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Influence of the 1997-98 El Niño on the surface chlorophyll in the California Current

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Abstract. Satellite-derived time series for the California Current System (CCS) showed marked changes in the surface chlorophyll *a* concentration (Chl, mg m^{-3}) associated with the 1997-98 El Niño. In addition to the previously known decrease in Chl off Southern California (Fiedler, 1984), we also observed a significant increase of Chl off Baja California. Whereas the extent of eutrophic (Chl > 1.0) areas decreased throughout the CCS, the extent of mesotrophic areas (0.2 < Chl < 1.0) off Baja California approximately doubled. The reduced area of eutrophic waters is attributed to weakened upwelling but the increase in the offshore mesotrophic area off Baja may be caused by blooms of nitrogen-fixing cyanobacteria. Using revised Coastal Zone Color Scanner data we detected similar changes during the 1982-83 El Niño.

1. Introduction

According to several indices the 1997-98 El Niño was one of the strongest on record [*McPhaden*, 1999; *Chavez et al.*, 1999]. In spite of the numerous reports of declines in mammal and bird populations, the effects on the surface chlorophyll *a* (Chl, mg m^{-3}) in the CCS are not evident in ship surveys [*Hayward* et al., 1999]. During the 1982-83 El Niño the nutricline deepened [*McGowan*, 1985] and surface Chl decreased as a result of weakened coastal upwelling [*Fiedler*, 1984]. New ocean color sensors provide a high-resolution time series of surface Chl in the California Current. A visual comparison of the monthly composited images shows remarkable differences between the El Niño year 1998 with 1997 and 1999 (Fig. 1). In addition to the reduction of the high Chl areas off Central and Southern California a significant increase in Chl off Baja California can be observed in 1998. We use imagery from the Ocean Color and Temperature Sensor (OCTS), the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Coastal Zone Color Scanner (CZCS) to show El Niño related changes in the Chl distribution.

2. Data and Methods

Time series were evaluated in a grid of 3-by-4 sub-areas defined by alongshore bands of, respectively, 0-100 km, 100-300 km and 300-1000 km off the coast, divided into 4 zones (Fig. 1D). CZCS data was available from November 1978 to June 1986 [*Feldman et al.*, 1989], OCTS data from 27-Oct-1996 to 29-Jun-1997 [*NASDA*, 1997], and SeaWiFS data from 6-Sep-1997 to the present [*McClain et al.*, 1998]. The spatial resolution was approximately 9 km for OCTS and SeaWiFS, and 19 km for CZCS. Examination of the monthly averages of the three sensors revealed significant differences in offshore waters (Fig. 2A) where large variations are not expected. Compared to the SeaWiFS Chl derived with the OC2-v2 algorithm [*O'Reilly* et al., 1998; *McClain*, 1998] the CZCS standard Chl product was significantly lower at low concentrations and higher at high concentrations. The OCTS version 4 Chl product from NASDA also showed significant underestimation compared to SeaWiFS at low Chl but was similar at higher concentrations. A possible decadal trend of increasing Chl is not indicated by ship-based measurements from the California Cooperative Fisheries Investigations (CalCOFI) cruises (Fig. 3A). 1999 had unusually high Chl levels that may have elevated the SeaWiFS average. Comparison of the SeaWiFS-derived estimates of Chl with ship measurements within ± 4 hr and ± 1 km has shown good agreement (r^2 = 0.92-0.93) [*Kahru and Mitchell*, 1999]. Therefore, for offshore waters we attribute most of the observed differences between sensors to methodological differences. To make CZCS and OCTS data comparable with SeaWiFS we recalculated CZCS and OCTS Chl using recently developed bio-optical algorithms. We applied the OC3e maximum band ratio algorithm [*O'Reilly* et al., 1998] to CZCS monthly composited normalized water-leaving radiances at 440, 520 and 550 nm wavelengths and a modified CAL-P6 algorithm [*Kahru and Mitchell*, 1999] to weekly 490 and 565 nm OCTS data. The reduced bias of these alternative algorithms compared to SeaWiFS is shown in Fig. 2B. We used the southwestern corner of the CalCOFI station grid for validation. Satellite-derived values from OCTS (CAL-P6 algorithm) and SeaWiFS (OC2-v2 algorithm) agree well with ship-measured Chl and show no significant bias (Fig. 3B). Fig. 3 also shows significant surface Chl variability even in the oligotrophic offshore waters.

