hand, D^* increases abruptly at HB's downstream asymmetry (∼44°N), before increasing further at CB. The latitudinal variation in D^* over HB is larger in September–October, but a significant increase at the asymmetry is also observed. Several studies have suggested that CB is the northernmost location where the upwelling jet leaves the coast [e.g., *Barth et al.*, 2000]. The SST frontal data confirms that the jet is deflected toward deeper waters at CB, but suggests that late in the upwelling season (July–October) the upwelling front (and jet) leaves the shelf to the north of that, around HB.

5. Discussion and Conclusions

[10] The interaction of the upwelling front and jet with topography has significant ecosystem implications. As the upwelling jet is deflected offshore around HB, it leaves a region on the inshore side of the Bank with very low PDF. This region is also characterized by very low SST gradient magnitude (Figure 3). In situ observations [*Castelao and Barth*, 2005a] reveal that large amounts of chlorophyll accumulate in the area of weaker flow, and it has been suggested that slower advection rates are responsible for that process [*Barth et al.*, 2005].

[11] As the upwelling jet and front separate from the topography at HB, nutrient-rich, upwelled water is advected toward the deeper ocean, greatly increasing the offshore extent influenced by coastal upwelling. The separated front is often continuous all the way to CB and south, located offshore of the shelf break, suggesting that HB acts as the northern boundary of the meandering California Current late in the upwelling season.

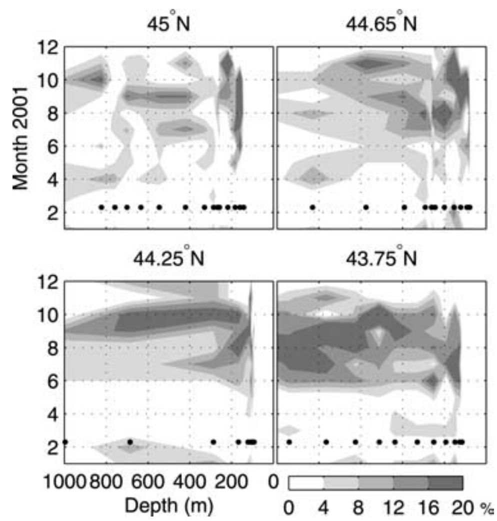

Figure 4. Time evolution of frontal probabilities (%) as a function of water depth along cross-sections around Heceta Bank, OR, during 2001. Black dots mark the center of the satellite pixel. Locations of cross-sections are shown in Figure 5.

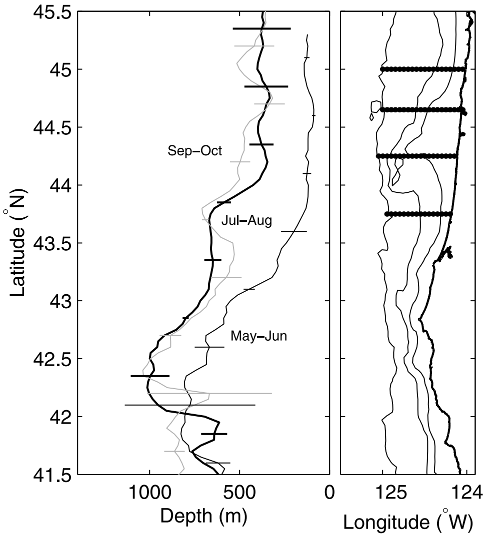

Figure 5. (left) Averaged depth (D*) occupied by SST fronts during May–June (thin line), July–August (thick line) and September–October (gray line) 2001–2003 as a function of latitude. Horizontal lines are ±1 standard deviation. Data is missing when gradient magnitudes <0.025°C km^{-1} along a constant latitude. (right) Bottom topography (100-, 200-, and 1000-m isobaths) for the same latitudinal range. Also shown are locations of the 4 transects plotted in Figure 4.

[12] The interactions of the flow with CB increase the mesoscale activity south of the Cape, where more convoluted SST fronts are observed. This substantially increases the coastal influence and frontal habitat downstream in the CCS. Fronts are generated first close to the coast during spring, but migrate offshore leaving a region of weaker gradients close to the coast during mid to late summer (Figure 3). The region inshore of the separated jet is generally characterized by high nutrient and chlorophyll concentrations [*Brink and Cowles*, 1991; *Huyer et al.*, 2005]. Although coastline and bathymetric curvature are important in jet separation at HB and CB, other processes, like wind stress intensification near the Cape, could also play a role in the process [*Samelson et al.*, 2002].

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