

Examining the global record of interannual variability in stratification and marine productivity in the low-latitude and mid-latitude ocean

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[1] Strengthened stratification of the upper ocean, associated with anthropogenic or climate-driven warming, is generally expected to inhibit marine primary productivity in light-replete, nutrient-limited environments, essentially, in the low and middle latitude ocean, based on the supposition that increased water column stability will inhibit vertical mixing and consequently the upward entrainment of deep nutrients into the euphotic zone. Herein, we examine the local stratification control of productivity on interannual timescales over the global subtropical and tropical ocean by directly comparing in situ measures of stratification (from hydrographic profile data) with contemporaneous values of ocean chlorophyll (from satellite data). In the subtropical ocean, we find no evidence of a strong local correlative relationship between these properties over the observational record, a result that challenges the widely held view that stratification variability is a primary driver of interannual variability in nutrient supply and productivity in these waters. A strong negative relationship is observed, however, in the tropical Pacific, suggesting that previously reported correlations between globally averaged stratification and productivity variability are driven by strong associations in this region. An examination of the long-term changes in our profile data also reveals trends of decreasing stratification scattered across the low-latitude and mid-latitude ocean, driven by faster rates of warming in the subsurface relative to the surface. This observation seemingly undercuts a fundamental assumption of the paradigm of local stratification control, namely that increases in upper ocean heat content necessarily produce strengthened stratification.

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1. Introduction and Background

[2] Photosynthetically driven primary production of organic matter by marine phytoplankton serves as the foundation for virtually all marine trophic networks [Duarte and Cebrian, 1996] and is a vital component of the biogeochemical cycles that are responsible for the large-scale distributions of carbon, oxygen, and nutrients in the global ocean [Sarmiento and Gruber, 2006]. The rate at which organic matter is generated is fundamentally modulated by variations in the amount of light energy and nutrients that

are available to phytoplankton communities in the surface ocean. At low and middle latitudes, where solar radiation is generally in abundant supply, the delivery of nutrients into the euphotic zone therefore becomes a critical determinant of new biomass production [Falkowski *et al.*, 1998]. Historically, nutrient supply has been treated largely as a function of vertical exchanges between the nutrient-depleted surface layer and relatively nutrient-rich waters directly below it, with an emphasis placed on the extent to which these exchanges are constrained by local vertical density gradients (stratification). This view reflects the expectation that variability in stratification will alter the water column's resistance to convective overturning and vertical mixing and, by extension, the entrainment of deep nutrients toward the surface. Thus, a strengthening of stratification (due, for example, to warming or freshening at the sea surface) will depress vertical nutrient supply and, consequently, productivity, while a weakening of stratification (due to surface cooling or salinification) will enhance vertical nutrient supply and productivity [see Doney, 2006].

[3] This model of local stratification control has long provided a first-order explanation for the observed seasonal

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cycles of marine productivity in light-replete, nutrient-limited environments (as described by *Follows and Dutkiewicz* [2002]). In recent years, it has been extended to explain variability on interannual and longer timescales. A number of modeling studies, for example, have predicted that a warming climate will produce long-term reductions in new production at low and middle latitudes, through enhancement of upper ocean stratification, and a weakening of upward nutrient fluxes from depth [*Bopp et al.*, 2001; *Boyd and Doney*, 2002; *Sarmiento et al.*, 2004; *Schmittner*, 2005; *Cermeño et al.*, 2008; *Riebesell et al.*, 2009].

[4] Numerous observational analyses have also attributed historical fluctuations in global records of surface chlorophyll (a proxy for phytoplankton biomass) to stratification changes produced by climate-driven changes in the upper ocean's heat content (including *Gregg et al.* [2005], *Behrenfeld et al.* [2006], *Polovina et al.* [2008], *Irwin and Oliver* [2009], *Martinez et al.* [2009], *Vantrepotte and Melin* [2009], and *Boyce et al.* [2010]). Recent expansions of oligotrophic regions in the subtropics, for example, have been linked to interannual increases in sea surface temperature (SST) at mid-latitudes [*Polovina et al.*, 2008; *Irwin and Oliver*, 2009]. An analysis by *Behrenfeld et al.* [2006] explicitly demonstrates a negative correlation (increasing stratification/decreasing productivity and vice versa) between anomalies in spatially averaged, low-latitude and mid-latitude productivity (modeled from satellite chlorophyll-*a* or chl-*a*) and anomalies in spatially averaged stratification (evaluated as $\rho_{200}-\rho_0$ from reanalyzed T, S fields). The correlation is observed for the period 1997–2004, which spans the peak intensity and aftermath of the very strongly positive phase of the El Niño-Southern Oscillation (ENSO) in 1997–1998, seemingly confirming the expectation that stratification control of nutrient supply constitutes the primary mechanistic linkage between interannual climate variability and marine productivity at low and middle latitudes. More recently, this result has been extended to decadal scales by *Martinez et al.* [2009] who examine global spatial patterns in stratification (inferred from satellite measures of SST) and phytoplankton biomass (inferred from satellite chl-*a*) and conclude that up to 60% of the ocean area at low and middle latitudes has experienced opposite changes in the two quantities over the period 1979–2002.

