A global view of bio-physical coupling from SeaWiFS and TOPEX satellite data, 1997–2001

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[1] Vertical fluxes of nutrient-rich water from below the nutricline to the ocean surface can be a limiting factor affecting surface chlorophyll, and the depth of the nutricline plays an important role in the regulation of surface productivity. Because subsurface nutrient data is less available than physical oceanographic data, satellite chlorophyll (SC) data has been compared to satellite sea-level anomalies (SLA), because SLA largely reflects changes in the thermocline depth, and the thermocline and nutricline are often colocated. Here global correlations between 46 months of TOPEX SLA and SeaWiFS SC are examined. These two measurements are predominately negatively correlated as smaller SLA implies a shallower thermocline/nutricline, which will increase the surface nutrient flux and increase phytoplankton concentrations. However, there are large areas in all ocean basins where the correlations suggest that SC are affected by processes other than thermocline depth changes. *INDEX TERMS:* 4227 Oceanography: General: Diurnal, seasonal, and annual cycles; 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling

1. Introduction

[2] The ocean is of paramount importance to understanding the global carbon cycle because of the huge carbon reservoir in the ocean and the relatively fast recycling of phytoplankton in the surface ocean. Ocean phytoplankton growth is primarily nutrient limited, and thus is affected by vertical mixing processes that deliver nutrients to the surface [*Lewis et al.*, 1986]. Subsequently, surface chlorophyll is impacted by the depth of the nutricline, as a shallower (deeper) nutricline increases (decreases) the vertical flux of nutrients to the surface. On a global scale it is not possible to directly compare the two as subsurface nutricline data is not available on the same spatial and temporal scales as satellite chlorophyll (SC) data is. Instead, SC has been compared to satellite sea-level anomaly (SLA) variability [*Murtugudde et al.*, 1999; *Cipollini et al.*, 2001; *Siegel*, 2001; *Uz et al.*, 2001; *Wilson and Adamec*, 2001], because SLA largely reflects changes in the thermocline depth, and the nutricline and thermocline are often colocated. While a strong relationship between SC and SLA has been seen on a variety of scales from the high productivity in upwelling areas with shallow thermoclines, to the mesoscale increases in productivity observed in the thermocline doming regimes of cyclonic eddies [*McGillicuddy et al.*, 1998] and propagating Rossby waves [*Cipollini et al.*, 2001; *Siegel*, 2001; *Uz et al.*, 2001], the global extent of this relationship has not been documented.

[3] There are significant geographical dependences on the relationships between SLA and themocline variability and between the depths of the thermocline and nutricline. While thermocline depth changes are the primary forcing behind SLA in the tropics, at mid-latitudes surface buoyancy fluxes dominate [*Stammer*, 1997; *Mayer et al.*, 2001]. Similarly, the tightest relationship between the thermocline and nutricline depths also occurs in the tropics. The difference between the depths of the thermocline and nutricline (defined as the depth of the maximum gradient) from annually averaged Levitus profiles is shown in Figure 1. Equatorward of 20° latitude the nutricline is on average 30 m deeper than the thermocline, while in the subtropics the thermocline is shallower by as much as 200 m. Hence, in the tropics, where SLA primarily reflect thermocline changes, and where the thermocline and nutricline are close together, one would expect SLA to affect SC.

[4] Here, correlations between TOPEX SLA and SeaWiFS SC are examined between Sept. 1997–June 2001 using SeaWiFS data from the global level 3 standard mapped images rebinned onto a $1° \times 1°$ grid. SLA from TOPEX Generation B Merged Geophysical Data records are temporally regridded onto 8-day cycles corresponding to the SeaWiFS data. The data processing is described in more detail in *Wilson and Adamec* [2001].

