THE COLOR SIGNATURE OF THE ENSENADA FRONT AND ITS SEASONAL AND INTERANNUAL VARIABILITY

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ABSTRACT

Using monthly composites of the ocean color sensor Coastal Zone Color Scanner, we generated time series of pigment concentrations for three transects and 22 locations off Baja California and the southern California coast in order to describe the signature of the Ensenada Front and its seasonal and interannual variability. We used averaging maps of pigment concentrations for non-El Niño and El Niño years to compare the differences between those periods. Our results show that the Ensenada Front signature has an M-shape and its spatial and seasonal displacement can be followed using the 0.25 and 0.5 mg m^{-3} chlorophyll-*a* concentration isolines. For El Niño years the M-shape is not very clear because of the strong penetration of Subtropical Pacific Waters along Baja California and the California coast, except during April, when upwelling is stronger. Such features were confirmed using SeaWiFS LAC images of chlorophyll-*a* concentration.

INTRODUCTION

Phytoplankton pigment concentration derived from satellites images can be used to describe surface oceanographic structures and their temporal and spatial variations (Traganza et al. 1980; Johannessen 1996; Luch-Cota et al. 1997; Müller-Karger and Fuentes-Yaco 2000). Peláez and McGowan (1986) first described one of the most spectacular examples of such structures in the California Current System (CCS), between Point Conception, California, and Punta Vizcaino, Baja California, México (fig. 1a). Pigment concentrations from July 1979 to April 1982, obtained from the sensor Coastal Zone Color Scanner (CZCS/NASA), were used to describe a frontal region separating oligotrophic (south)

