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Sea level anomalies control phytoplankton biomass in the Costa Rica Dome area

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[1] Satellite data show that chlorophyll-a concentration (Chl-a) in the northeastern tropical Pacific is well correlated with sea level anomaly (SLA). This correlation spans a wide spectrum of scales from large-scale phenomena like ENSO to mesoscale cyclonic and anticyclonic eddies. Negative SLA (e.g. during La Niña events and in cyclonic eddies) is associated with the lifting of isopycnals in the nutricline and increased Chl-a due to enhanced phytoplankton growth, while positive SLA (e.g. during El Niño events and in anticyclonic eddies) is associated with a deeper nutricline and reduced Chl-a due to decreased phytoplankton growth. The coupling between SLA and Chl-a anomaly in the Costa Rica Dome (CRD) area is tighter than has previously been recorded anywhere in the world ocean. 70% of the interannual variations in Chl-a anomaly in the CRD area is explained by a combination of the positive and negative effects of SLA. **Citation:** Kahru, M., P. C. Fiedler, S. T. Gille, M. Manzano, and B. G. Mitchell (2007), Sea level anomalies control phytoplankton biomass in the Costa Rica Dome area, *Geophys. Res. Lett.*, *34*, L22601, doi:10.1029/2007GL031631.

1. Introduction

[2] Wind jets blowing through mountain gaps of southern Mexico and Central America into the Pacific Ocean are known to produce a rapid oceanic response leading to the generation of oceanic eddies in the Gulfs of Tehuantepec, Papagayo and Panama [*Stumpf*, 1975; *Stumpf and Legeckis*, 1977; *McCreary et al.*, 1989; *Barton et al.*, 1993; *Chelton et al.*, 2000; *Willett et al.*, 2006]. These eddies have long been suspected to be important in transporting nutrients and biogenic material from the continental margin to the interior of the ocean, a process recently quantified by *Samuelsen* [2005]. Indeed, the eddies are known to have distinctive signatures in ocean color [*Müller-Karger and Fuentes-Yaco*, 2000; *Gonzalez-Silvera et al.*, 2004] and sea-surface height [*Willett*, 1996]. While most studies have dealt only with the anticyclonic eddies which are larger and have longer life-span, the cyclonic eddies may be as numerous but dissipate relatively quickly [*Gonzalez-Silvera et al.*, 2004]. *Palacios and Bograd* [2005] performed a census of eddies and found that the weaker cyclonic eddies did not satisfy their criteria of eddy detection. They also found that the anticyclonic eddy activity (the number of anticyclonic eddies, their intensity and lifespan) intensified during El Niño years and decreased during La Niña years.

[3] 'Eddy pumping' has been suggested as a mechanism by which ocean eddies and meanders on scales of tens to hundreds of kilometers drive the vertical motion of water, including lifting subsurface nutrients into the euphotic zone [*Falkowski et al.*, 1991; *McGillicuddy et al.*, 1998; *Oschlies and Garçon*, 1998]. *Wilson and Adamec* [2001, 2002] and *Wilson and Coales* [2005] have analyzed global relationships between sea surface height, mixed layer depth, thermocline depth and Chl-a and concluded that the dominant mechanism in the tropics is the thermocline uplift corresponding to negative sea level anomaly that enhances phytoplankton growth and concentration. With the availability of high-quality, long time series of sea level anomaly [*Ducet et al.*, 2000] and ocean color [*McClain et al.*, 2006] it is now possible to map important relationships of the phytoplankton environment at scales of tens and hundreds of kilometers using satellite data.

2. Data and Methods

[4] Satellite-derived Level-2 and Level-3 datasets of chlorophyll-a concentration (Chl-a) were obtained from the NASA Ocean Color website (http://oceancolor.gsfc.nasa.gov/). Monthly and 8-day Chl-a composites calculated from OCTS (1996–1997) and SeaWiFS (1997–2007) normalized water-leaving radiances using the maximum band-ratio algorithm [*O'Reilly et al.*, 1998] were used to create monthly and 8-day anomalies as the ratio of a current Chl-a to the long-term average Chl-a of the same time period and expressed as percentage anomaly, i.e. 100*(Anomaly – 1). Similarly, sea-surface temperature (SST) anomalies were constructed from the monthly Pathfinder version 5 data (http://www.nodc.noaa.gov) and expressed as the difference from the long-term mean SST of the same period.