2. Results and Discussion

2.1. Seasonal Cycle

[5] The seasonal cycles of SC and SLA were calculated from the best-fit to the annual and semi-annual harmonic components and the correlations between them are shown in Figure 2. Due to the small number of degrees of freedom ($N = 4$), only absolute correlations above 0.95 are significant. However, even statistically significant correlations do not necessarily imply causality, especially when both datasets have strong seasonality [*Chelton*, 1982]. The utility of the correlations is to show where SLA and SC are in phase, and where they are not, to better understand the underlying physical processes affecting both parameters. As expected the two are predominately (66%) negatively correlated, however there are significant areas with positive correlations in the subpolar regions, the western tropical Atlantic, the western and central subtropical Pacific, and between 10°S–30°S in the Indian Ocean.

2.1.1. Subpolar Regions.
[6] Positive correlations are seen poleward of 40° latitude, with the exception of the Pacific sector of the Southern Ocean where there are mixed positive and negative correlations. The change from negative to positive correlations at 40°N coincides with the transition zone between low SC in the sub-tropical gyres and high SC at mid- to high-latitudes, which arises from the deeper mixed layer depths (MLD) that develop north of 40°N during winter [*Glover et al.*, 1994]. These winter MLDs penetrate through to the nutricline and increase surface nutrient concentrations. However, in winter at higher latitudes light is a limiting factor, and thus phytoplankton blooms are delayed
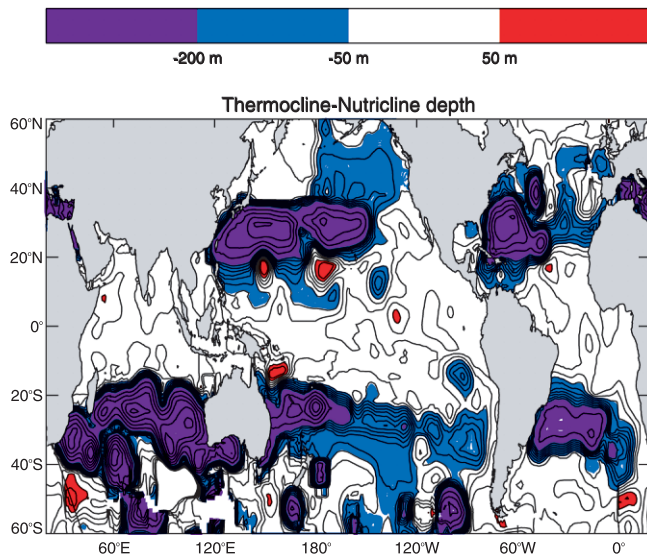
Figure 1. Difference between annually averaged thermocline depth and nitricline depth, calculated from Levitus data. Purple and blue contours show where the nitricline is deeper than the thermocline by more than 200 m and 50 m respectively. Where the nitricline is more than 50 m above the thermocline is contoured red. Contour interval is 100 m below -200 m, and 25 m above -200 m.

until solar radiation increases in the spring. Positive SLA occur then since subpolar SSH variability is dominated by seasonal steric changes [*Stammer*, 1997; *Vivier et al.*, 1999]. Thus, positive SLA-SC correlations in the subpolar regions probably result from summer irradiance increasing SSH while also providing needed light to phytoplankton.

[7] However, the smaller degree of positive correlation (in spatial extent and correlation magnitude) between SLA and SC in the Pacific sector of the Southern Ocean suggests different dynamics. This weaker correlation is probably caused by the less pronounced SC seasonal cycle relative to other subpolar regions. The lack of strong summer blooms in the southern Pacific could be due to iron limitation [*Moore and Abbott*, 2000]. Productivity in the entire Southern Ocean is believed to be limited by the micro-nutrient iron [*Martin et al.*, 1990], and iron concentrations in the Pacific sector are lower than in the Atlantic and Indian sectors [*Duce and Tindale*, 1991]. Light limitation could also contribute to the marginal summer bloom as the Pacific sector also has lower summer irradiance than the Atlantic and Indian sectors [*Mitchell et al.*, 1991].