[5] The expectation that productivity variability on interannual and longer timescales is driven by local stratification control of nutrient supply, however, is directly challenged by recent examinations of over two decades of in situ data from time series stations in the western subtropical North Atlantic (BATS program) and eastern subtropical North Pacific (HOT program). At both locations, interannual variability in local productivity has been shown to have essentially no correlative relationship with variability in local stratification over the observational record, 1988–2010 [*Dave and Lozier*, 2010; *Lozier et al.*, 2011]. These analyses of time series station data provide a rigorous test of the local stratification control model, since they make a direct comparison of in situ stratification data (as opposed to reanalysis data or satellite SST, used in previous studies) and productivity values measured at the same time and place. Yet the results can only provide definitive information for a single location in the ocean. Extending the

analysis to the basin-scales and global-scales entails comparison of similarly contemporaneous stratification and productivity (or biomass) measures drawn from large spatial data sets, an undertaking that has until recently been hampered by a shortage of available data. The advent of satellite ocean color measurements and the proliferation of hydrographic profiles from autonomous floats and other observing platforms over the last decade, however, has greatly expanded the number of contemporaneous measurements of stratification and chlorophyll. *Lozier et al.* [2011] take full advantage of this development and match monthly SeaWiFS chl-*a* data from the subtropical North Atlantic with individual stratification values determined from over 35,000 profiles, demonstrating that variability in the two quantities is not strongly correlated on interannual timescales in this basin over the period 1997–2009. Similar results are obtained for a range of different measures of stratification and productivity, and also when the data are simply averaged over the spatial domain at each time step.

[6] These results suggest that the correlations between globally averaged stratification and productivity reported previously do not apply everywhere and instead reflect strong associations in a particular region. An interesting question, therefore, is which region this might be. In the subtropical North Pacific, the impact of stratification variability on productivity has previously been assessed at a single time series station [*Dave and Lozier*, 2010], with the observed lack of correlation there being suggested to reflect weakness in the interannual physical forcing at that location. It remains an open question, however, whether extending the analysis across this basin to incorporate regions where the interannual forcing is stronger would produce the same result. Moreover, no comparison of interannual stratification and productivity variability has yet been made in any of the other subtropical basins, or for the tropical ocean. A test of the relationship seems especially warranted in the tropics since this region bears the strongest footprint of ENSO variability, which is a dominant component of variability in global records of ocean temperature and productivity [*Behrenfeld et al.*, 2006; *Martinez et al.*, 2009]. This study therefore addresses the question: How has interannual variability in productivity in the global low-latitude and mid-latitude ocean been impacted by variability in local stratification?

2. Comparison of Stratification and Productivity Variability

2.1. Linking Stratification and Chl-*a*

[7] This analysis is primarily directed toward examining the relationship between stratification and marine productivity variability in the tropics and subtropics, that is, in relatively strongly stratified and light-replete waters at low and middle latitudes where productivity variability can generally be assumed to be nutrient limited. For consistency with previous analyses linking stratification and marine productivity [*Behrenfeld et al.*, 2006], the spatial domain for this study (hereafter referred to as the global domain) consists of all waters bounded by the climatological 15°C isotherm, which matches very closely with the climatological position of the poleward 2 mmol m⁻³ isolines for surface nitrate concentration (see Figure 1) and

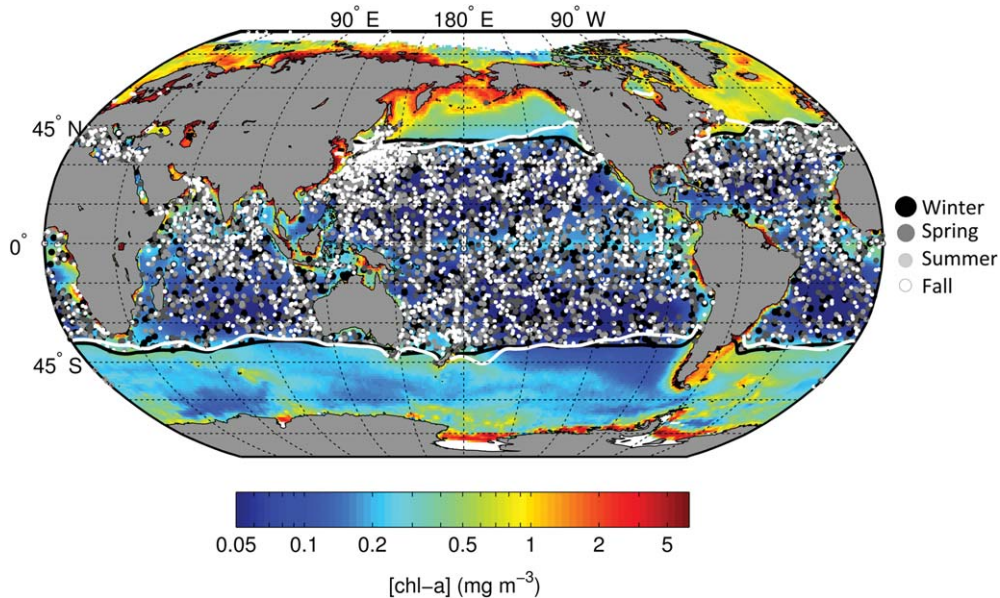


Figure 1. Annual mean SeaWiFS chlorophyll-*a* concentrations (chl-*a*, in units of mg m^{-3}) in the global ocean. The markers indicate the locations of the ~ 1.1 million hydrographic observations (shown at 1/200 actual density) obtained for the spatial domain of this study, that is all waters enclosed by the climatological 15°C isotherm (for consistency with *Behrenfeld et al.* [2006]). The black contour shows the 15°C isotherm and the white contour shows the 2 mmol m^{-3} isoline for surface nitrate concentration. The seasonal distribution of these profiles is indicated by their color: 29% in winter, 26% in spring, 21% in summer, and 24% in fall. Seasonal definitions for the Northern (Southern) Hemisphere are as follows: winter, JFM (JAS); spring, AMJ (OND); summer, JAS (JFM); and fall, OND (AMJ).

