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Chlorophyll variability in eastern boundary currents

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Abstract. The first three years of SeaWiFS data (1997-2000) provide the most complete quantification to date of chlorophyll seasonal variability along the full latitudinal extent of the four major eastern boundary currents (EBCs). Comparisons to previously published chlorophyll seasonal climatologies deduced from the relatively sparse coverage provided by the Coastal Zone Color Scanner (CZCS) show significant differences in both southern hemisphere EBCs, while northern hemisphere regions are qualitatively similar. Comparisons between chlorophyll and cross-shelf Ekman transport seasonal cycles, calculated from coincident satellite scatterometer data, show seasonal maxima have similar phases over most of the California Current, at higher (> 32°S) latitudes in the Peru-Chile and Benguela Currents (> 30°S) and at lowest latitudes (< 20°N) in the Canary Current. Latitudinal zones within which phases diverge are indicative of alternate and/or more distant forcing.

Introduction

The four major eastern boundary current (EBC) systems, the California, Canary, Peru-Chile and Benguela Currents, are characterized by latitudinally varying seasonal cycles of equatorward coastal wind stress [*Bakun and Nelson*, 1991]. Resulting offshore Ekman transport brings cold, nutrient-rich subsurface water into the euphotic zone, elevating chlorophyll concentrations. At lowest latitudes, seasonal variability in local forcing is linked to shifts in the ITCZ. Poleward of this there is often a region of reduced seasonality and year-round upwelling favorable (equatorward) wind stress. With increasing latitude, basin-scale pressure fields create greater seasonality at mid latitudes where summer upwelling strength / persistence increases and that of winter decreases, becoming downwelling favorable. Factors influencing upwelling variability within EBCs have recently been reviewed [*Hill et al.*, 1998].

Early comparisons between EBC regions relied on either climatological data or available cruise data and thus suffered from the inevitable lack of synopticity, biases introduced by seasonal, interannual and latitudinal differences and variations in methodology [*Minas et al.*, 1986]. The Coastal Zone Color Scanner (CZCS) provided the first opportunity to compare synoptic scale variability of phytoplankton biomass over EBC regions [*Thomas et al.*, 1994; *Hill et al.*, 1998]. Except over the California Current, however, CZCS data also suffer from potential biases due to large data gaps. Here we use the first three years of SeaWiFS data to provide a first, comprehensive quantification and comparison of the seasonal cycles of chlorophyll over the four EBCs.

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Data and Methods

Daily level-2 global area coverage SeaWiFS chlorophyll data produced with standard (OC4) NASA global coefficients are received routinely from the Goddard Space Flight Center Distributed Active Archive Center. These were subsampled over the four study areas and regridded to a standard projection at 4 km resolution. All scenes with valid data within the study region, from September 1997 to August 2000, were used to form a three-year timeseries of monthly composites. These were subsampled to calculate mean chlorophyll concentrations within a 100 km wide east-west (~cross-shelf) transect beginning at the coast for each 4 km latitude bin. Monthly profiles were then smoothed with a 400 km (in latitude) box-car to assist visualization of dominant patterns and seasonal cycles.

Results

The first three years of near-shore (100 km) SeaWiFS chlorophyll data in each of the EBC regions are shown in Figure 1. Three-year climatologies are shown in Figure 2. California Current maximum chlorophyll concentrations are evident at highest latitudes (> 45°N, off Oregon and Washington), with seasonal maxima in spring and summer (April-September), minima in winter (January-February). At mid latitudes (35° – 45°N), concentrations are consistently >1.0 mg m^{-3} except early in the time series and seasonality is weaker than that further north, although maxima (minima) are still evident in spring-summer (winter). Within this latitudinal range, maximum concentrations are evident off central-northern California (35° – 40°N). South of ~ 35°N winter minimum concentrations are <1.0 mg m^{-3} and a region of minimum seasonality is apparent centered at ~ 32°N (the Southern California Bight). South of this (the Baja peninsula), maximum concentrations (>2.0 mg m^{-3}) develop during spring-summer (April-June) with annual minima in late summer-fall (September-November).

