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The large-scale summer circulation of the California current

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Abstract. Satellite data from the Geosat altimeter and the Advanced Very High Resolution Radiometer (AVHRR) are used to show the large-scale structure of the surface circulation of the California Current System in summer. These data show the connection between an equatorward jet and temperature front off Oregon that lies within 100 km of the coast, similar to that first observed in the 1960's and 1970's, and a jet that meanders along the convoluted offshore edge of a temperature front off California, as repeatedly observed in the 1980's.

Introduction

Studies of seasonal upwelling in the California Current System (CCS) off central Oregon and Washington in the 1960's and 1970's first described an alongshore equatorward jet that develops along a narrow temperature front in spring and summer (caused by upwelling of colder water next to the coast). Velocities in the jet are of order 0.25 ms^{-1} [*Huyer,* 1983]. The strong gradient in sea surface temperature (SST) and the jet move offshore during strong, upwelling-favorable (southward) winds, but remain oriented fairly uniformly parallel to the coast. The jet and front move back toward the coast and become more convoluted during wind relaxations [*Holladay and O'Brien,* 1975].

Field studies off central and northern California in the 1980's found strong, narrow jets (velocities of 0.6–1.2 ms^{-1}, with widths of ~20–50 km), along convoluted temperature fronts revealed by satellite images [*Breaker and Gilliland,* 1981; *Mooers and Robinson,* 1984; *Kosro and Huyer,* 1986; *Rienecker and Mooers,* 1989; *Brink and Cowles,* 1991, and other papers in the same volume]. While much is now known about the structure of these jets on scales of several hundred kilometers and less, most surveys have covered too small a region to show their relation to the overall structure of the CCS. Exceptions to this are surveys reported by *Freitag and Halpern,* [1981] and *Smith,* [1992], which appear to show a connection between the flow along an SST front near Cape Blanco (43°N) and the eddy field farther south. There is still debate, however, as to the seasonal development of the system, the origin of the jets and eddies and their relation to the larger scale California Current [*Strub et al.,* 1991]. They have been characterized as offshore squirts caused by local convergences [*Davis,* 1985], as manifestations of an offshore eddy field that impinges the coast [*Mooers and Robinson,* 1984] or as part of a larger alongshore jet that extends along much of the U.S. west coast [*Huyer et al.,* 1991; *Smith,* 1992]. The large-scale satellite fields presented in this paper provide more complete, synoptic coverage than possible with field surveys and add support to the interpretation that during midsummer the convoluted jet and temperature front off California is connected to the jet and front off Oregon.

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Data

Altimeters are satellite radar sensors that measure the surface height of the ocean. This height includes the height associated with currents and the height associated with the marine geoid (gravity field), which would be the height of a perfectly still ocean. Since the marine geoid is poorly known, a mean altimeter height field must be subtracted to eliminate the unknown geoid, which otherwise dominates the signal. This also eliminates the mean velocity field, leaving height 'anomalies', contours of which are approximate streamlines of the temporally varying flow field.

The Geosat altimeter flew in an exact repeat-orbit mission with 17-day repeats beginning in November 1986. The data used here are from the first two years of this mission, after which data dropouts became more numerous. These data were regridded to positions every 7 km along subsatellite tracks (track separation approximately 130 km at mid-latitudes) and corrected for environmental errors at the Jet Propulsion Laboratory [*Zlotnicki et al.,* 1990]. Flags set during this processing were used to eliminate data from over land or suspected to be affected by errors in the tidal model, pointing error, etc. Orbit errors were removed by first fitting multiple orbits to a 1/revolution harmonic and then filtering the data to remove scales longer than 3000 km. The two year mean height was removed to eliminate the marine geoid. A climatological mean dynamic height field, relative to 500 m, was calculated from the mean density field of *Levitus* [1982] and added to the data to partially compensate for the removal of the altimeter mean. This climatological mean flow consists of a slow (≤ 0.1 ms^{-1}) and broad southward flow.