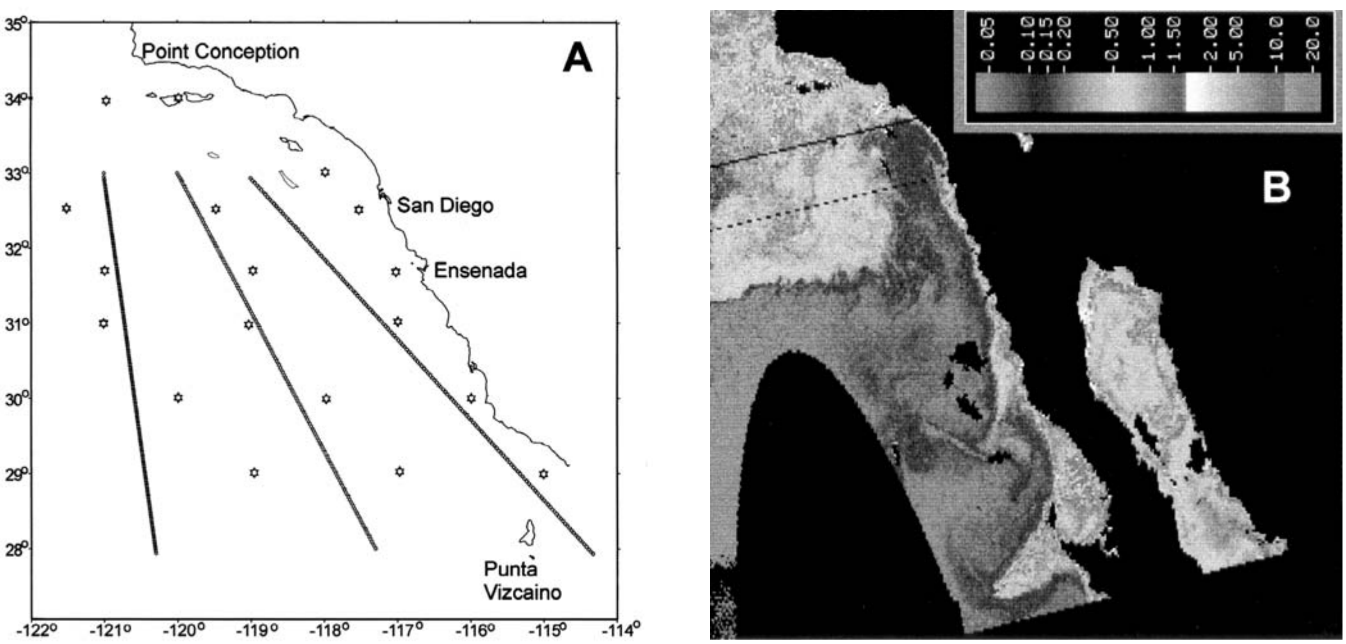

Figure 1. *A*, Study area showing the location of transects and points (*stars*) from which temporal series of pigment concentration were taken; and *B*, CZCS image with its corresponding color palette.

and eutrophic waters (north) (fig. 1b), which was considered a persistent structure throughout the year.

The northern and southern parts of this frontal zone were described later in more detail by Thomas and Strub (1990), who also used CZCS imagery from 1979 to 1983 and 1986. Their results showed stronger signals in the northern area of the frontal zone, where pigment concentrations are above 2.0 mg m^{-3} while in the southern area pigment concentrations are always below 1.0 mg m^{-3}. The front is detectable most of the year, but it is strongly developed from late March to early July and shows a latitudinal displacement of about 150 km throughout the year (Thomas and Strub 1990; Haury et al. 1993). However, there is an abrupt change that always comes north off the Baja California coast; it is referred to as the Ensenada Front (Haury et al. 1993).

Although several studies have been made in this zone (Pelaez and McGowan 1986; Thomas and Strub 1990; Gaxiola-Castro and Alvarez-Borrego 1991; Haury et al. 1993; Thomas et al. 1994; Kahru and Mitchell 2000; Kahru and Mitchell 2001), they do not describe the Ensenada Front signature in detail. Therefore, the goal of the present work is to evaluate the ocean color signature of the Ensenada Front and its seasonal and interannual variation, considering events like El Niño.

DATA AND METHODS

Monthly composites of pigment concentration from CZCS imagery, from November 1978 to June 1986, were used to generate time series for three transects (600 km) and 22 locations in the Ensenada Front area (fig. 1a). These locations and transects were chosen according to visual observation of CZCS images, like those shown in Figure 1b, and with the objective of avoiding artifices of false color palette. The spatial resolution of CZCS images was 4 km processed as explained in Santamaría-del-Angel et al. (1994).

Non-El Niño and El Niño periods were defined according to time series extracted from Sea Surface Temperature (SST) imagery. We extracted data for the transects described above (fig. 1a) from monthly composites with 18 km of spatial resolution obtained from the Advanced Very High Resolution Radiometer (AVHRR/NOAA), for the period from June 1982 to June 1986. We calculated SST anomalies following Santamaría-del-Angel et al. (1994) and used these to separate non-El Niño months from El Niño months. No AVHRR data were available from November 1978 to May 1982; we classified these months following Lenarz et al. (1995) indications.

We calculated an average picture for each period (non-El Niño and El Niño) using time series extracted from CZCS images for those locations indicated in Figure 1a. We did that using monthly average pigment concentration for each month corresponding to a non-El Niño and El Niño event.

Image composting over a long time period (e.g., a month) produces significant smearing and aliasing of fronts and may even create artificial fronts. We used LAC (Local Area Coverage) data from the ocean color sensor Sea-viewing Wide Field-of-view Sensor (SeaWiFS/NASA) to confirm the results obtained with CZCS monthly composites. We processed images from September 1997 to November 2001 that include the El Niño event of 1997–98. We processed chlorophyll maps at 1.1 km nadir resolution, using SeaDAS version 4.1 (released on 9 Nov. 2001).