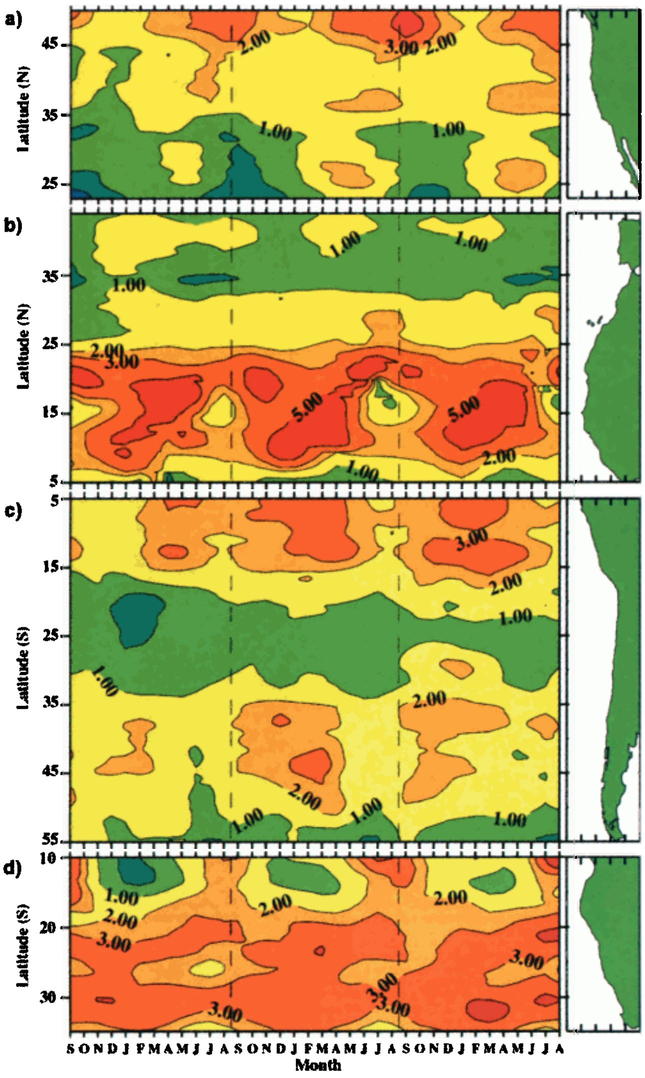

Figure 1. Monthly SeaWiFS chlorophyll (mg m^{-3}) within 100 km of the coast contoured as a function of time (September 1997 - August 2000) and latitude in (a) the California (23°-50°N), (b) the Peru-Chile (5°-55°S), (c) the Canary (5°-43°N) and (d) the Benguela Currents (10°-35°S).

In the Canary Current (Figure 1b), overall highest concentrations are present from 10° – 20°N and lowest concentrations are centered at ~ 35°N (just south of the Strait of Gibraltar). Interpretation of all patterns south of ~ 35°N in the Canary Current remains tentative due to potential chlorophyll overestimation and/or temporal biases caused by absorbing Saharan dust [*Moulin et al.*, 2001]. From 5° – 10°N, the seasonal maximum in chlorophyll occurs in December-January and a distinct minimum is apparent in April-May. Progressing north from 10° to 20°N, the annual maximum (and minimum) occurs later in the season with increasing latitude. By 20°N, seasonal maxima are in May-June and a semi-annual periodicity is evident with an additional peak in October-November. Between 23° and 25°N concentrations decrease sharply to <2.0 mg m^{-3}. From 25°N to 35°N seasonality is weak but with a summer (July-August) maximum in 1999-2000 from 25° – 30°N. North of 35°N (the Iberian Peninsula), weak seasonality is also evident, with maxima centered in winter-early spring (February-April).

The Peru-Chile Current (Figure 1c) has overall maximum concentrations at lowest latitudes (off Peru 5° – 15°S) where the seasonal maxima are centered on austral summer-early fall (January-April) and minima in winter (August). Two areas of more persistent elevated concentrations are centered at ~ 7°S and 12°S. From ~ 18° – 30°S (northern Chile), concentrations are < 1.0 mg m^{-3} and seasonality is weak. Poleward of ~ 30°S, however, chlorophyll annual cycles follow canonical EBC seasonality, with maxima (minima) developing in austral summer (winter). Persistent elevated concentrations are centered at 37°S and 43°S. Poleward of 50°S, monthly mean winds are rarely upwelling-favorable [*Bakun and Nelson*, 1991], concentrations are generally < 1.0 mg m^{-3}) and the seasonal cycle is inconsistent. The climatology shows a weak minimum in winter (Figure 2c).