[5] Weekly maps of SLA merged from TOPEX/POSEIDON, Jason and ERS-1/2 data created by AVISO [*Ducet et al.*, 2000] for the 1992–2006 period were used (http://www.aviso.oceanobs.com). As the detection of individual eddies by the shape of the SLA field, e.g. by the existence of certain closed contours, is rather subjective, we do not try to separate individual eddies here but attempt to measure eddy activity in general. As a measure of cyclonic eddy activity we calculated monthly root mean square (RMS) of negative SLA in 7×7 pixel windows (RMSNEG) of the updated SLA dataset. Similarly, monthly root mean square of positive SLA in 7×7 pixel windows (RMSPOS) was used as a measure of the anticyclonic eddy activity. Monthly time series of SLA, RMSNEG and RMSPOS were correlated with monthly Chl-a anomalies.

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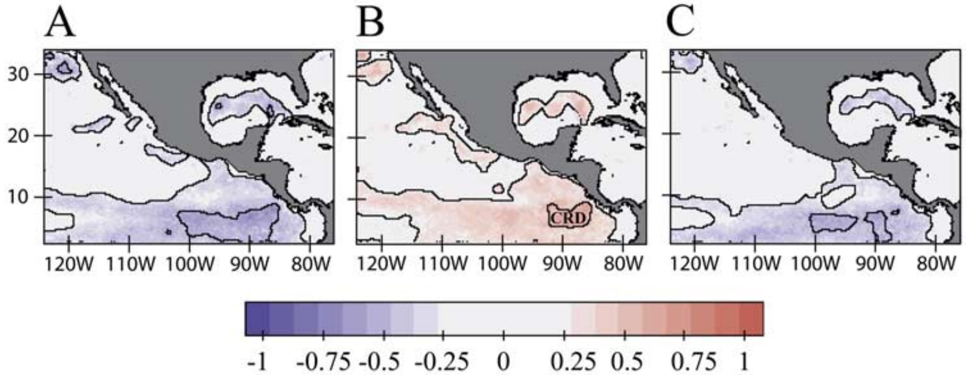

Figure 1. Correlation coefficient r of Chl-a anomaly with (a) sea level anomaly (SLA), (b) RMS of negative SLA, and (c) RMS of positive SLA. Isolines for r equal to $|0.25|$ and $|0.5|$ are shown. The spatial domain CRD ($\sim$720 $\times$ 330 km) in Figure 1b specified as an area with $r > 0.5$ is the approximate location of the Costa Rica Dome. $|r| > 0.23$ is significant at $P < 0.01$.

[6] To evaluate the correlation between two time series at different frequency bands we used squared coherency. Squared coherency was calculated with STATISTICA™ v.6 (http://www.statsoft.com) and is considered significant if it exceeds

$$\frac{2F_{2,\nu-2}}{\nu - 2 + 2F_{2,\nu-2}} = 1 - \alpha^{\frac{2}{\nu-2}}$$

This relationship is derived from the F-distribution with α = 0.05 and ν being the number of equivalent degrees of freedom. Bias in the squared coherency is related to spectral estimator and the number of ν. Small number of ν may cause a large positive bias in coherency estimates, whereas low frequency peaks may be affected by over-smoothing (see *von Storch and Zwiers* [1999] for further details). For monthly time series we found that squared coherency peaks higher than 0.39 are significant ($P < 0.05$; significance estimated for $\nu = 14$).

3. Results

[7] Figure 1a shows the spatial distribution of the correlation coefficient between Chl-a anomaly and SLA. Chl-a anomaly has significant negative correlation with SLA over large areas of northeastern tropical Pacific, most notably downstream of the typical path of the eddy trajectories [e.g., *Palacios and Bograd*, 2005]. The negative correlation becomes insignificant north of about 10° N latitude, where the thermocline deepens [*Fiedler*, 2002, Figure 1]. Spatial correlation patterns between Chl-a anomaly and the RMS of negative SLA and the RMS of positive SLA (Figures 1b and 1c) are approximately similar but with opposite sign. RMSNEG can be considered a proxy for cyclonic eddy activity, and RMSPOS is a proxy for anticyclonic eddy activity. The compact area of strong positive correlation between RMSNEG and Chl-a anomaly ($\sim$720 km east-west $\times$ 330 km north-south) defined by $r \geq 0.5$ (CRD in Figure 1b) coincides with the general location of the Costa Rica Dome, an area with a shallow, doming thermocline [*Fiedler*, 2002]. Time series of various parameters were constructed in this spatial domain (Figures 2 and 3).