RESULTS AND DISCUSSION

Considering SST anomalies, the period from July 1982 to December 1984 and from January to June 1986 were El Niño months. 1985 was considered a non-El Niño year. According to Lenarz et al. (1995), November 1978 to June 1982 were also non-El Niño months. Our calculations for typical average months for each period (non-El Niño and El Niño) were based on the time series taken from the transects and locations indicated above (fig. 1a). Figure 2 shows contour maps of these average pigment concentrations for April, August, and November, both for non-El Niño (fig. 2a) and El Niño (fig. 2b) periods. Such months were chosen to represent different hydrographic and climatic conditions. August was related to summertime, November to wintertime, and April is the month when upwelling events off Point Conception are strongest (Dugdale et al. 1997).

We used contour maps (fig. 2) to follow the latitudinal displacement of the frontal zone where the 0.25 mg m^{-3} isoline appears to delimit two areas. The southern area is characterized by low pigment concentrations and relatively homogeneous conditions, whereas the northern area is more structured and graded. This pattern has been previously noted not only with CZCS imagery (Pelaez and McGowan, 1986; Thomas and Strub 1990; Kahru and Mitchell 2000) but also by modern ocean color sensors like the Ocean Color and Temperature Sensor (OCTS) (Kahru and Mitchell 2000) and SeaWiFS (Kahru and Mitchell 2001). In situ data of chlorophyll-*a* concentration (Gaxiola-Castro and Alvarez-Borrego 1991; Haury et al. 1993; Kahru and Mitchell 2001), inorganic nutrients (Traganza et al. 1980; Haury et al. 1993), and temperature (Haury et al. 1993) have corroborated those satellite data.

An M-like shape characterizes the 0.25 mg m^{-3} isoline, mainly for non-El Niño periods (fig. 2a). The valley between the "M" oceanic and coastal peaks aforementioned can usually be observed between 119° and 121°W, which corresponds to the average longitude of Point Conception (see fig. 1). This region in the South-