The most temporally persistent elevated chlorophyll concentrations in the Benguela Current (Figure 1d) are over relatively broad zones centered at ~ 22°S and ~ 31°S. Lowest concentrations (<1.0 mg m^{-3}) are evident at lowest lati-

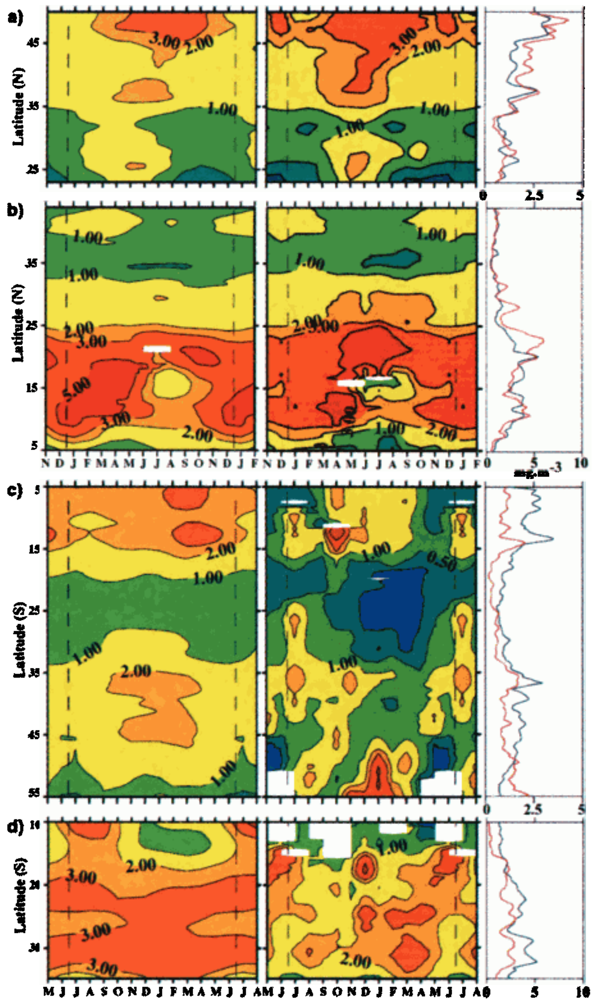

Figure 2. Climatological seasonal cycles of 100 km wide coastal SeaWiFS chlorophyll (left) and CZCS pigment (center) concentrations in (a) the California, (b) the Peru-Chile, (c) the Canary and (d) the Benguela Currents, contoured as a function of time (hemispherical summer is centered), and latitude. Also shown (right) is the latitudinal distribution of annual mean concentrations from SeaWiFS (blue) and CZCS (red).

tudes (< 18°S, off Angola), associated with strong seasonality, maxima in austral winter (July-September), minima in summer (January-March). Poleward of this, annual minima shift to earlier in the year; October-November at 20°S and June-July at 25°S. Beginning at ~ 25°S, seasonality follows canonical EBC patterns (annual minima (maxima) centered in austral winter (summer)). This seasonality weakens near 31°S, but distinct winter minima again become evident poleward of this.