The altimeter data are flagged as suspect and not used within 30–50 km of the coast, although contours of height shown below are extrapolated to the coast. Field data from summer off northern California generally show colder water lying inshore of a strong jet, which flows along the sharp gradient in SST (see below). In this paper we combine the contoured altimeter height fields with satellite SST fields (from channel 4 of the Advanced Very High Resolution Radiometer [AVHRR], with 1 km resolution extending to the coast) to show the location of the temperature fronts. In the 30–50 km closest to the coast, the edge of the coldest water is a better estimate of the location of the southward jet than the extrapolated contours of altimeter heights. In addition, both the altimeter fields, which take 17 days for

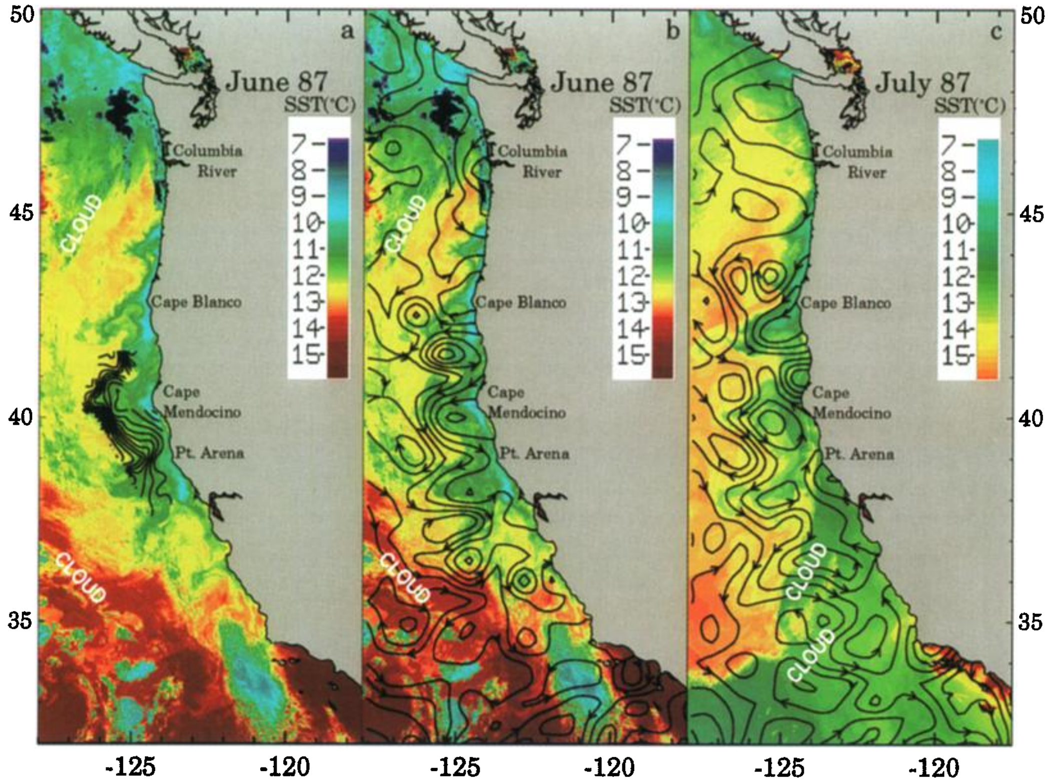

Figure 1. Summer 1987. (a) Dynamic height relative to 500 db from a cruise June 9–18, 1987, contoured at 2.5 cm intervals and overlain on an AVHRR image from June 16, 1987. Geosat heights from individual 17-day cycles in (b) June and (c) July, 1987, contoured at 5 cm intervals and overlaid on SST fields coincident in time with the altimeter cycles (June 16-18 and July 14-15). The climatological mean dynamic height relative to 500 m has been added to the data.