encompasses the oligotrophic regions (defined as all waters with climatological $\text{chl-}a < 0.1 \text{ mg m}^{-3}$) in all five major subtropical basins (North Atlantic, South Atlantic, North Pacific, South Pacific, and South Indian). Within this global domain, we assess productivity as the variability in phytoplankton biomass indicated by the SeaWiFS chlorophyll-*a* data set, which spans the period September 1997–December 2010. We assess stratification as the temperature differential between the sea surface and subsurface ($T_0 - T_{200}$, with the depth range chosen for consistency with *Lozier et al.* [2011] and *Behrenfeld et al.* [2006]) using data from 1,099,971 hydrographic profiles obtained over this domain for the same time period. A description of the methods used to obtain, quality control, and analyze the data, as well as a summary of the differences between our methodology and those of previous studies comparing stratification and productivity, is provided in Appendix A and the supporting information. Briefly, we compare stratification and chl-*a* variability by matching independent profile observations of stratification with corresponding daily SeaWiFS chl-*a* data averaged within a “capture-radius” defining a region over which the associated profile measurement is representative. Thus paired, the profile and satellite ocean color data provide over 13 years of contemporaneous measurements that represent seasonal and interannual variability in all the major subtropical basins (see supporting information Figures S1–S4). To assess interannual variability, we subtract the local climatological monthly mean from individual profiles and their associated chl-*a* values and then average the resulting anomalies for each month of each year within 810 separate $5^\circ \times 5^\circ$ subdomains spanning the global domain.

2.2. Temporal Trends and Spatial Patterns

[8] A calculation of the temporal trends in global domain-averaged stratification and chl-*a* over the SeaWiFS period, 1997–2010, reveals a statistically significant ($p < 0.05$) negative trend in stratification but no significant trend in chl-*a* (Table 1). The weakening of stratification is somewhat surprising given the well-documented increase in global upper ocean heat content that has occurred over the past decade, due in part to greater radiative heating at the surface [*Levitus et al.*, 2009; *von Schuckmann et al.*, 2009; *von Schuckmann and Le Traon*, 2011]. The spatial representativeness of this global, negative stratification trend is evidenced by its persistence when the calculation is repeated using data that have been averaged over all oligotrophic waters and also in the individual oligotrophic regions within each of the five major subtropical basins (Table 1).

[9] By contrast, the long-term signal (or lack thereof) in global domain-averaged chl-*a* is not spatially representative. When the calculation is repeated using data averaged within the entire oligotrophic ocean, a significant negative trend emerges, although we note that this trend is able to explain relatively little ($\sim 15\%$) of observed interannual variability. Moreover, when the data are averaged within the oligotrophic regions of the five subtropical basins, a significant negative trend is observed only in the subtropical North Pacific and South Indian basins, while the other basins exhibit no significant trends. Thus, in waters where nutrient limitation is expected to be the strongest, the long-term trends in stratification and chl-*a* either have no association or have the

Table 1. Statistically Significant ($p < 0.05$) Trends in Profile-Measured Stratification and Satellite chl- a in the Oligotrophic Regions of the Major Subtropical Basins, and also the Global Low-Latitude and Mid-latitude Domain Used for This Study^a

Subtropical Basin	Stratification (T_0-T_{200})			[Chl- a]		
	Trend ($^{\circ}\text{C yr}^{-1}$)	r^2 (Var. Explained)	n (Months)	Trend ($\text{mg m}^{-3} \text{ yr}^{-1}$)	r^2 (Var. Explained)	n (Months)
North Atlantic	-1.3×10^{-2}	0.06	160			153
South Atlantic	-2.3×10^{-2}	0.22	160			153
North Pacific	-2.6×10^{-2}	0.16	160	-3.8×10^{-4}	0.32	153
South Pacific	-4.5×10^{-2}	0.54	160			153
South Indian	-3.8×10^{-2}	0.44	160	-5.7×10^{-4}	0.21	153
All oligotrophic	-3.2×10^{-2}	0.57	160	-1.8×10^{-4}	0.15	153
GLOBAL	-4.4×10^{-2}	0.66	160			153

^aStatistics are obtained from a linear least squares regression model applied to area-weighted, monthly anomaly time series (see supporting information). Similar results are observed when an alternate measure of stratification (T_0-T_{100} , T_0-T_{150}) is used. Absent values indicate that there is no significant trend; “ n ” indicates the number of monthly time steps for which there are data.

same sign, a result that is clearly inconsistent with the local stratification control model. Our trend analysis thus yields two initial sets of observational results: (1) trends in stratification and chl- a do not have an observable association at the global scale but appear to be positively associated in some oligotrophic basins and (2) stratification appears to be decreasing across the low-latitude and mid-latitude ocean, even as the ocean is being warmed from above.

[10] To further explore the first result, we examine spatial maps of stratification and chl- a trends within the 5° subdomains of our global domain (Figure 2). The maps reveal distinct spatial patterns in the sign, strength, and significance of trends for each property and clearly demonstrate that the spatial averaging of data even at the basin scale results in the loss of important spatial information about these trends. For stratification, significant trends are observed in 287 out of 810 subdomains, accounting for 31% of the area of our global domain and distributed mostly across the lower latitudes of the Atlantic, Pacific, and Indian sectors. For chl- a , significant trends are observed in 293 subdomains, also accounting for 31% of the area of our global domain but distributed closer to the mid-latitudes and along the peripheries of the basins. These patterns exhibit very little spatial overlap: whereas 476 of 810 subdomains (51% of the global domain area) exhibit significant trends in either stratification or chl- a , only 104 subdomains (11% of the global domain area) are characterized by significant trends in both properties. A scatter comparison also shows no clear relationship between the sign of the stratification and chl- a trends in the subdomains, regardless of whether the trends are significant or nonsignificant and also regardless of whether or not the subdomains lie in oligotrophic regions, where productivity would be expected to be most sensitive to delivery of allochthonous nutrients from depth (Figure 3). In other words, even in basins where there are concurrent, significant trends in the time series of basin-averaged stratification and chl- a variability (see Table 1), the absence of locally concurrent trends at the scale of the subdomains indicates the absence of a strong mechanistic connection between the two.