As a measure of the spatial distribution of the phytoplankton standing crop we calculated the areal extent of oligotrophic, mesotrophic and eutrophic waters. We classify areas with surface Chl < 0.2 as oligotrophic, 0.2 < Chl < 1.0 as mesotrophic and Chl > 1.0 as eutrophic. As the spreading of high Chl waters is often in the form of upwelling filaments moving southwest [*Abbott and Zion*, 1985], we add the calculated areas within zones A to D.

Sea-surface temperature (SST) distributions were evaluated using the Pathfinder (1987-1999) and MCSST datasets (1981-1986) [*Vasquez* et al., 1995]. For each of the 12 sub-areas we calculated the monthly mean SST using all available data. As a proxy for the area affected by upwelling, we calculated the areal extent of waters colder than the respective sub-area monthly mean by, respectively, 1 and 2° C.

As an index of the El Niño-La Niña cycle we used the extratropical Northern Oscillation Index (NOIx) that is calculated from the difference between anomaly sea-level pressures at 35°N, 135°W and 10°S, 130°E [*Schwing* et al., 2000].

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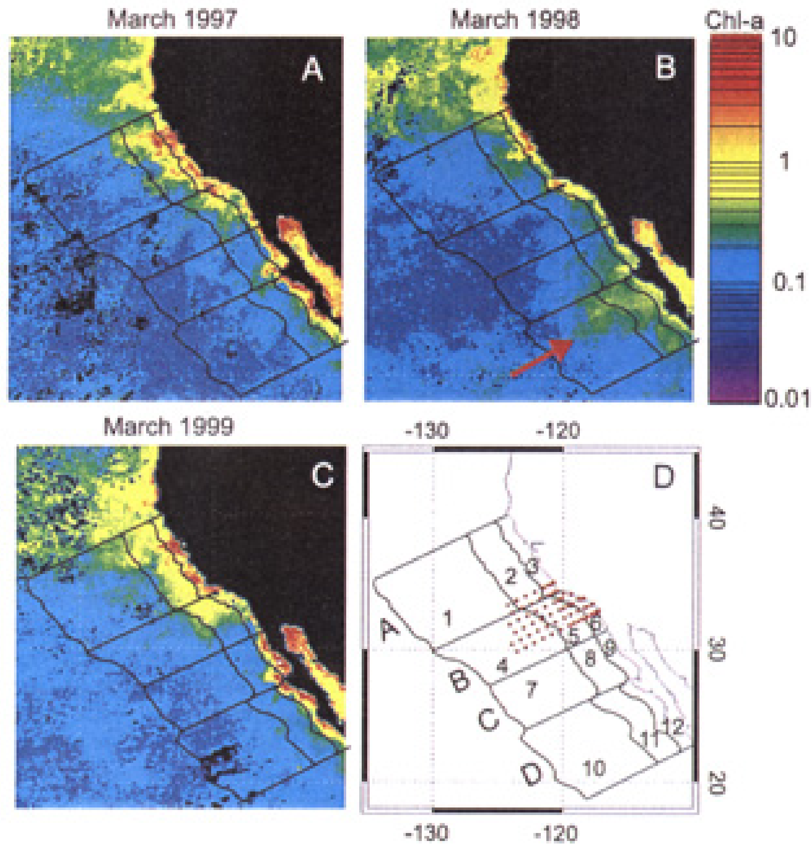

Figure 1. **A-C,** March composites of Chl derived from OCTS (1997) and SeaWiFS (1998-1999). The effect of the 1998 El Niño includes reduced eutrophic (Chl > 1.0) areas for all zones and increased mesotrophic (0.2 < Chl < 1.0) areas off Baja California (red arrow). **D,** Study area with the grid of 3-by-4 sub-areas (1 to 12), forming zones of central California (**A**), southern California (**B**), northern Baja (**C**) and southern Baja (**D**). CalCOFI stations are shown as red dots.