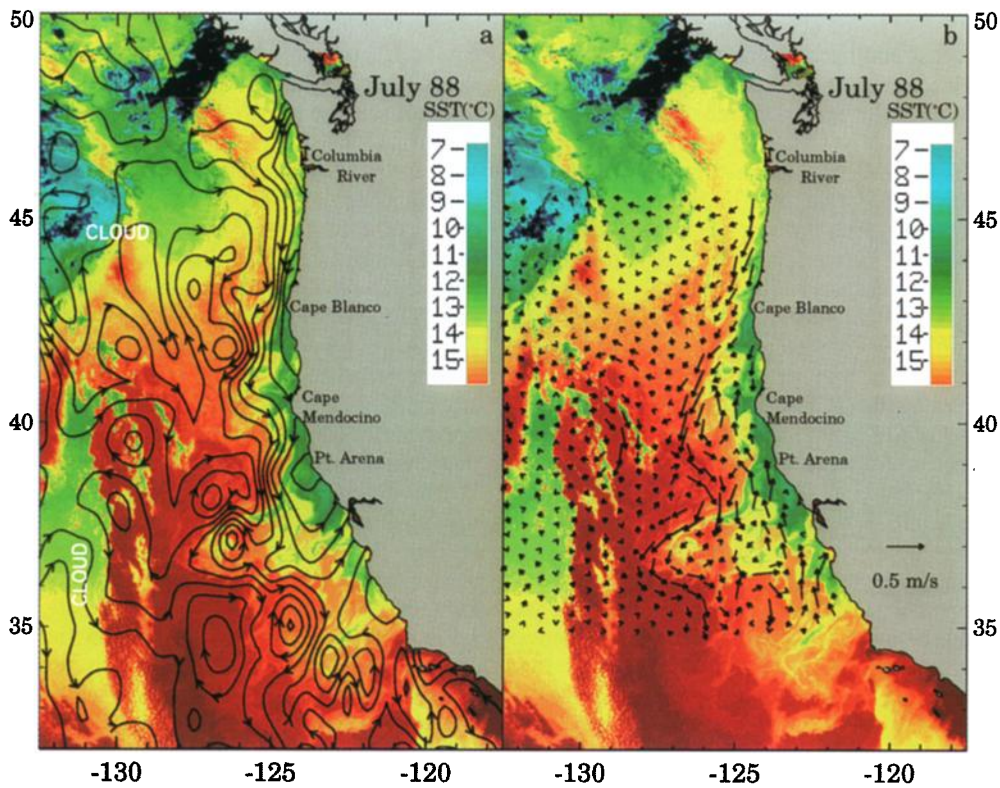

Figure 2. Summer 1988. Two independent estimates of the flow fields in mid-July, 1988: (a) Geosat height from a single cycle in July 1988, contoured and overlaid on a coincident SST field (July 17, 1988), as in Figure 1; and (b) estimates of surface velocity from automated feature tracking (Kelly and Strub, 1992) using five pairs of SST images over a 36 hour period around July 17, 1988, overlaid on the same July 17 SST field as in (a).

complete coverage, and field surveys, which take a week or more for completion, have the potential for distorting currents that change over periods of several days. The AVHRR fields, however, are nearly instantaneous, allowing comparisons between the AVHRR SST fields and the altimeter and survey height fields to test the degree of distortion in the height fields.

Results

In Figure 1a we show the dynamic height field from a field survey in June of 1987 between 37.5°–41.5°N, overlaid on an AVHRR image from mid-June. In Figures 1b and 1c, we present the altimeter height fields from single 17-day cycles during June and July 1987, overlaid on mid-June and mid-July AVHRR SST fields. Contours of dynamic or altimetric heights are approximate streamlines for the surface flow, with the direction of the flow indicated by the arrows (lower heights to the left when facing in the direction of the flow). The speed of the current is inversely proportional to the spacing between the contours. Besides providing comparisons between field and satellite data, these figures show the difference in the coverage provided by the satellite data in comparison to conventional ship surveys.

Field surveys in February and March 1987 did not find a strong jet in the region 50 km and farther offshore, while a strong, equatorward jet was clearly found in April, May and June 1987 [*Kosro et al.,* 1991]. In the April–June surveys, the equatorward meandering jet separated colder (inshore) water from warmer (offshore) water (Figure 1a). In a separate study, surface drifters deployed closer to the coast between 37°– 41°N in March 1987 sampled a strong jet located 20–40 km from the coast [*Magnell et al.,* 1990]. These field data suggest a seasonal development of this jet in 1987 between 37°– 41°N, with the jet originating closer to the coast. On the offshore side of the jet in June, 1987 (Figure 1a), *Kosro et al.,* [1991] found a shallow (20 m deep) and narrow (10–20 km wide) band of very fresh water at the northern boundary of the survey region (41.5°N). It was hypothesized that this fresher water originated much farther north in the Columbia River plume [*Strub et al.,* 1991].

The larger fields of satellite altimeter data in Figures 1b and 1c indicate generally equatorward flow from southern Oregon (42.0°– 44.0°N) to southern California, following the scalloped edge of the colder water. In the region of the field survey during June, 1987 (37.5°– 41.5°N), there is good agreement between the dynamic height field derived from in situ measurements of density (Figure 1a) and the altimeter height and AVHRR SST fields (Figure 1b). The location of the jet in both the dynamic height field (Figure 1a) and altimeter height fields (Figures 1b and 1c) along the strong gradient in the instantaneous SST field indicates that these height fields do not badly distort the flow field, although specific instantaneous features may be misplaced by 50–100 km in the survey and altimeter fields. The general agreement of satellite and in situ data gives us confidence in the ability of the combination of altimeter and AVHRR fields to represent the large-scale structure of the circulation. Although the extrapolated contours of altimeter height intersect the coast and imply a break in the alongshore jet near Cape Blanco in June and between Cape Blanco and Cape Mendocino in July, we infer the continuity of this jet from the continuous nature of the strong SST gradient in these same regions.