[11] This result stands in contrast to previous comparisons of the spatial patterns and long-term trends in stratification and marine productivity over the global ocean,

which indicate that a large portion of the ocean’s area, up to 60%, is marked by opposite sign changes in the two properties [Behrenfeld *et al.*, 2006, see Figure 3; Martinez *et al.*, 2009, Figure 1]. The analysis presented here, however, indicates that not more than 352 of 810 subdomains in the global domain (accounting for 37% of the area of the global domain for this study) exhibit opposite sign changes, and in only 39 (4% of the global domain area) of these domains are both trends significant (Figure 4). We note that our comparison is based on stratification data measured in situ, whereas in the previous studies stratification was either estimated using reanalyzed density fields or inferred from remotely sensed SSTs. In addition, the trends calculated here are based on the application of a linear regression model, whereas the previous analyses calculate simple differences in property fields on either side of a time interval, and do not specifically address the statistical significance of those differences.

[12] The second observation from the global trend analysis is perhaps the most interesting and seemingly contradictory feature of the long-term changes observed in our data set, a decrease in average stratification for the global domain that coincides with a well-documented warming of the upper ocean over the same period. The spatial map of stratification trends within the 5° subdomains of our global domain (Figure 2a) reveals that long-term decreases in stratification are observed in 644 of 810 subdomains, accounting for 69% of the area of our global domain, although we note that the negative trends are significant in only 270 subdomains (30% of the global domain). Our examination of the temperature trends at the surface and in the subsurface over our 5° subdomains (Figure 5) reveals an intriguing detail: the temperature changes in the subsurface are generally more positive than at the surface over much of the global ocean, regardless of whether the trends are significant or nonsignificant or whether the subdomains lie in oligotrophic or nonoligotrophic regions (see also supporting information Figure S5). In other words, even though temperatures in the upper ocean are generally increasing almost everywhere, the subsurface is warming at a faster rate than the surface. This result thus demonstrates that a warming of the upper ocean does not necessarily result in strengthened stratification, challenging a basic assumption of the local stratification control model.