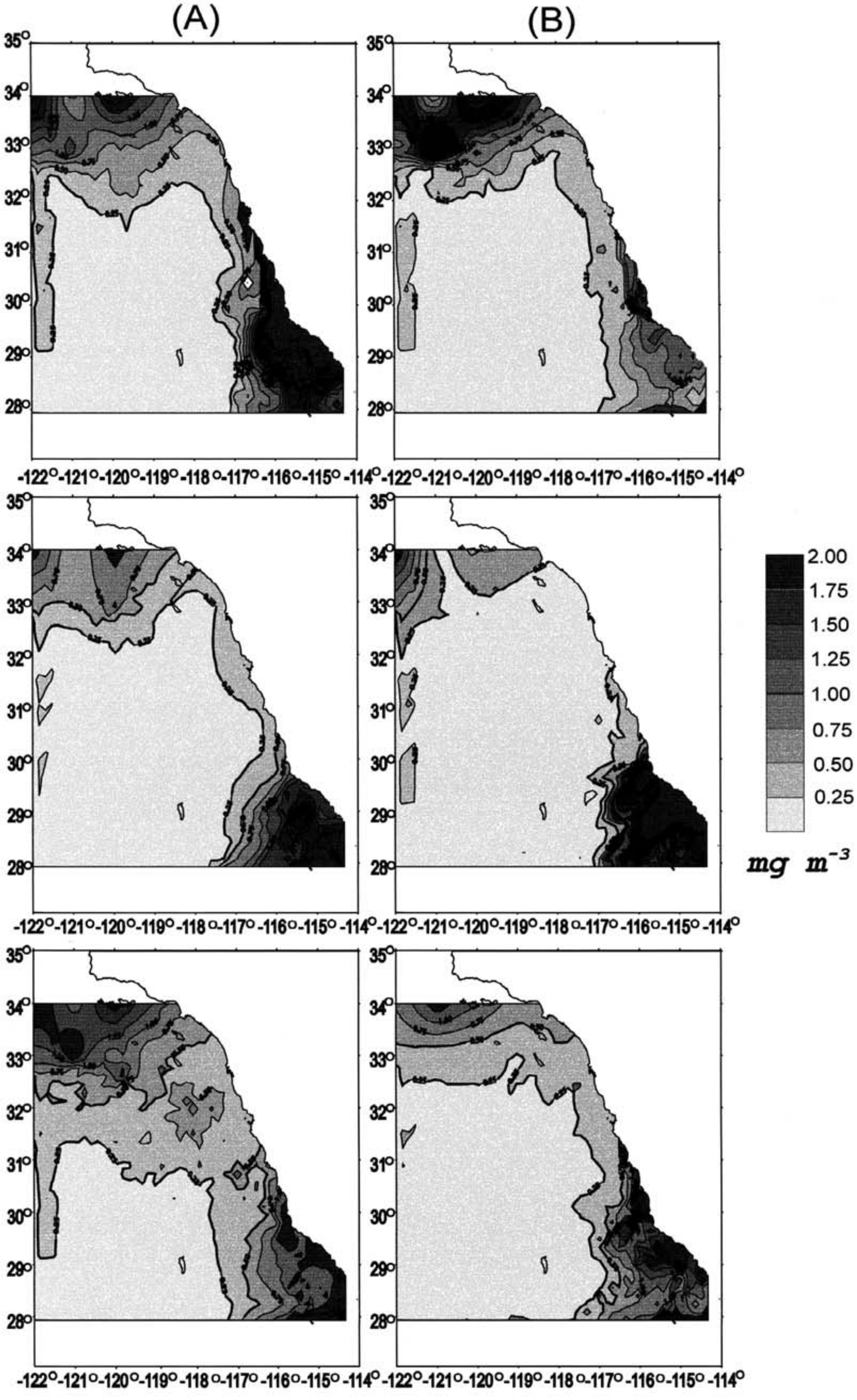

Figure 2. Contour plots of average pigment concentrations (mg m^{-3}) for April, August, and November during non-El Niño (*A*) and El Niño (*B*) periods.