2.1.2. Atlantic. [8] There are negative correlations in the upwelling areas in the eastern tropical Atlantic (ETA) in the Guinea Dome and in the eastern equatorial region where thermocline changes drive the fall bloom [*Longhurst*, 1993; *Signorini et al.*, 1999]. However, positive correlations dominate in the western Atlantic basin between $20°S-25°N$. The northern part of this region is within the area of the Amazon discharge [*Müller-Karger et al.*, 1988]. There is debate about what causes the high SC values off of northeast Brazil. *Longhurst* [1993] attributes these blooms to nutrients brought to the surface by upwelling from eddies generated by the North Brazil Current retroflection. *Müller-Karger et al.* [1995] argue that the blooms are due to the discharge and advection of water from the Amazon. Additionally, both the Amazon and Orinoco discharge have large amounts of colored dissolved organic matter that may cause satellite measurements, which are validated primarily on case I waters [*O'Reilly et al.*, 1998], to overestimate chlorophyll levels. The positive SLA-SC correlations support the idea that

elevated chlorophyll in the western Atlantic, and extending eastward across the basin via the North Equatorial Current, is caused by the Amazon discharge, as steric changes from the influx of warm water will increase SLA.

[9] However, the areas along the western equator and south of the equator are not influenced by fluvial discharge, and other mechanisms are needed to explain why SC there does not seem controlled by thermocline depth changes. The western Atlantic thermocline is deeper than the eastern [*Hastenrath and Merle*, 1987], and changes in a deeper thermocline are less likely to effect surface nutrient fluxes. Another factor that could contribute is the presence of a salinity-driven barrier layer [*Sprintall and Tomczak*, 1992]. In the western Pacific, where there is also a salinity barrier layer [*Lucas and Lindstrom*, 1991], SLA and SC are also decoupled.

[10] An additional cause for the decoupling could be *Trichodesmium* blooms, as they are nitrogen fixers and hence do not rely upon the vertical flux of nitrate from the thermocline. Nitrogen fixation by *Trichodesmium* can introduce as much nitrate into the euphotic zone of the tropical Atlantic as the vertical flux across the thermocline [*Capone et al.*, 1997]. The areas in the tropical Atlantic with positive SLA-SC correlations also have higher levels of *Trichodesmium* [*Orcutt et al.*, 2001].

2.1.3. Pacific. [11] In the Pacific, there is a horseshoe shaped band of positive correlations centered at the equator in the western warm pool and extending southeast and northeast to $20°S$ and $20°N$. As in the western Atlantic, the positive correlations in the western warm pool could be due to the salinity barrier layer [*Lucas and Lindstrom*, 1991]. The positive correlations along $20°S$ and $20°N$ could be from the deepening of the thermocline in these regions, which lessens the thermocline's impact on the surface euphotic layer. Additionally, *Trichodesmium* could also play a role.

2.1.4. Indian. [12] Negative correlations dominate in the Indian Ocean except off the western coast of Australia and in a band extending between $10°S-30°S$ where there is strong annual cycle of Rossby wave propagation [*Masumoto and Meyers*, 1998]. While thermocline depth changes from Rossby wave propagation do affect SC [*Cipollini et al.*, 2001; *Siegel*, 2001; *Uz et al.*, 2001], in the subtropical Indian Ocean the seasonal SC cycle is much stronger than the more localized effects of Rossby wave propagation
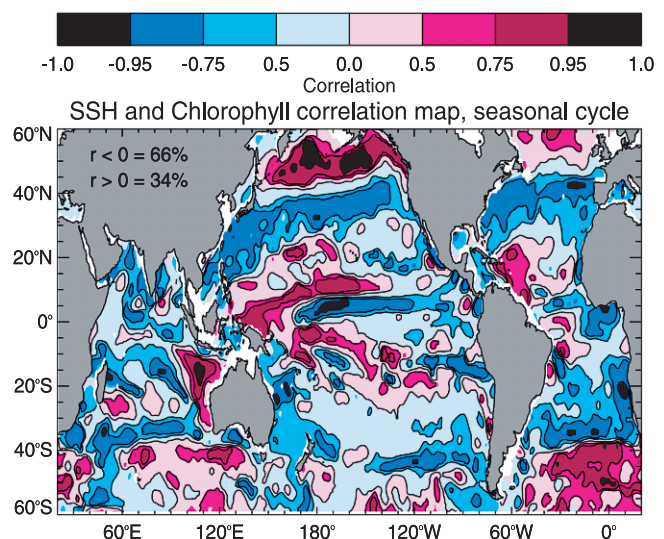

Figure 2. Correlations between the seasonal cycle calculated by harmonic analysis from TOPEX SLA and SeaWiFS SC data. Absolute correlations above 0.95 are significant at the 95% confidence level (N = 4). The percentages (area weighted) of positive and negative correlations are given in the upper lefthand corner.

