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Anomalous satellite-measured chlorophyll concentrations in the northern California Current in 2001–2002

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[1] Five years (1997–2002) of northern California Current SeaWiFS ocean color data put cold, low salinity hydrographic anomalies observed in summer 2002 into a spatial/temporal context and present their biological ramifications. Monthly mean chlorophyll concentrations were >1.0 mg m^{-3} larger than the previous 3 year average over the entire shelf from British Columbia (BC) to northern California (CA) in 2001–2002, spatially most extensive over the BC and Washington (WA) shelves but strongest (>2.0 mg m^{-3}) on the southern Oregon shelf. Positive anomalies develop in August 2001 off BC and October 2001 off WA. By October 2002, shelf anomalies are reduced. Offshore, spatially extensive anomalies develop off CA (36°–42°N) in fall 2002, disappearing by December. Concurrent altimeter data show over 1000km of equatorward displacement. The positive chlorophyll anomalies, their spatial patterns and displacement are consistent with advection of subarctic, nutrient-enriched water into the California Current. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4516 Oceanography: Physical: Eastern boundary currents; 4223 Oceanography: General: Descriptive and regional oceanography. **Citation:** Thomas, A. C., P. T. Strub, and P. Brickley, Anomalous satellite-measured chlorophyll concentrations in the northern California Current in 2001–2002, *Geophys. Res. Lett.*, *30*(15), 8022, doi:10.1029/2003GL017409, 2003.

1. Introduction

[2] The California Current system north of ~38°N is characterized by strong seasonality in wind forcing. Winter monthly mean wind stress is poleward and downwelling-favorable. Summer equatorward and upwelling-favorable winds drive offshore Ekman transport, upwelling of nutrient-rich, cold, subsurface water and enhanced equatorward transport within a coastal jet [*Strub et al.*, 1991]. Upwelled nutrients support elevated coastal phytoplankton concentrations with seasonal cycles of wind forcing and phytoplankton concentrations in phase and well correlated [*Thomas et al.*, 2001]. Superimposed on this seasonality is strong interannual variability especially hydrographic and chlorophyll anomalies associated with negative, El Nino, phases of the ENSO cycle [e.g. *Fiedler*, 1983; *Huyer and Smith*, 1985; *Thomas and Strub*, 2001]. *Chelton and Davis* [1982] hypothesize that transport into the California Current from the North Pacific Current varies out of phase with transport into the Gulf of Alaska over ENSO cycles. Increases in equatorward transport are correlated with large-scale decreases in temperature and salinity and increases in zooplankton biomass in the California Current [*Chelton et al.*, 1982]. During the summer of 2002, field data from British Columbia (BC) and Oregon (OR) [*Freeland et al.*, 2003] show strong negative temperature and salinity anomalies (negative spiciness) near the pycnocline (30–150m). Off OR, the change in spiciness in July was about −2.5, opposite in sign but similar in magnitude to anomalies associated with the 1997–98 El Nino reported by *Smith et al.* [2001]. Off BC, negative spiciness anomalies extended at least 1500 km offshore in 2002 and appear to have started in 2001.

[3] Here we use SeaWiFS ocean color satellite data to examine the ramifications of these 2002 hydrographic anomalies on phytoplankton concentrations in the northern California Current, providing temporal and spatial context to field measurements. Comparisons to concurrent wind forcing and altimeter-derived meridional displacement calculations provide a picture of local verses remote forcing.

2. Data and Methods

[4] Five years of daily, 4km resolution SeaWiFS chlorophyll (OC4v4) data are regridded to a standard projection over the California Current. All daily scenes are used to form a time series of 64 monthly composites for the period September 1997 to December 2002. All calculations are carried out in units of chlorophyll concentration (mg m^{-3}). A three year time period (September 1998–August 2001) is used to form a seasonal climatology from which monthly anomalies over the entire time series are formed, avoiding large negative anomalies associated with the 1997–1998 El Nino and large positive anomalies reported here. Time series of monthly mean chlorophyll concentrations on the continental shelf at four locations are calculated by spatially averaging pixels within polygons defined by 120km of coastline, the offshore position of the 500m bathymetric contour and boundaries extending perpendicular to the mean coastline orientation. These sites (Figure 1) are