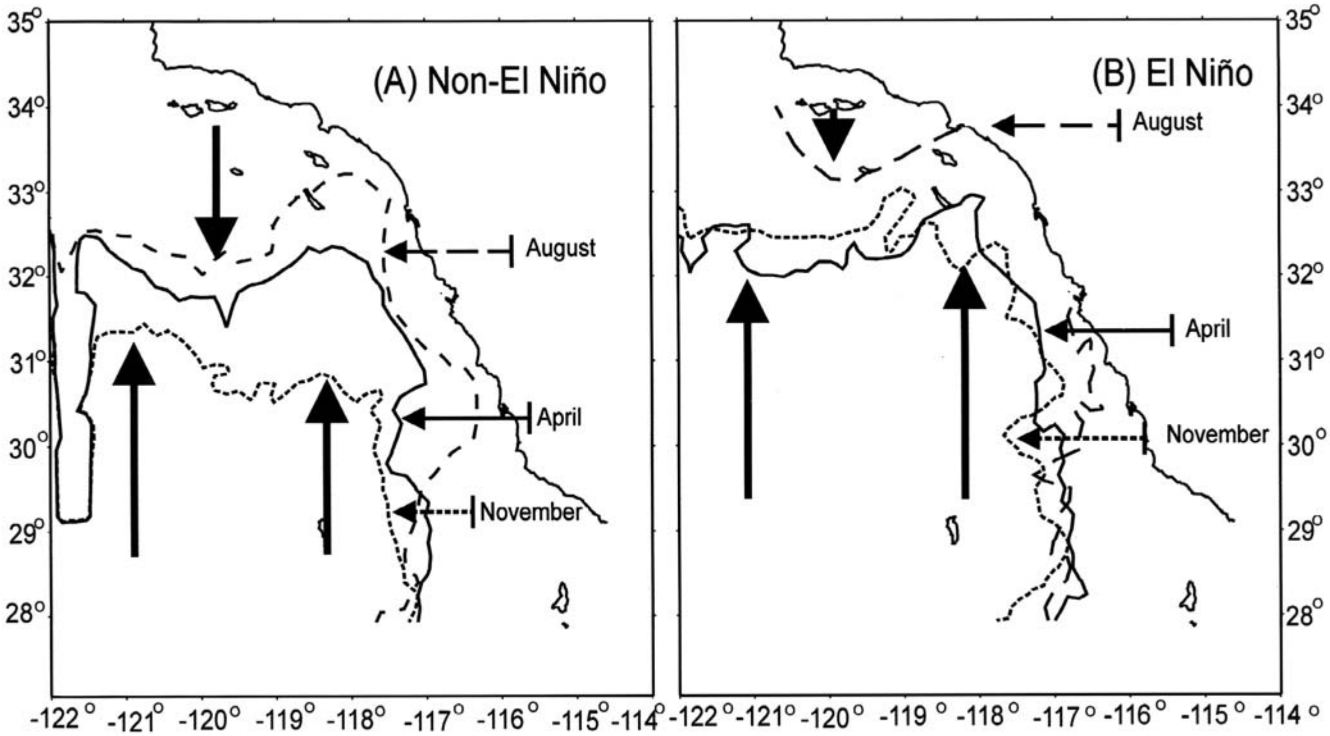

Figure 3. Schematic representation of 0.25 mg m^{-3} isoline seasonal migration during non-El Niño (*A*) and El Niño (*B*) years. Arrows indicate the direction of movement of water masses.

ern California Bight (SCB) corresponds to a break point in the coastal morphology, which promotes upwelling events (Dugdale et al. 1997). Cold, nutrient-rich, low-chlorophyll waters are upwelled close to the coast and moved offshore as a plume with increasing chlorophyll concentration (Dugdale et al. 1997).

This region is also associated with the Southern California Eddy (SCE) (Batteen 1997), a cyclonic gyre that promotes the flux of coastal waters to the south. The SCE originates through the interaction between the Coastal Counter Current (CCC), which flows from south to north, and the SCB coastal morphology off Point Conception. The main effect of this interaction is a change in the direction of the CCC, which makes a U-turn. The SCE effect helps to extend this upwelling plume southwards to promote the valley effect on the Ensenada Front M-shape, which is enclosed by the oligotrophic waters of the two external M-peaks.

Temporal variability of the 0.25 mg m^{-3} isoline is clearly visible in Figures 2 and 3. For non-El Niño months (fig. 3a) it can be seen that from winter (November) to summer (August) there is a northward migration of the frontal zone, which moves from 30–31°N to 32°30'N. However, the oceanic peak of the "M" is slowed down while the coastal one moves farther north, probably as a result of the effect of the SCE and the southwards flux of the upwelling plume on the shape of the frontal zone.

During El Niño months (fig. 3b) the M-shape is clearly visible in April, and the temporal variability of that boundary is slightly different. During August the low concentration zone (below 0.25 mg m^{-3} isoline) moves north (around 33°N) and closer to the coastline, whereas in November it is observed just below the latitude of 33°30'N and more to the north than during a non-El Niño November (fig. 3a). Comparing both periods, it is clear that in El Niño months the 0.25 mg m^{-3} isoline is moved farther north enclosing the eutrophic waters of the SCE to latitudes above 33°N. This can be associated with the intrusion of the oligotrophic Subtropical Pacific Water to northern California during El Niño periods, as previously reported by several researches (Emery and Hamilton 1985; Huyer and Smith 1985; Wyrtki 1985; Rienecker and Mooers 1986; Johnson and O'Brien 1990; Thomas and Strub 1990; Kahru and Mitchell 2000; Kahru and Mitchell 2001; Mitchell 2000).