With respect to seasonal development, bands of cold SST became permanent features of the AVHRR images in late March 1987, appearing next to the coastal capes [*Kosro et al.,* 1991], while the altimeter fields from late March and April, 1987, (not shown) were the first to reveal lower heights in the region 50–100 km from the coast, between 35°– 39°N and 42°– 44°N. These regions of low heights expanded and connected in May and June to form the fields from June and July shown in Figure 1. This structure was gone by late December. Thus, these satellite observations, in combination with the previously described field observations lead to the hypothesis that an SST front and jet developed within 20–40 km of the coast by mid-March 1987, moved offshore in April and became the convoluted jet observed in subsequent surveys and satellite data. Previous observations off California in 1981 and 1982 also documented the fairly rapid development of a front and jet after the onset of southward winds and its offshore migration beyond the shelfbreak in April [*Strub et al.,* 1987]. This is in contrast to observations off Oregon, where the front and jet remain over the shelf for most of the spring and summer [*Huyer,* 1983]. Thus, we believe the results from 1987 are representative of other years.

After a similar seasonal development of the SST fields in 1988, field surveys in June and July 1988 concentrated on the region between 37°–39°N, where a jet was found flowing offshore from Point Arena to the southwest, with peak velocities of approximately 1.2 ms^{-1}, as determined by surface drifters [*Swenson et al.,* 1992]. A ribbon of fresher water was again observed on the offshore edge of the jet [*Huyer et al.,* 1991]. In Figure 2a, the altimeter field from July, 1988, shows that this offshore jet connects to a strong cyclonic eddy at 37°N, 127°W and then continues to the south into a more convoluted eddy field. There is good agreement between this representation of the flow field and the hydrographic and drifter data [*Huyer et al.,* 1991; *Brink and Cowles,* 1991]. The satellite data shows even more strongly than in 1987 that the jet observed in the surveys at 125°W, 37.5°N is part of a continuous flow, this time from well north of the Columbia River to southern California, providing supporting evidence that the ribbon of fresh water came from much farther north.

An independent estimate of the flow field in July 1988 was calculated using an automated feature tracking procedure [*Emery et al.,* 1986] on a sequence of 6 AVHRR images within a 36-hour period. *Kelly and Strub* [1992] describe the method in detail and show overall agreement between the satellite estimates and the velocities derived from field surveys and surface drifter tracks during July, 1988, although the method underestimates the maximum magnitudes of velocities in the jet. Here, the method is applied to a larger, relatively cloud-free region between 35°– 46°N.

The resulting field of surface velocities (Figure 2b) includes many of the features found in the altimeter height field. Specifically: 1) a narrow jet is found on the offshore side of an SST front, 20–50 km from the coast off central Oregon (44.0°– 45.0°N); 2) the front and jet separate from the shelf around Cape Blanco (42°– 43°N); 3) the jet forms a large meander around Cape Mendocino, then flows onshore and to the south, into the jet that flows southwest from Point Arena; and 4) the jet continues around the cyclonic eddy and through a field of two anticyclonic eddies that were also sampled by the drifters [*Brink et al.*, 1991].

The cyclonic eddy at 37°N, 127°W was particularly well documented by the drifters and shown to persist for at least three months, entraining and releasing drifters during June–August [*Swenson et al.*, 1992]. Other altimeter fields (not shown) suggest that it existed from May through October. The anticyclonic eddies at approximately 35°N, 124°W and 35°N, 126°W were shorter lived. The anticyclonic eddy farther offshore at 39°–40°N, 129°–130°W in July 1988, more clearly seen in Figure 2a, can be traced back in the altimeter fields to an eddy found in February 1988, closer to the coast. Thus, eddies associated with the jet may last up to six months. Closer to shore, eddies such as these have also been shown to cause strong offshore transports of sediment and organic matter [*Washburn et al.*, 1993].

Summary

Geosat altimeter data from two years, along with coincident AVHRR and field data, show a similar circulation pattern in mid-summer for the California Current system – a large-scale jet lies on the offshore side of colder water over much of the region off the western USA. The observed SST gradient and inferred jet lie fairly close to the coast (20-50 km) off Oregon and both are observed in satellite and field data to extend farther from the coast off California, in a convoluted meandering pattern. Eddies associated with the jet may persist for 3-6 months and play an active role in offshore transport. The exact nature and dynamics of the development of the large-scale mid-summer jet are still unknown, leaving unanswered questions about the difference in behavior off Oregon and California, the location and dynamics of the separation of the jet from the shelf, and the relation of the jet to the surrounding eddies.

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