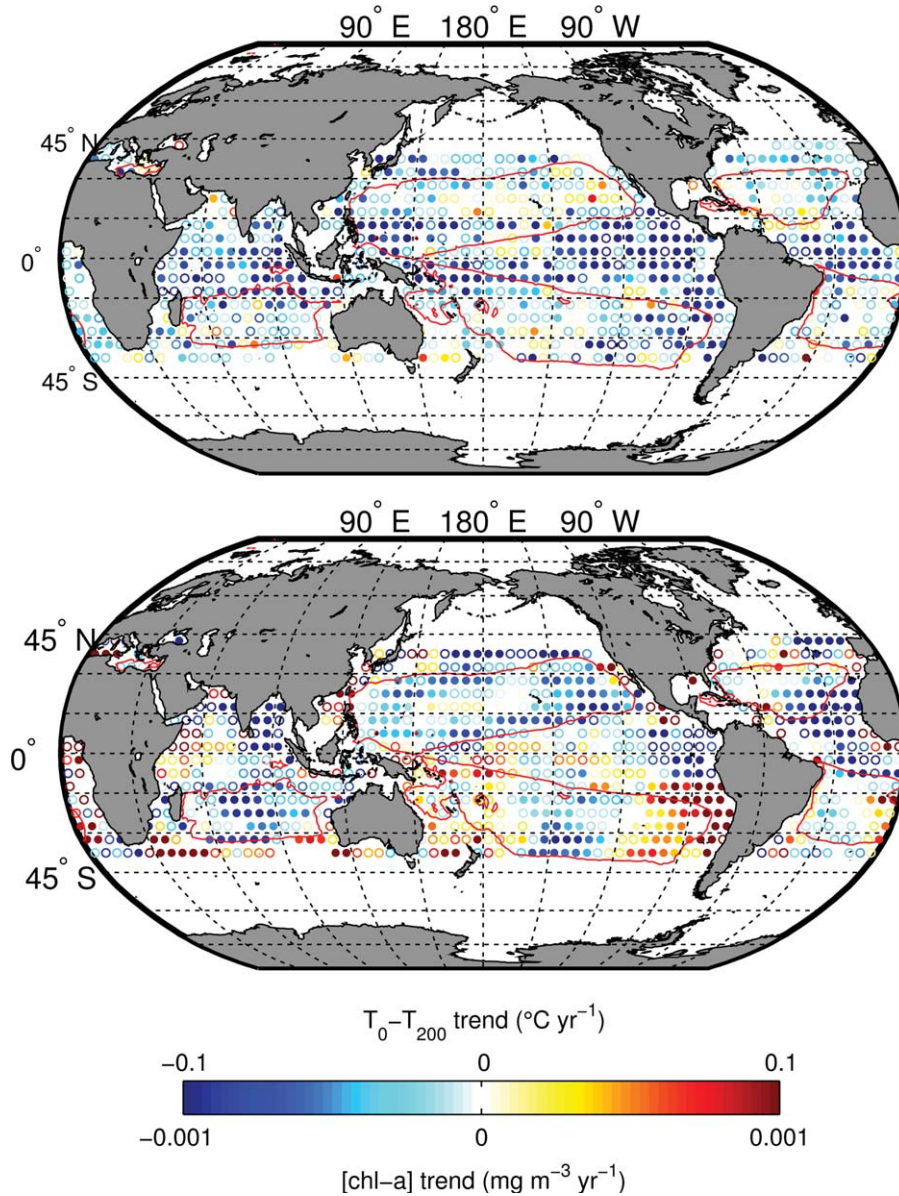


Figure 2. Trends in (a) profile measures of stratification ($T_0 - T_{200}$) and (b) SeaWiFS chl-*a* within $5^\circ \times 5^\circ$ subdomains for the period 1997–2010. The circles show subdomains in which there are at least 50 months of profile stratification data. The color of each circle indicates the trend in each property, with warmer colors reflecting positive trends and cooler colors reflecting negative trends. Filled circles indicate subdomains in which trends are statistically significant ($p < 0.05$). The red contours delineate the climatological boundaries of the major oligotrophic regions. The time series were constructed by subtracting the corresponding long-term monthly mean from every profile value, then averaging these local anomalies within each subdomain in each month. After removing outliers, trends were determined by applying a linear least square regression model to each anomaly time series (see supporting information). Similar spatial patterns are observed when shallower metrics for stratification (e.g., $T_0 - T_{100}$, $T_0 - T_{150}$) and profile-captured chl-*a* values are used. The global patterns in chl-*a* trends are similar to those reported by *Henson et al.* [2010].

2.3. Interannual Correlations

[13] In their analysis of the impact of climate forcing on marine productivity, *Behrenfeld et al.* [2006] demonstrate a strong negative correlation ($r = -0.85$, $p < 0.05$) between time series of globally averaged stratification and net primary productivity (NPP) variability over the first half of the SeaWiFS record (1997–2004) which spans the peak

intensity and aftermath of the very strong 1997–1998 El Niño event [see *Behrenfeld et al.*, 2006, Figure 2b]. When we repeat this comparison over the same spatial and temporal domain using our profile-measured stratification data and profile-captured chl-*a* data, a negative association is also observed ($r = -0.63$, $p < 0.05$, see Figure 6g). We note that the correlation calculated using the profile data is

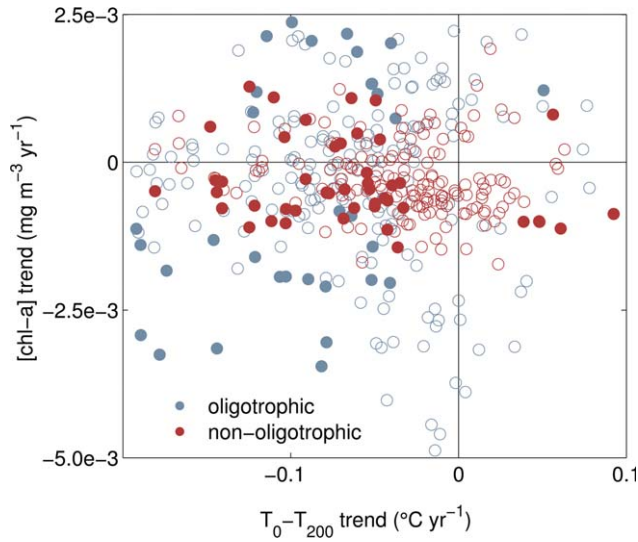


Figure 3. Trends of anomalies in stratification (T_0-T_{200}) versus trends of anomalies in SeaWiFS chl- a within the $5^\circ \times 5^\circ$ subdomains, where at least one property trend is significant. Red circles indicate subdomains lying in the oligotrophic regions ($[\text{chl-}a] < 0.1 \text{ mg m}^{-3}$), whereas blue circles indicate subdomains in nonoligotrophic regions. Filled circles indicate subdomains where both stratification and chl- a trends are statistically significant. A similar result is obtained when shallower metrics for stratification (e.g., T_0-T_{100} , T_0-T_{150}) are used.

weaker than the correlation previously reported by *Behrenfeld et al.* [2006], and that this difference is perhaps attributable to the fact that the earlier analysis compares stratification with estimates of marine productivity that incorporate SST data [*Behrenfeld and Falkowski*, 1997].

[14] A significant, albeit weaker, negative correlative relationship is also observed when detrended variability in profile stratification and chl- a data are compared over the full span of the SeaWiFS record (1997–2010: $r = -0.34$, $p < 0.05$, see Figure 6g). The relative weakness of this association suggests that strong ENSO forcing during the first half of the record played an important role in driving the observed global correlations between stratification and productivity. Nonetheless, the persistence of a significant, negative association over the entire data set is apparently consistent with the expectation that stratification control of nutrient supply is a primary mechanistic linkage between interannual climate variability and marine productivity at low and middle latitude.