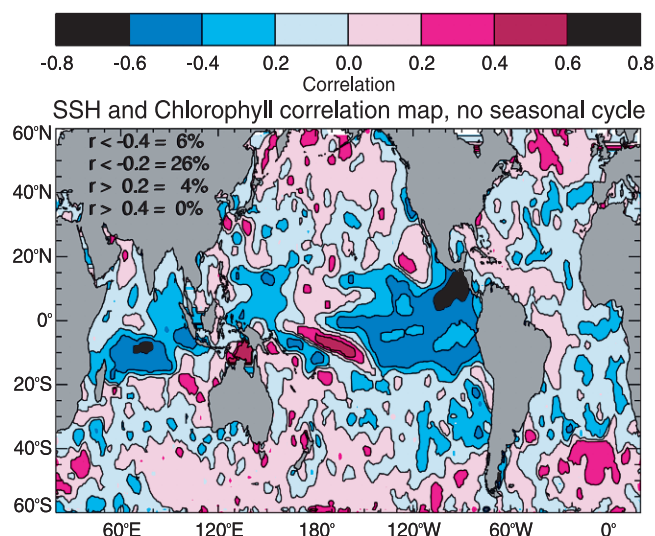**Figure 3.** Correlations between SLA and SC without the seasonal signal. The contour interval is 0.20. Absolute correlations above 0.2 are significant at the 99% confidence level (N = 174). The percentages (area weighted) of significant positive and negative correlations are given in the upper lefthand corner, as are the percentages of strong (|r| > 0.4) correlations.

[Cipollini et al., 2001]. The pattern of oscillating positive and negative correlations across the southern Indian Ocean, results from an invariant seasonal SC cycle, which peaks in Aug., and a SLA cycle whose maximum changes across the basin with the propogation of Rossby waves.

2.2. Interannual Variability

[13] To see the effects of interannual variability, notably the ENSO event in 1997/98, on SLA-SC coupling the seasonal cycle was subtracted from both data sets and their correlations are shown in Figure 3. The correlations are lower than those in Figure 2 because there are more independant data points (N = 174) than in the harmonic analysis. Absolute correlations above 0.2 are significant at the 99% confidence level.

[14] The areas with significant correlations are mostly concentrated in the tropical (20°N–20°S) Indian and Pacific Oceans, the regions most affected by ENSO. Strong bio-physical coupling in the Pacific during ENSO events has been shown to be not just confined to the equatorial region, but extending out to 20° latitude [Wilson and Adamec, 2001]. In the tropical Pacific negative correlations occur in the western warm pool and in the eastern cold tongue region, but positive correlations, or statistically insignificant correlations, dominate along the dateline, the pivot point of the thermocline oscillations associated with ENSO. The negative correlations in the western warm pool on an interannual timescale are in contrast to the positive correlations during the seasonal cycle. There are very sharp transitions between positive and negative correlations between 0–10°S and 150°W–160°E in the South Pacific, which could be the result of migration of the South Pacific Intertropical Convergence Zone [Vincent, 1994].

[15] Most of the ocean follows the expected inverse relationship between SLA and SC on both seasonal and interannual timescales. There are significantly large areas where the correlations suggest that nutrient fluxes are being driven by processes other than thermocline depth changes, or by physical processes that are remote in time and/or space (i.e. horizontal advection). While the positive correlations in subpolar regions can be explained, to fully understand the bio-physical dynamics in other areas will require simultaneous data on the subsurface structure. This data can be

simulated by computer modelling and will be the focus of future studies.

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