3. Results

Time series of the extent of the mesotrophic and eutrophic waters during the 1997-1999 El Niño-La Niña cycle are shown in Fig. 4. The annual cycle of mesotrophic waters has a winter maximum associated with increased surface Chl in the offshore areas. The maximum extent of eutrophic waters occurs in the spring-summer period and is associated with intensified coastal upwelling. Consistent with observations of the 1983 El Niño [*Fiedler*, 1984], the extent of mesotrophic and eutrophic waters off Southern California (Zone B) was reduced in the El Niño year of 1998 compared to 1997 and 1999. The extent of eutrophic waters during the 1997-98 winter and the following spring was lower in each zone. However, the extent of mesotrophic waters off Northern and Southern Baja increased 2-3 times in the 1997-98 winter compared to the previous or subsequent year.

The extent of areas colder than monthly mean SST (for each sub-area) (Fig. 5) was minimal during late 1997 and early 1998 in all zones but was most reduced in the three southern zones. For almost 8 months during the 1997-98 winter no pixels in zone C were colder by 1° C or more than the respective long-term monthly mean of the sub-area. The relationship between the extent of mesotrophic waters and the extent of colder than normal waters changes from a negative correlation off Baja to a positive correlation off Southern California (Figs. 4, 5), indicative of different causal mechanisms. The extent of eutrophic waters is always positively correlated with the extent of colder than normal waters, implying that coastal upwelling leads to elevated Chl.

Using the CZCS and MCSST time series we detect very similar patterns during the 1982-83 El Niño (Fig. 6). First, the maximum extent of mesotrophic waters off northern and southern Baja occurred during the 1982-83 winter. Second, the extent of eutrophic waters showed a similar drop during the 1983 El Niño. Compared to the 1997-98 El Niño the decrease in the extent of cold SST and high Chl occurred later, i.e. in spring-summer rather than winter. Off central and southern California, maxima in the winter extent of mesotro-

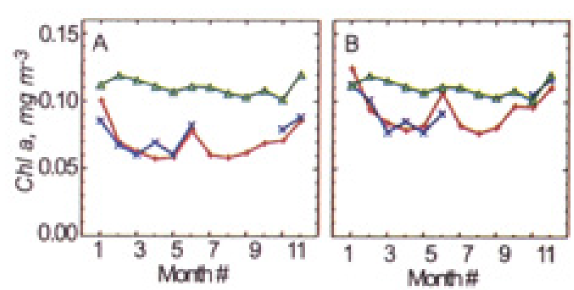

Figure 2. Average annual cycle of Chl in area 10 from CZCS (red, +), OCTS (blue, X) and SeaWiFS (green, Δ) for standard products (**A**) and after applying the OC3e algorithm to CZCS and CAL-P6 algorithm to OCTS (**B**).