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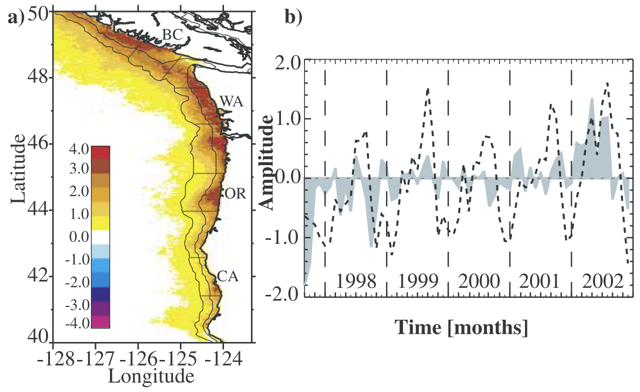

Figure 1. The a) spatial pattern showing the 100m and 500m isobaths and b) associated time series (dashed line) of the dominant mode of an empirical orthogonal function decomposition of the September 1997 to December 2002 monthly SeaWiFS chlorophyll fields. To highlight the strength and timing of anomalies, also shown on b) are amplitude anomalies (shaded).

centered at 49.3°N (BC), 47.2°N (Washington, WA), 44.65°N (OR) and 41.9°N (northern California, CA).

[5] Alongshore displacements over 90 day periods are calculated using paired sea surface height measurements from the same latitude from either two Topex/Poseidon altimeter crossovers or an altimeter crossover and coastal tide gauges where they are available. The difference (ΔH) between two sea surface height observations, their cross-shelf separation and the geostrophic relationship are used to obtain the 90 day displacement: $D = g\,[f\Phi * \Delta x]^{-1} * \Delta H * 90$ days, where g is the gravitational constant, f is the Coriolis parameter at latitude Φ, and Δx is the distance (~225 km) between the two sea surface height observations. Mean displacement over the whole study region in each 90 day period is the average of values from four latitudes between 41°N and 52°N.

3. Results

[6] An empirical orthogonal function (EOF) decomposition of the 64 month image time series (Figure 1) summarizes the dominant time and space variability of chlorophyll patterns. Pretreatment removed the temporal mean at each location prior to calculation. The first mode (36% of total variance, modes 2 and 3 represent 7% and 5% respectively) spatial pattern is dominated by a strong cross-shore gradient, high over the shelf and weak offshore. Maxima are located off BC (~49°N), the entire WA shelf (48°–46.5°N) and in two isolated regions off OR, one near the mouth of the Columbia River (~46°N) where satellite estimates of chlorophyll concentration are potentially biased by CDOM and suspended sediment and a second associated with a widening of shelf topography at 44.5°N near Heceta Bank. The first mode amplitude time series (Figure 1) is dominated by the strong seasonal cycle, positive in late summer (July–September), negative in winter (November–February). Interannual variability is highlighted by subtracting the 3-year mean seasonal cycle calculated over the center three years from each annual cycle to show monthly anomalies. Maximum and/or most persistent anomalies occur at the beginning (1997–98, associated with El Nino) and end (2001–2002) of the time series. Positive anomalies at the end of the time series are persistent but relatively weak in 2001, rise sharply in February 2002 and are maximum in May, July and August 2002. Positive anomalies end abruptly by September 2002.