Kahru and Mitchell (2000) summarized the effects of El Niño on the CCS. They observed the influence of two separate effects: (1) the reduction of the eutrophic areas throughout the region off Point Conception due to reduction in upwelling; (2) the increasing extent of an offshore bloom off Baja California. Their results are

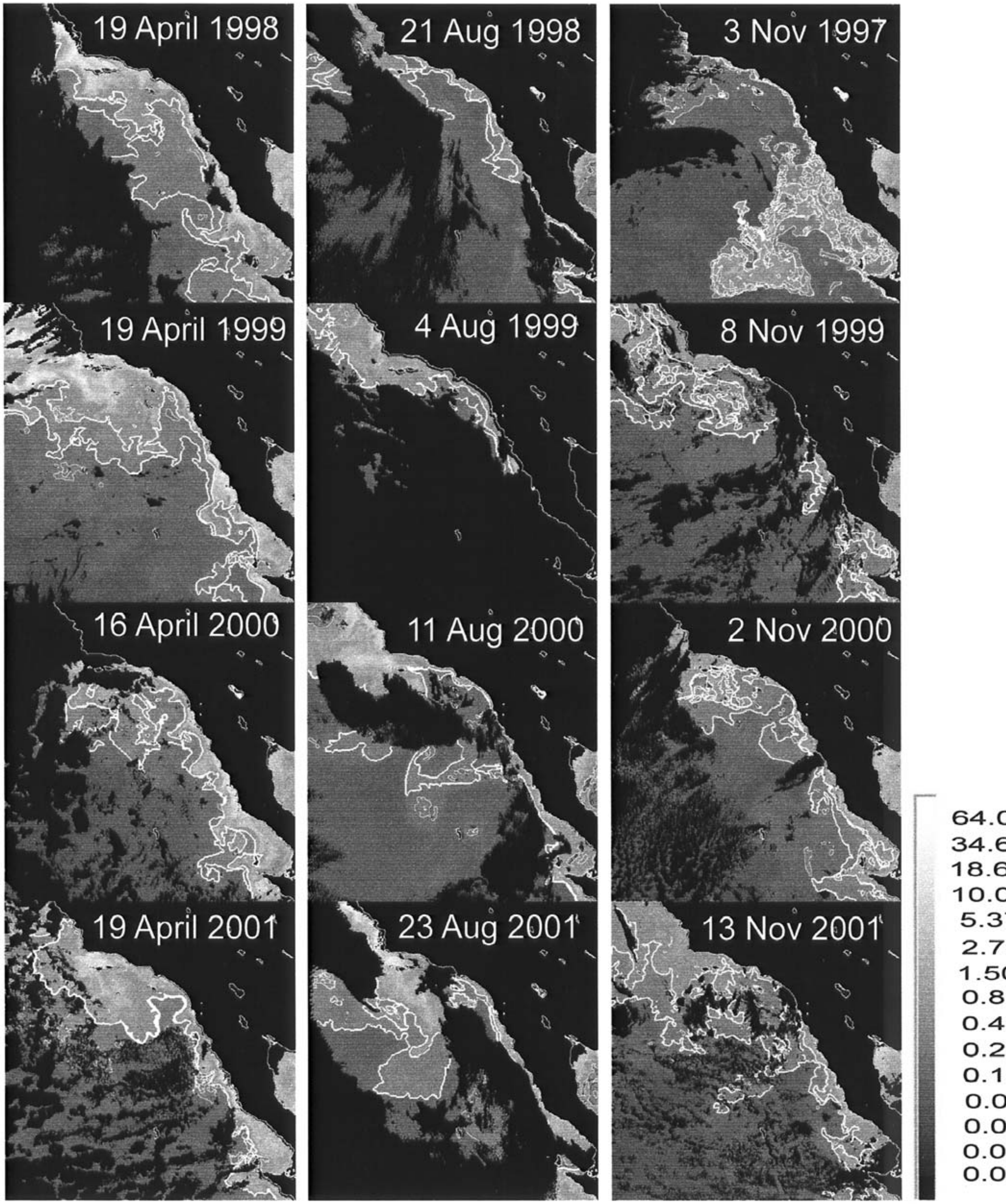

Figure 4. SeaWiFS LAC images of chlorophyll-*a* concentration (mg m^{-3}) from 1997 to 2001. Land and clouds were masked black.