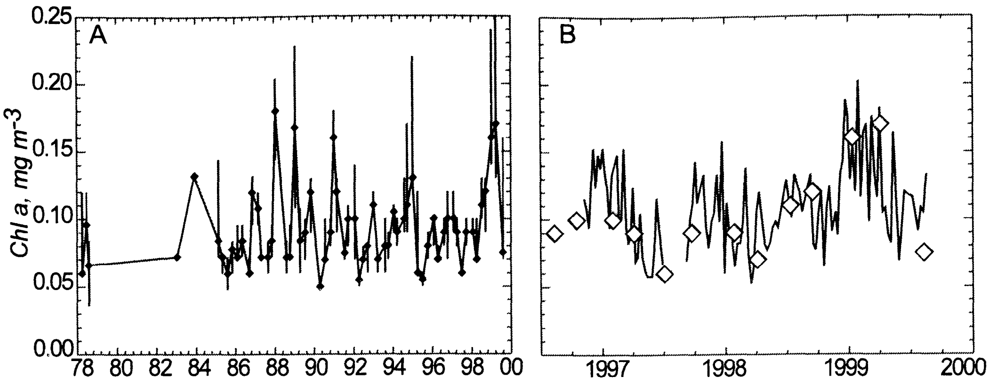

Figure 3. Time series of Chl in the central part of area 4 corresponding to the southwest corner of the CalCOFI grid. **A,** Near-surface (≤ 10 m depth) ship-measured median (♦) and min-max range for CalCOFI stations 90.110, 90.120, 93.110, 93.120. Values before cruise 8907 were multiplied by 1.2 to compensate for the loss of picoplankton due to the use of GF/C filters [*Venrick and Hayward*, 1984]. **B,** Weekly median satellite-derived Chl from OCTS (CAL-P6 algorithm) and SeaWiFS (OC2-v2) with ship-measured median (◊). Year labels in this and following figures are centered at January 1 of a corresponding year.

phic waters occurred both during the winters of 1981-82 and 1982-83. While the El Niño in 1998 abruptly turned into La Niña in 1999 with increased areas of cold upwelled waters and high Chl, the El Niño in 1983 was followed by another year of reduced upwelling, and the areal extent of mesotrophic and eutrophic areas were persistently low through 1984.

4. Conclusions

We have shown that in addition to the previously known [*Fiedler*, 1984; *Strub et al.*, 1990; *Thomas et al.*, 1994] reduction in cold, high Chl surface waters of the California Current, both the 1982-83 and 1997-98 El Niño events were as-

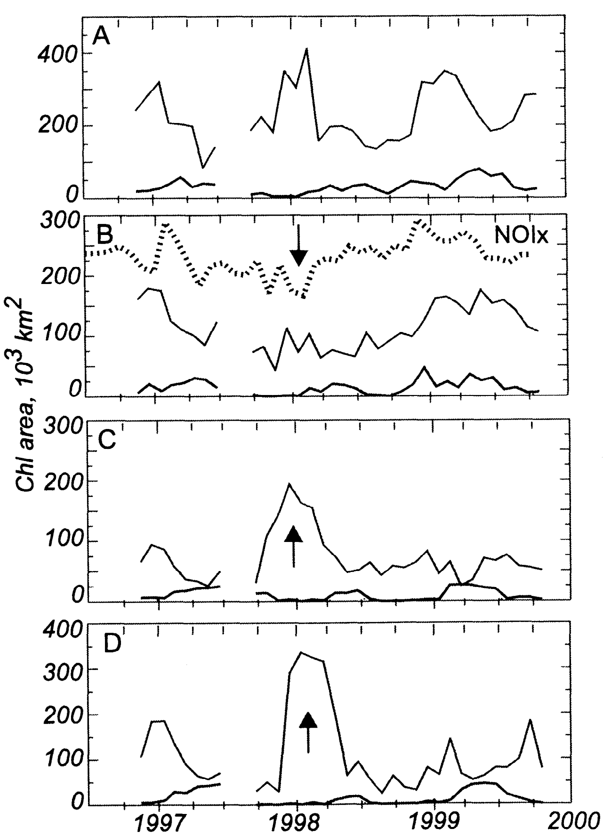

Figure 4. Time series of the areal extent of mesotrophic (top line, 0.2 < Chl < 1.0) and eutrophic (bottom line, Chl > 1.0) waters in zones A-D derived from OCTS and SeaWiFS data. Minima in the overlaid extratropical Northern Oscillation Index (dashed line, panel B) correspond to El Niño events.