[7] The five year variability of shelf chlorophyll concentrations at four latitudes within the study area (Figure 2) provide temporal context. The seasonal cycle evident in the EOF dominates the signals. Only off OR and CA do summer maxima in 2001–2002 appear larger than previous summers. Anomalies, however, show that shifts in phase of the seasonal cycle rather than differences in absolute summer maxima account for much of the interannual variability. Anomalies off BC are positive in early spring (February–April) 2001 but then decrease. Beginning in August 2001, positive anomalies persist until October 2002 with maxima in October 2001 and April–July 2002. Off WA, anomalies start to increase in September 2001 and become strongly positive by October. These persist until August 2002, weakening in winter (December–January). The OR shelf early in the time series is characterized by smaller anomalies than those farther north. Positive anomalies begin in September 2001, weaken in winter (December–January) and then become strong again in spring (March) persisting until November 2002. Positive anomalies on the northern CA

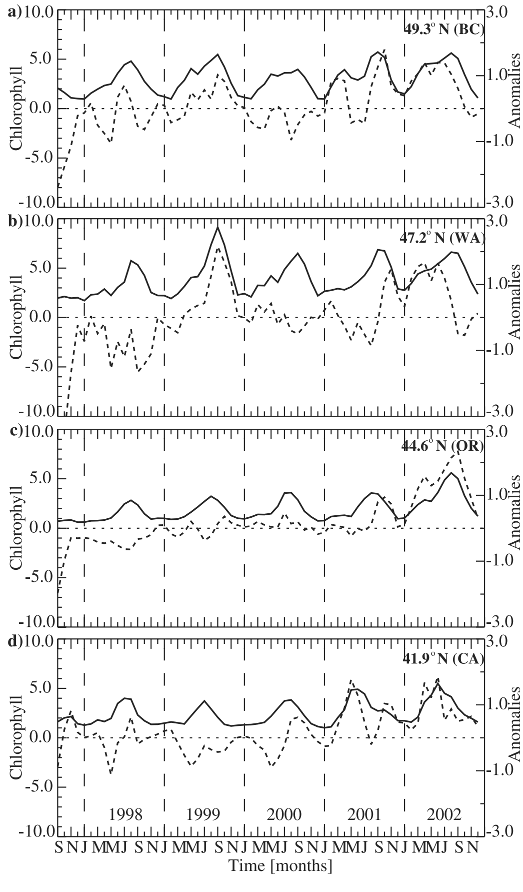

Figure 2. Time series of mean monthly SeaWiFS chlorophyll concentration (solid line) and anomalies (dashed line), both in mg m^{-3}, on the shelf at four locations a) Vancouver Island, b) Washington, c) Oregon and d) northern California.

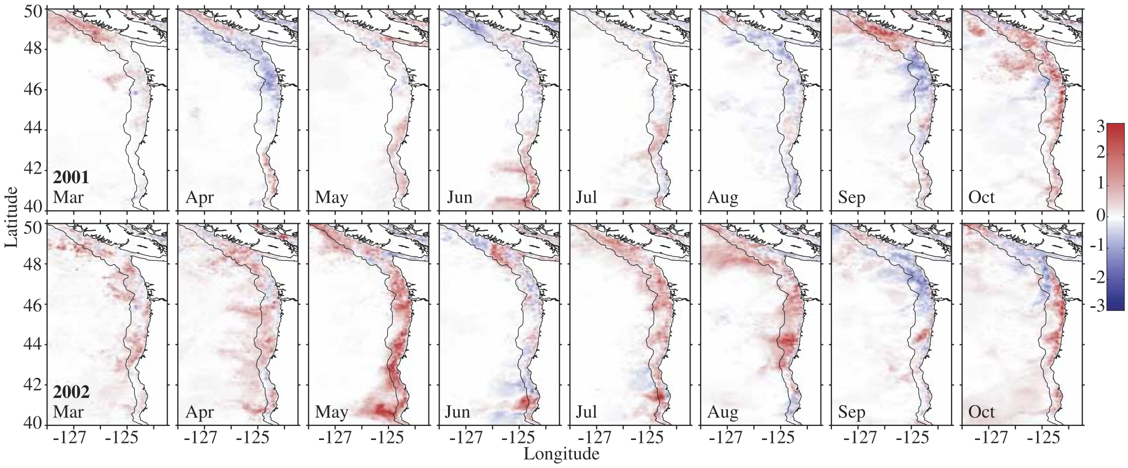

Figure 3. Monthly SeaWiFS chlorophyll anomaly fields (mg m^{-3}) for specific months within the 2001–2002 period characterizing the timing and spatial pattern of positive chlorophyll anomalies in the northern California Current.

shelf begin in March–April 2001, similar to those off BC. These weaken in summer (July–September), strengthen again in fall (October–November) and are weak through the winter. Large positive anomalies are present in spring-early summer 2002(April–June) and then weaken but stay positive through the remainder of the time series.