[8] The response in Chl-a to the drop in negative SLA (Figure 3, bottom) and a sharp increase in positive SLA (Figure 4, bottom) during the 1997–1998 El Niño event was practically instantaneous and no delay in the response of Chl-a could be detected. Even when comparing 8-day Chl-a and 7-day SLA data (not shown) no significant delay could be detected. The El Niño event of 1997–1998 was extremely anomalous and may cause the high correlations between SLA and Chl-a anomaly. We therefore excluded the drastic El Niño event in the calculations and repeated the calculations for the 1999–2006 period but the correlations

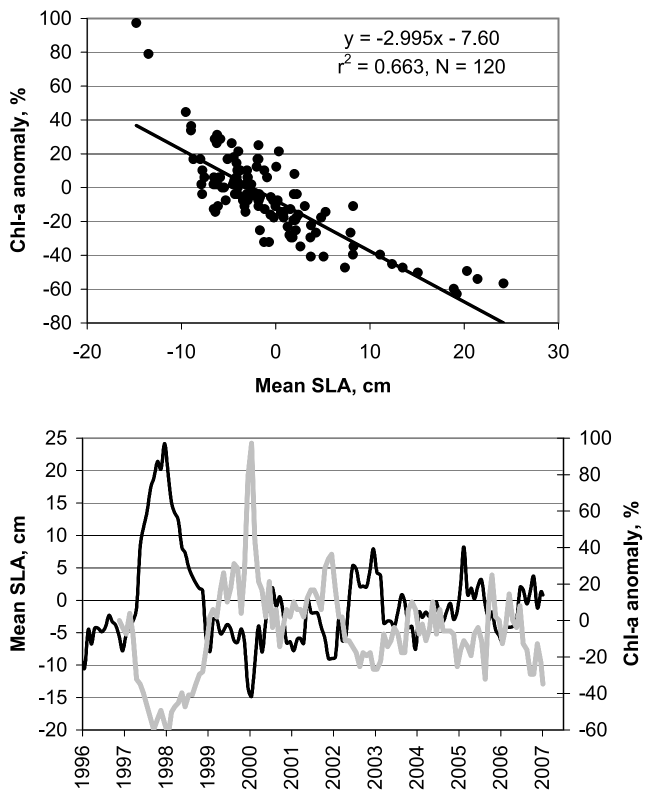

Figure 2. (top) Scatter plot and (bottom) time series of monthly mean SLA (black line, left axis) and Chl-a anomaly (gray line, right axis) in area CRD of Figure 1b.

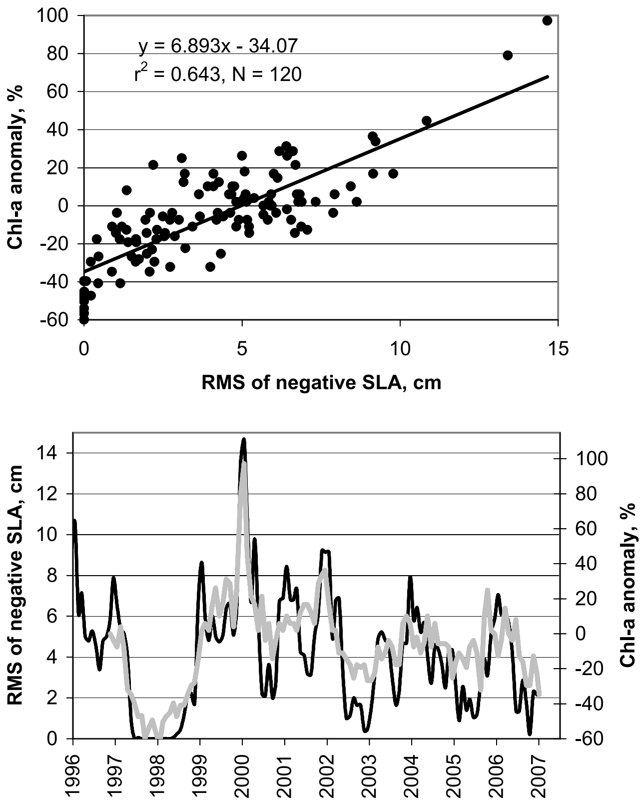

Figure 3. (top) Scatter plot and (bottom) time series of monthly mean RMS of negative SLA (black line, left axis) and Chl-a anomaly (gray line, right axis) in area CRD of Figure 1b.