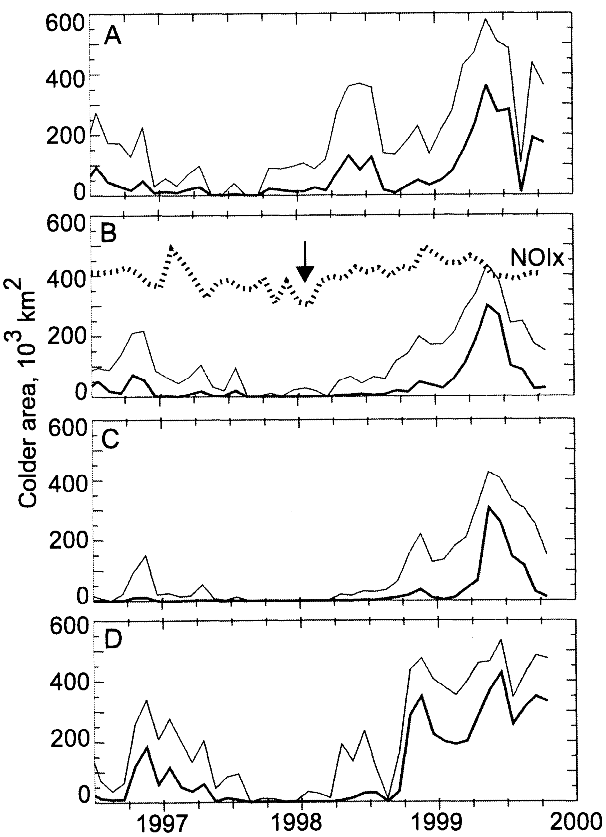

Figure 5. Time series of the extent of cold SST anomalies in zones A-D. The curves show total areas with SST colder by 1.0 (top line) and 2.0 °C (lowest line) than the monthly mean for each sub-area. NOIx is shown in panel B.

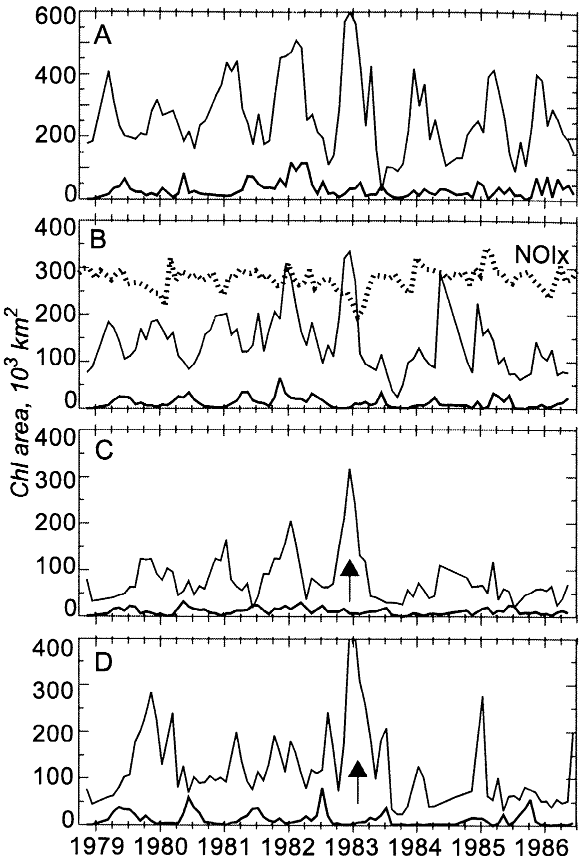

Figure 6. Time series of the extent of mesotrophic and eutrophic waters as in Fig. 4 but derived from the recalculated CZCS data using the OC3e algorithm. NOIx is shown in panel B.

sociated with 2-3 fold increase in the extent of mesotrophic waters off Baja California. The effects of El Niño on the surface Chl in the California Current are therefore manifested as two separate effects: (1) the reduction of eutrophic areas throughout the region and mesotrophic areas off Southern California, evidently due to the reduction in upwelling of the cold and nutrient-rich waters; (2) increase in the extent of mesotrophic areas off Baja. The increased area of mesotrophic Chl and elevated SST off Baja extends from about 100 to 700 km offshore and is not likely to be caused by coastal upwelling. We hypothesize that these offshore blooms in warm stratified waters are caused by nitrogen-fixing cyanobacteria [c.f. *Karl et al.*, 1995].

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