[15] As we transition to the basin scale, however, this global correlation breaks down. Time series comparison of detrended stratification and chl- a variability averaged within the oligotrophic regions of the five major subtropical basins corroborates the findings previously reported from subtropical time series comparisons at HOT and BATS and for the basin-wide comparison in the subtropical North Atlantic: the two properties are not correlated on interannual scales (Figures 6a–6f). A scatter comparison of seasonal stratification and chl- a averaged globally over all the

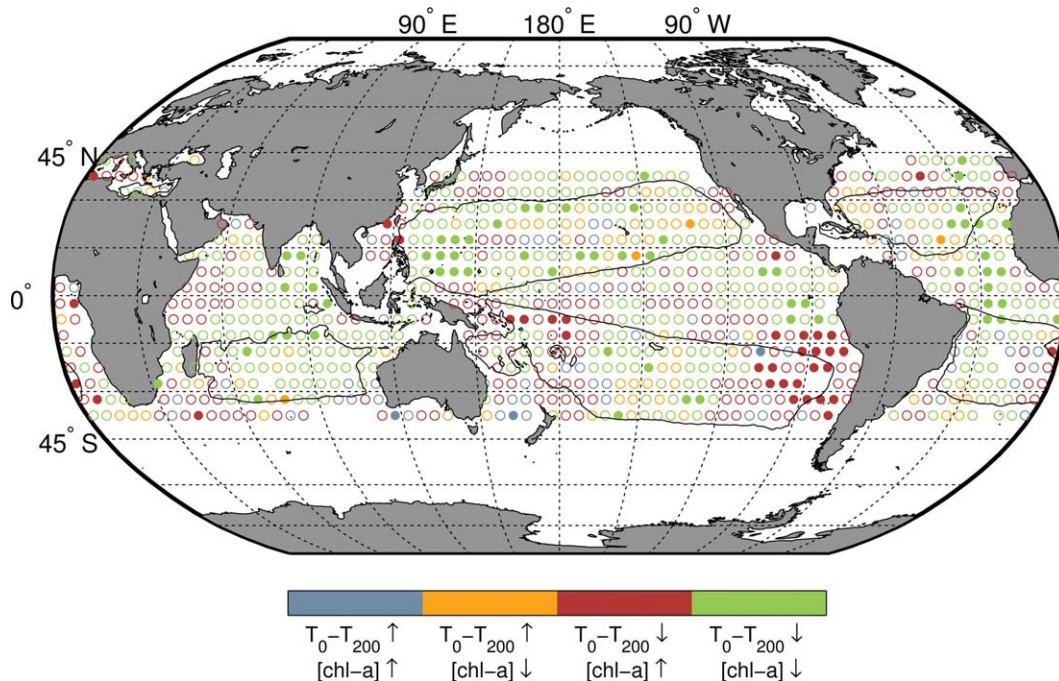


Figure 4. Trends in profile measures of stratification (T_0-T_{200}) and SeaWiFS chl- a within $5^\circ \times 5^\circ$ subdomains for the period 1997–2010. The circles show subdomains in which there are at least 50 months of profile stratification data. The color of each circle indicates the relative signs of the trends in both properties. Filled circles indicate subdomains in which trends for both stratification and chl- a are statistically significant ($p < 0.05$). The black contours delineate the climatological boundaries of the major oligotrophic regions. Similar spatial patterns are observed when shallower metrics for stratification (e.g., T_0-T_{100} , T_0-T_{150}) and profile-captured chl- a values are used.