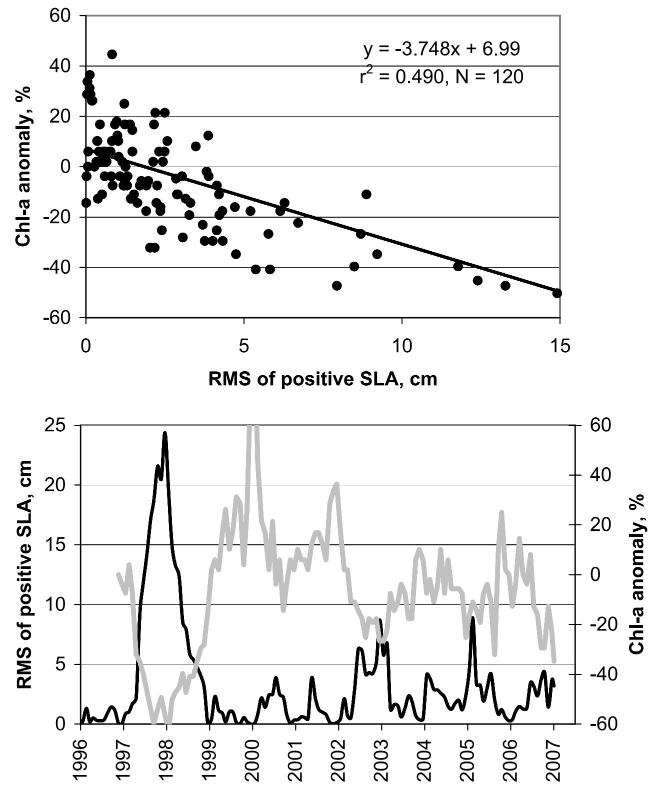

Figure 4. (top) Scatter plot and (bottom) time series of monthly mean RMS of positive SLA (black line, left axis) and Chl-a anomaly (gray line, right axis) in area CRD of Figure 1b.

stayed highly significant, although their absolute values decreased (Table 1). For example, r^2 between RMS of negative SLA decreased from 0.663 for the whole period to 0.563 for the 1999–2006 period. We can predict Chl-a anomaly in the Costa Rica Dome area with the following equation:

$$\text{ChlAnom} = 0.789 + 0.051 * \text{RMSNEG} - 0.017 * \text{RMSPOS}, \quad (1)$$

where RMSNEG and RMSPOS are the RMS of negative and positive SLA, respectively. This relationship explains over 70% of the total variance (R^2 = 0.705) in Chl-a anomaly. The positive relationship between SLA and SST anomaly (not shown) is even stronger (r^2 = 0.725 for the 1999–2006 period).

[9] Visual inspection of Figures 2, 3, and 4 shows that in addition to the strong correlation between SLA and Chl-a anomaly at large temporal scales, e.g. El Niño-Southern Oscillation (ENSO), many features at much shorter scales are also correlated. We confirmed this with cross-spectral analysis. Figure 5 shows that the squared coherency (similar to the squared coefficient of correlation for certain frequencies) shows significant correlation at a number of time scales. The significant coherence at 2.4 months is likely to be caused by the passage of mesoscale eddies. The high coherence at longest scales is consistent with ENSO variability. The intermediate scales of high coherence may be due to seasonal changes.

4. Discussion

[10] The negative correlation between Chl-a and SLA, especially in the tropics, has been observed earlier [*Wilson and Adamec*, 2001] and explained by deepening of the thermocline (and associated nutricline) at positive SLA and shoaling of the thermocline (and nutricline) at negative SLA. The increase in phytoplankton biomass (Chl-a) in cyclonic eddies is believed to be the result of increased local production due to the lifting of the high-nutrient waters into the euphotic layer in areas of shoaling of the thermocline [*Benitez-Nelson et al.*, 2007]. The interactions between Chl-

Table 1. Coefficient of Determination Between SLA and Its Positive and Negative Parts With Chl-a Anomaly in Area CRD of Figure 1b[a]

Variable	1996–2006	1999–2006
SLA	0.663	0.553
RMS of negative SLA	0.643	0.572
RMS of positive SLA	0.490	0.314
RMSNEG & RMSPOS	0.705	0.579

[a]Coefficient of determination, r^2. "RMSNEG & RMSPOS" means using both RMS of negative and positive SLA in a multiple linear regression to predict Chl-a anomaly. Significance was tested for the "effective" degrees of freedom caused by autocorrelation and results were significant in all cases (P < 0.01).