[8] Monthly image maps (Figure 3) quantify spatial patterns associated with the 2001–2002 chlorophyll anomalies presented above, showing smaller scale features and features not in phase with region-wide trends, each of which may have been assigned to higher modes of the EOF decomposition. Positive anomalies are present on the BC shelf in March 2001 but then weaken through the summer. In September 2001, strong positive anomalies extend along the entire shelf north of 48°N, with negative (or weak) anomalies to the south along the WA and OR shelves. By October 2001, positive anomalies are present through the entire shelf region of the study area, extending over 200km offshore off WA (47°N). Weak winter anomalies (Figures 1 and 2) when chlorophyll concentrations are seasonally low are not shown. By March and April 2002, positive anomalies are again present along all study area shelves and extend seaward of the 500m isobath off each of the BC, WA and OR coasts. Maximum anomalies are evident in May 2002, extending through the entire study area with highest values (>3.0 mg m^{-3}) in the southern portion of the study area (OR and northern CA). Anomalies are strongest over the shelf, but extend over 200km offshore at ~41°N. In July, positive anomalies are weaker, but still occupy the entire study area. By September and October, negative anomalies are present off WA and parts of BC and only those off OR and northern CA remain positive.

4. Discussion and Conclusions

[9] Satellite data show that the cold, fresh hydrographic anomalies of 2002 [*Freeland et al.*, 2003] are accompanied by widespread positive (>1.0 mg m^{-3}) anomalies in surface chlorophyll concentrations primarily over the shelf but extending over 200 km offshore at specific latitudes in some months. The temporal context available from the satellite data show that positive anomalies coherent over the entire study area began in fall 2001. Hydrographic and nutrient properties off OR and BC in June and July 2001 were already near the extreme range of variability [*Freeland et al.*, 2003; *Wheeler et al.*, 2003], suggesting that even earlier (spring 2001) positive chlorophyll anomalies off BC (Figure 2) may be related to the hydrographic anomalies. The absence of spring 2001 positive chlorophyll anomalies off OR and WA casts doubt on whether the coincident early northern CA positive anomaly (Figure 2) is related.

[10] Increased upwelling-favorable winds, evident through much of 2002 and episodically in 2001 (http://pfeg.noaa.gov) would increase nutrient flux into the euphotic zone supporting positive chlorophyll anomalies. Wind forcing anomalies, however, are not significantly stronger or more persistent than those earlier in the SeaWiFS mission and increased offshore Ekman transport off OR and BC should result in increased salinities in the upwelling region, opposite to those observed. Although increases in upwelling likely contribute to the increases in chlorophyll concentrations, they cannot entirely explain the anomalies.

[11] The negative spiciness anomalies of 2002 are associated with increases in nitrate, phosphate and silicate concentrations off Oregon [*Wheeler et al.*, 2003]. These authors also show a 2–3 fold increase in primary production resulting from this nutrient enrichment and chlorophyll fluorescence values over the shelf 2–5 times those measured in summer 2001 and 2000. *Freeland et al.* [2003] argue that increased zonal transport from the central Pacific and also increased alongshore transport out of the Gulf of Alaska are consistent with the anomalies they observe. Alongshore displacements concurrent with the SeaWiFS data averaged over the range 41°–52°N calculated from satellite altimeter data (Figure 4) show the strong seasonality in alongshore flow, consistent with seasonality in large scale wind forcing, negative (southward) during summer and positive (northward) during winter. The time series suggests increasingly weak and shorter duration winter northward advective periods and stronger, longer summer southward advective periods. During the first two years (1997–1998) cumulative northward displacement increases, largely resulting from strong poleward flows in late 1997 associated with the El Nino [*Strub and James*, 2002]. Beginning in early

2000, cumulative displacement begins to decrease, indicative of increasing equatorward transport consistent with the advection of low salinity, low temperature, nutrient enriched sub-arctic water into the California Current. Total southward displacement from early 2000 is ~1000 km suggesting that oceanic characteristics normally present in the vicinity of southern Alaska are now off BC, WA and OR.