also evident in our schematic representation shown in Figure 3b, which shows that pigment concentrations above 0.25 mg m^{-3} during summer are very close to Point Conception and that during April, when upwelling conditions are stronger, the M-shape of the 0.25 mg m^{-3} concentration is clearly visible. Besides, it is during November that the influence of the offshore bloom can be noted at approximately 30°N (November arrow in fig. 3b).

The ocean color sensor SeaWiFS, launched in September 1997, is part of a new generation of ocean color sensors that have a better radiometric resolution than CZCS. Besides, monthly composites of CZCS images could lead to significant smearing and aliasing of fronts or could even have created artificial fronts. To confirm those results obtained with CZCS, we processed SeaWiFS LAC images (1.1 km spatial resolution) from 1997 to 2001 (fig. 4) for the same months used for calculating average pigment concentration (fig. 2). We superposed 0.25 and 0.5 mg m^{-3} isolines over the images to enhance front migration and for comparison with Figures 2 and 3. Those images from 1997 and 1998 correspond to El Niño years, and it is possible to observe the same pattern discussed earlier, such as stronger upwelling in April off Point Conception and oligotrophic conditions off California and north of Baja California during winter and summer. The image of 3 November 1997 clearly shows the strong offshore bloom off Baja California, which has been previously associated with El Niño years by Kahru and Mitchell (2000). During this time the typical Ensenada Front is practically unrecognizable.

For non-El Niño months, the M-shape of the Ensenada Front is also clearly visible, following not only the 0.25 mg m^{-3} but also the 0.5 mg m^{-3} isoline. The stronger effect of the upwelling plume is observed in April, as noted previously, with exception for August 2001 when its intensity was comparable to that from April. This behavior confirms the strong interannual variability of the Ensenada Front in this zone.

The use of specific pigment (CZCS) or chlorophyll (SeaWiFS) concentration isolines to follow the displacement of the Ensenada Front is somewhat subjective considering the differences in algorithms for biomass retrieval between sensors, and for comparison with others in the future. For example, the parameter calculated for CZCS is "pigment" (chlorophyll-*a* + phaeopigments), whereas for SeaWiFS it is chlorophyll-a (Chl-*a*). In general, CZCS pigment underestimates the SeaWiFS chlorophyll-*a* at low Chl-*a* and overestimates at high Chl-*a* (Kahru and Mitchell 2000). Despite these constraints, it is possible to follow the position of the Ensenada Front using the 0.25 and 0.5 mg m^{-3} isolines and using both sensors because such Chl-*a* concentrations are in the middle of the range where CZCS and SeaWiFS seem to have the best agreement. However, a better representation of the position of the frontal zone could be obtained using an edge-detection method such as that described by Cayulla and Cornillon (1992), which was firstly applied for SeaWiFS images by Miller (2000). This subject has to be addressed by future investigations.

CONCLUDING REMARKS

This study showed the characteristic M-shape of the Ensenada Front, whose signature can be followed by observing the 0.25 and 0.5 mg m^{-3} isolines of chlorophyll-*a* concentration. Its latitudinal displacement was followed using CZCS imagery first, and later confirmed by SeaWiFS. In addition, it is important to consider that in El Niño years the front position (0.25 mg m^{-3} isoline) is located farther north than during non-El Niño years, mainly during November (winter) and April (upwelling). These results will be very useful for future cruise planning considering the strong seasonal and interannual variability of the front position. However, for a better representation of the frontal zone position, we suggest the use of an edge-detection method such as that described by Cayulla and Cornillon (1992) and Miller (2000).

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