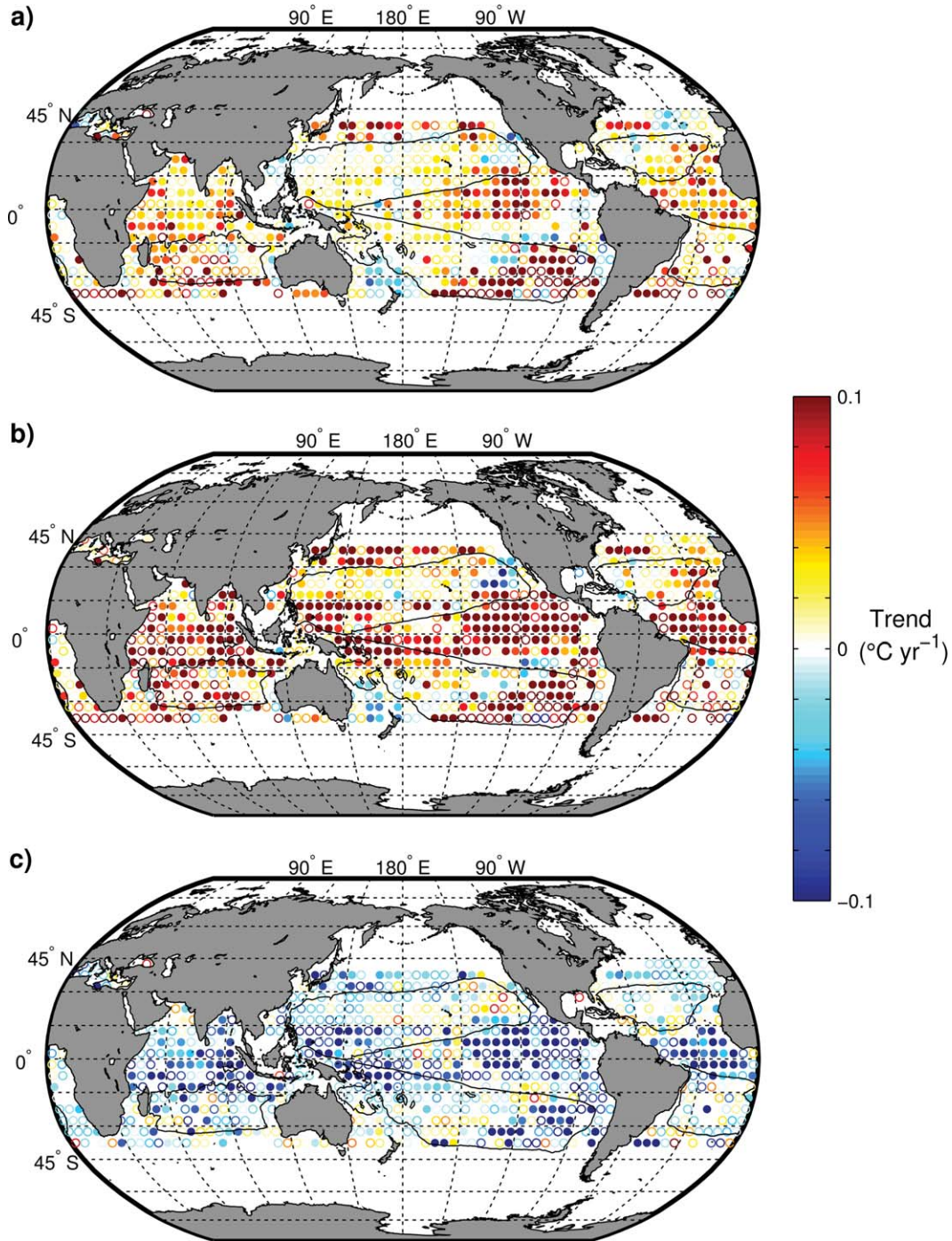


Figure 5. Trends in profile measures of (a) T_0 , (b) T_{200} , and (c) the difference in those trends (T_0 trend - T_{200} trend) within $5^{\circ} \times 5^{\circ}$ subdomains for the period 1997–2010. The circles show subdomains in which there are at least 50 months of profile stratification data. For Figures 5a and 5b, the color of each circle indicates the trend in each property, with warmer colors reflecting positive trends and cooler colors reflecting negative trends. For Figure 5c, warmer (cooler) colors indicate subdomains where the T_0 trend is more (less) positive than the T_{200} trend, that is, where the surface is warming more (less) rapidly than the subsurface. Filled circles indicate subdomains in which trends are statistically significant ($p < 0.05$). The black contours delineate the climatological boundaries of the major oligotrophic regions. Similar spatial patterns are observed when shallower metrics for stratification (e.g., $T_0 - T_{100}$, $T_0 - T_{150}$) and profile-captured chl-*a* values are used.