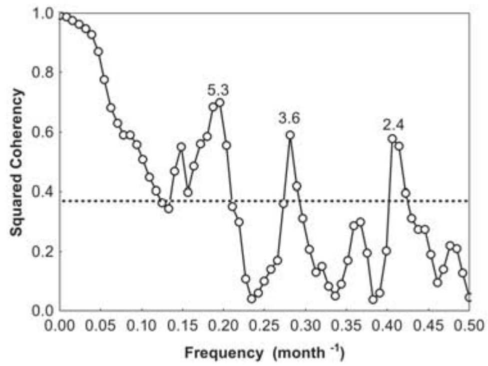

Figure 5. Squared coherency spectrum between monthly time series of RMS of negative SLA (RMSNEG) and Chl-a anomaly in the Costa Rica Dome area. The peaks at frequencies 0.19, 0.28, 0.41 month^{-1} correspond to periods of 5.3, 3.6, and 2.4 months, respectively. The dashed horizontal line indicates the approximate 95% significance level.

a and eddy dynamics are very complex and involve a number of mechanisms which are not well known. Upwelling at the periphery of anticyclonic eddies [*McGillicuddy et al.*, 2007; *Kahru et al.*, 2007] can cause local increase of Chl-a. However, in our satellite study with ~25 km resolution of SLA and 9-km resolution of Chl-a we cannot effectively evaluate these small-scale mechanisms and have to resort to statistical correlations at relatively low spatial scales. Contrary to *Lopez-Calderon et al.* [2006] who concluded that both cyclonic and anticyclonic eddies increase local Chl-a in the north-eastern tropical Pacific, we find significant negative correlation between Chl-a and positive SLA, a proxy for anticyclonic eddies. Both cyclonic and anticyclonic eddies often occur in groups and when using low-resolution, average SLA, the negative and positive anomalies can partly cancel each other and their net effect is altered. When the positive and negative components of SLA are separated then the negative effects of the positive SLA are obvious (Figure 4). It is also significant that when using the positive and negative components of SLA separately, the resulting coefficient of determination is higher than when using the mean SLA alone (0.705 versus 0.663 for the whole period). This may be caused by the smoothing effect of the 7 × 7 pixel window when calculating the RMS of SLA. Cross-spectral analysis confirms that Chl-a anomaly is coherent with SLA at a number of temporal scales, e.g. corresponding to ENSO, seasonal changes and mesoscale eddies.

[11] An alternative hypothesis (the "hay rake" mechanism) for the apparent increase in Chl-a was proposed by *Dandonneau et al.* [2003] who argued that ocean color anomalies associated with sea level anomalies are not actually caused by increased Chl-a but rather by the accumulation of detrital material in convergence zones of ocean eddy fields. The "hay rake" mechanism does not seem to be valid in the Costa Rica Dome area as periods of increased Chl-a are associated with periods of cold SST that is consistent with upwelling of cold, nutrient-rich waters due to "eddy pumping".

[12] *McGillicuddy et al.* [2007] recently proposed a new mechanism for sustained upwelling in anticyclonic mode-water eddies caused by eddy-wind interactions. The eddy/wind interaction tends to sustain anticyclonic eddies and dampen cyclonic eddies. This may be one of the explanations of the longer life time of anticyclonic eddies. However, in this region increased Chl-a is clearly associated with cyclonic eddies and eddy/wind interaction is expected to reduce the effect of eddy-induced upwelling.

5. Conclusions

[13] The coupling between sea level anomaly and Chl-a anomaly in the Costa Rica Dome area is tighter than has previously been reported anywhere in the global ocean. Negative SLA is associated with increased Chl-a, and positive SLA with decreased Chl-a. Positive or negative SLA reflects, respectively, deepening or shoaling of the thermocline. This mechanism is especially effective in modulating the nutrient supply to the euphotic zone in the Costa Rica Dome area due to its shallow thermocline, close proximity of the thermocline and the nutricline, and the effect of the energetic mesoscale eddies impinging on the area. 70% of the interannual variations in Chl-a anomaly in the Costa Rica Dome area is explained by the combination of the positive effects of the negative SLA (including La Niña and cyclonic eddies) and the negative effects of the positive SLA (including El Niño and anticyclonic eddies).

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