[12] Anomalies over a wider California Current region for two example months in 2002 (Figure 5) show that at the height of northwest shelf anomalies (summer, Figure 3), positive shelf anomalies >2.0 mg m^{-3} are continuous north of 40°N, extending to at least 55°N. South of 40°N, positive anomalies are present, but their spatially isolated nature suggests they could be a result of mesoscale variability associated with upwelling and filaments and/or the short (3-year) climatology from which anomalies are calculated. In the fall (October, Figure 5) however, spatially extensive anomalies >1. 0 mg m^{-3} extend over 400km offshore in the region 36°–42°N. These occur after anomalies on the northwest shelf weaken (Figure 3), suggesting continuing equatorward displacement of anomalous hydrographic, planktonic and nutrient conditions within the main California Current jet though summer and into the fall in patterns consistent with a fall offshore expansion of the jet [*Strub et al.*, 1991]. Offshore anomalies weaken but are still present in November 2002 and disappear in December (not shown).

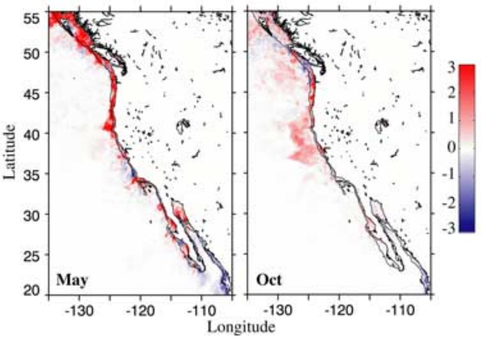

Figure 5. Monthly SeaWiFS chlorophyll anomaly fields (mg m^{-3}) for May and October 2002, characterizing spatial patterns over the larger California Current.

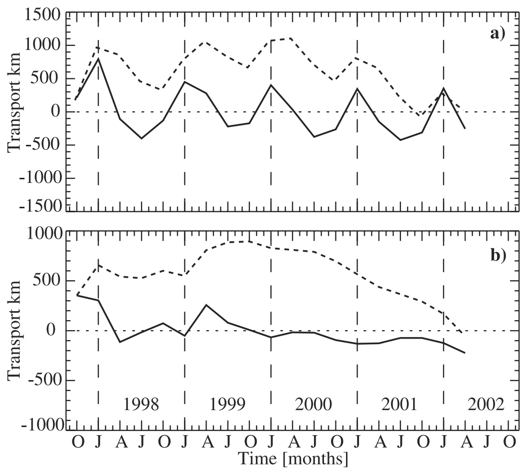

Figure 4. Altimeter-derived a) seasonal mean (solid line) and cumulative (dashed) alongshore transport and b) anomalies for the region 43–53°N from mid 1997 to mid 2002.

[13] Causal mechanisms for the increase in subarctic flow into the California Current appear to be linked to large-scale wind stress and surface temperature anomalies in the North Pacific [*Murphree et al.*, 2003] and increases in both alongshore and basin-scale eastward zonal transport [*Strub and James*, 2003]. This equatorward displacement of nutrient-rich water into the California Current resulted in widespread positive chlorophyll anomalies. These are primarily on the shelf in the northwest where upwelling causes the halocline to outcrop at the surface, but extend well offshore in the fall off central CA when increases in wind-driven mixing would increase vertical flux. These increases in phytoplankton biomass likely have ramifications for higher trophic levels consistent with the link between southward transport and increased zooplankton biomass shown by *Chelton et al.* [1982]. An examination over even larger spatial scales than those presented here is required to quantify the full geographic extent of the chlorophyll anomalies associated with this increased sub-arctic influence in the California Current.

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