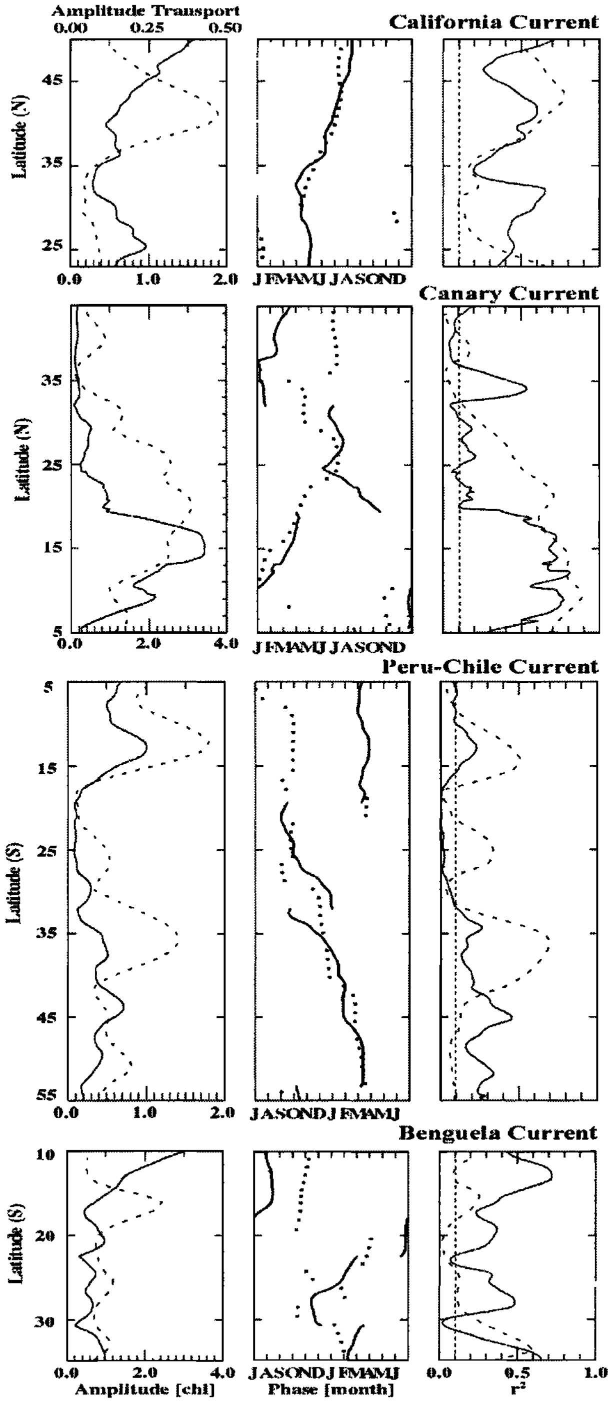

Figure 3. Amplitudes and phases of the seasonal maximum and an estimate of the variance explained (r^2, showing 95% confidence level) for a least squares fit annual plus semi-annual harmonic at each latitude to the 3 years of SeaWiFS chlorophyll (mg m^{-3}, solid line) and the co-incident 3 years of cross-shelf Ekman transport ($m^3 m^{-1} s^{-1}$, broken line). Phase is plotted with summer centered in each hemisphere.

Discussion and Summary

Previous views of large-scale chlorophyll seasonal cycles over EBC regions use CZCS data [e.g. *Strub et al.*, 1990; *Weeks and Shillington*, 1994; *Thomas et al.*, 1994]. Each points out potential errors introduced by missing data resulting from the non-operational nature of the CZCS mission. Figure 2 compares the eight-year (1978-1986) CZCS monthly climatology of pigment concentration with the SeaWiFS chlorophyll climatology (each measures slightly different bio-optical quantities), contrasting annual means by latitude. CZCS data coverage is greatest over the California Current and the latitudinal distribution of annual means is similar in the two climatologies. Both sensors indicate elevated concentrations poleward of ~ 45°N. The CZCS atmospheric correction, however, overestimated concentrations at large solar zenith angles (winter high latitudes) [*Strub et al.*, 1990] resulting in weak seasonality. Here, SeaWiFS data show distinct seasonality in phase with expected wind forcing (summer upwelling maximum). SeaWiFS patterns south of 45°N are consistent with CZCS-measured pigment seasonality [e.g. *Strub et al.*, 1990; *Thomas and Strub*, 2001] suggesting that both instruments provide realistic large-scale seasonal patterns over most of the California Current.

In the Canary Current (Figure 2b), latitudinal distributions of annual means are consistent between the two data sets and there is qualitative agreement in seasonality at most latitudes. Both show a July-September minimum between 20°N and 10°N consistent with previous calculations [*Hill et al.*, 1998; *Bricaud et al.*, 1987]. Two differences are the stronger CZCS seasonality at 20° – 30°N (in phase with a summer wind forcing maximum) and the phase of the annual cycle at latitudes < 10°N (SeaWiFS April-May minimum; CZCS July-August minimum) where CZCS coverage is poor.

Very sparse CZCS coverage over the two southern hemisphere EBCs creates biases leading to strong differences between the two climatologies. In the Peru-Chile Current (Figure 2c), overall latitudinal distributions of annual means are similar, but CZCS concentrations are low, consistent with previous work [*Chavez*, 1995]. At all latitudes, CZCS data provide a disjoint and often biased view of seasonality. Of special note are differences between the annual maximum off Peru (< 15°S) (late summer in the SeaWiFS data but spring-early summer in the CZCS data) and differences off central Chile (30°S and 45°S). Here, the CZCS climatology suggests maxima (minima) in winter-spring (summer) while SeaWiFS consistently measures annual maxima (minima) centered on austral summer (winter), the season of maximum (minimum) upwelling-favorable winds [*Thomas*, 1999]. At highest latitudes (> 45°S), poor CZCS coverage results in an erratic signal where SeaWiFS data show a mid-winter (July) annual minimum. Overall, the SeaWiFS annual maxima off Chile are in phase with upwelling-favorable wind forcing suggesting that seasonality evident in CZCS data [*Thomas et al.*, 1994], even within individual years of strongest coverage [*Thomas*, 1999], is biased by missing data. In the Benguela Current (Figure 2d), similarities in latitudinal distributions of annual means and lower CZCS concentrations are repeated. Climatological 3-month

CZCS composites [*Weeks and Shillington*, 1994] suggest a fall (April-June) maximum and winter (July-September) minimum 17° – 28.5°S, but a summer maximum and spring minimum > 28.5°S. Although distorted, this difference is evident at mid latitudes in the monthly CZCS data shown here and is consistent with patterns now sampled much more extensively by SeaWiFS. At lowest latitudes (< 15°S) however, missing CZCS data cannot reproduce the strong seasonality sampled by SeaWiFS. At highest latitudes (> 32°S), SeaWiFS measures a stronger seasonal cycle, in phase with seasonal wind forcing.

Least-squares fits of annual plus semi-annual harmonics to the smoothed 3-year SeaWiFS time series at each latitude provide quantitative summaries of chlorophyll seasonal cycles in the four EBCs (Figure 3). For comparison to local forcing, these are plotted against similar harmonic fits to temporally coincident cross-shelf Ekman transport at each latitude computed from monthly mean alongshore wind stress calculated from ERS scatterometer data. In the California Current, maxima of both chlorophyll and wind forcing are approximately in phase poleward of ~ 30°N, shifting progressively later into summer with increasing latitude. South of this, the winter wind maximum leads chlorophyll by 3-4 months. In the Canary Current, maximum amplitudes occur equatorward of 30°N, although shifts in dominance between annual and semi-annual cycles cause discontinuities in phase of the seasonal maximum. Poleward of 32°N where amplitudes (of both) and r^2 (of wind) are small, the chlorophyll winter seasonal maximum is dissociated from the summer maximum in Ekman transport. From 32-25°N, forcing leads (1-2 months) or is in phase with the chlorophyll maximum, but from 25-20°N a strong semi-annual chlorophyll signal results in dissociated seasonal maxima. From 5-20°N, forcing leads the chlorophyll maxima by 1-2 months with each shifting progressively later into the season with increasing latitude. In the Peru-Chile Current, maximum amplitudes are present off Peru (5-15°S) and off central Chile (35-45°S), but shifts in strength of the semi-annual component create latitudinal discontinuities in phase. Off Peru (< 18°S), the spring wind forcing maximum is ~ 180° out of phase with the fall chlorophyll maximum, consistent with ship measurements [*Chavez*, 1995]. From 18-32°S, small amplitudes and r^2 values of chlorophyll and/or wind make interpretation difficult. Poleward of this, both are in phase with a maximum that shifts progressively later into the summer with increasing latitude. In the Benguela Current regions of low r^2 and changes in strength of the semi-annual versus annual cycle again make interpretation difficult. Poleward of ~ 28°S, wind leads chlorophyll by 1-2 months. Equatorward of 22°S, the winter chlorophyll maximum is dissociated from the seasonal maximum in local forcing.

The first 3 years of SeaWiFS chlorophyll data provide our most complete picture of large-scale seasonality in the 4 major EBCs to date. Several patterns emerge from the comparison of satellite chlorophyll and cross-shelf Ekman transport. Mid-latitude seasonal maxima in both tend to occur in spring and summer, consistent with wind forced upwelling. The exception appears to be off the Iberian Peninsula, where wind forcing is weak. Regions where wind forcing and higher pigment concentrations are seasonally disjoint tend to occur at lower latitudes (the exception is the Canary Current), where equatorial current systems, surface heat fluxes, and distant forcing along the equatorial wave guide may be important. The results set the stage for in-depth regional examinations of the biophysical interactions responsible for these patterns.

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