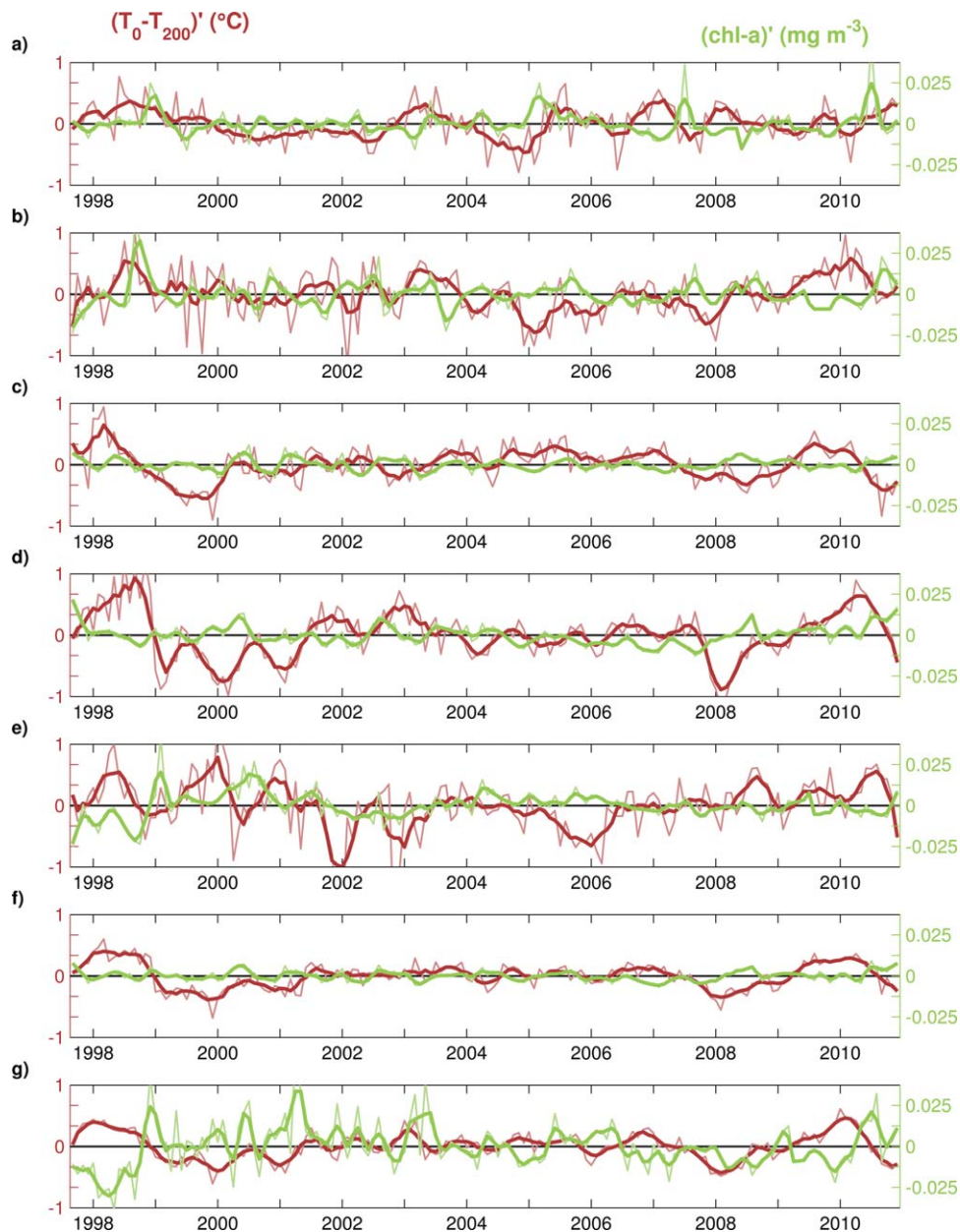


Figure 6. Detrended stratification and surface chl-*a* anomalies from September 1997 to December 2010 in the oligotrophic regions of the subtropical (a) North Atlantic, (b) South Atlantic, (c) North Pacific, (d) South Pacific, (e) South Indian ocean, (f) all oligotrophic regions, and (g) the global domain for this study. The time series show T_0-T_{200} anomalies ($^{\circ}\text{C}$, red), as measured by hydrographic profiles, and chl-*a* anomalies (mg m^{-3} , green), as measured by the “profile-captured” SeaWiFS data. Thin (bold) lines show monthly (5 month running) averages. For any and all oligotrophic regions (Figures 6a–6f), neither the unsmoothed nor smoothed time series exhibit a significant ($p < 0.05$) correlative relationship in any basin. For the global domain, the time series exhibit a significant negative correlation, as noted in the text. Similar results are obtained when stratification is assessed as T_0-T_{100} , and T_0-T_{150} , and when basin-averaged satellite chl-*a* values are used.

oligotrophic regions (Figure 7) again shows that, while stratification and chl-*a* exhibit the expected negative association seasonally (see the intergroup relationship), no significant correlations between the two properties are not observed within a particular season (see the intragroup relationships, $p > 0.05$ in all cases). Similar results are obtained when the chl-*a* data are simply averaged over the global

oligotrophic ocean at each time step and when satellite-derived productivity fields are substituted for chl-*a* (supporting information Figure S6). The lack of correlation thus indicates that chl-*a* variability in the global oligotrophic ocean has not been directly impacted by stratification variability over the recent observational record; this result stands in contrast with previous studies that have argued for a

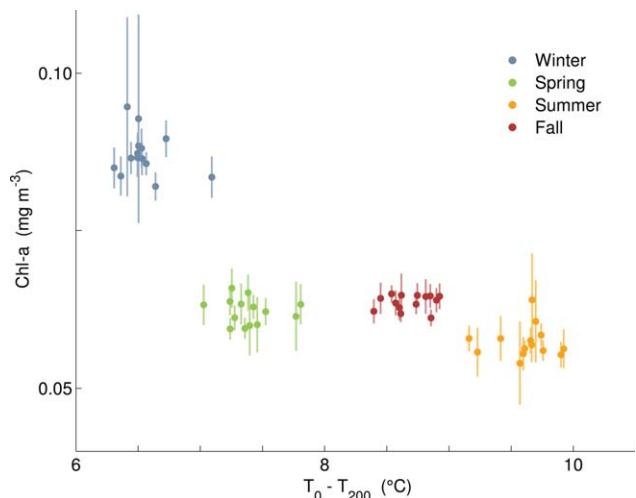


Figure 7. Seasonally averaged anomalies in stratification ($T_0 - T_{200}$) versus contemporaneous, profile-captured SeaWiFS chl-*a* from winter 1997–winter 2010 over all the major oligotrophic regions. The vertical bars show ± 5 standard errors for chl-*a*. Each seasonal value shown is produced by averaging the monthly anomalies shown in the previous figure for all subtropical basins and then adding the corresponding seasonal mean for the global subtropical ocean. The resulting points are colored to indicate the seasons, as defined in Figure 1. Northern and Southern Hemisphere data are offset by 6 months to allow for seasonal grouping. Within each seasonal grouping, there is no significant correlation between stratification and chl-*a* ($p > 0.05$).

linkage between stratification changes and oligotrophic variability [Polovina *et al.*, 2008; Irwin and Oliver, 2009].

[16] When the comparison is extended across the global domain for this study, we observe that only 70 of 810 subdomains, accounting for less than 8% of the area of the global domain for this study, exhibit a significant relative relationship able to explain more than 10% of the observed variance in chl-*a* (Figure 8). In the Southern Hemisphere associations between the two properties are generally weaker and/or mixed. By contrast, spatially coherent patterns of negative correlation are observed along the northern and northwestern oligotrophic boundaries in the North Pacific and, to a lesser extent, the North Atlantic. This pattern may suggest that biomass variability in the frontal zones separating the oligotrophic regions from more productive waters toward the north is relatively strongly impacted by interannual variability in local physical forcing, in contrast to the relatively quiescent interior portions of the oligotrophic regions. We note, however, the overall strength of the associations in these waters is still very low, with the majority of the correlations being able to explain less than 10% of observed chl-*a* variability. The one region that does exhibit a relatively strong, spatially coherent pattern of negative correlation is the central and western equatorial Pacific. This result provides compelling evidence that the global correlations reported by Behrenfeld *et al.* [2006] are largely a reflection of ENSO-driven variability in this region. This argument is bolstered by a comparison of local variability stratification and chl-*a* with the globally averaged signals for each property. In each

case, the global signal is most strongly positively correlated to changes occurring in the equatorial Pacific (Figure 9).

[17] We note that stratification varies between ocean basins, as evidenced by the fact that seasonal $T_0 - T_{200}$ values averaged over all the oligotrophic regions ($\sim 6.5 - 10.5^\circ\text{C}$, see Figure 7) are generally stronger than those averaged from the North Atlantic ($\sim 3 - 8.5^\circ\text{C}$) [see Lozier *et al.* 2011, Figure 3b]. Thus, the same measure of stratification may not be appropriate everywhere; in more strongly stratified basins, shallower metrics may be more suitable. Repetition of our analyses using temperature differentials between the surface and 100 and 150 m produces essentially the same results, that is, no interannual association between time series of spatially averaged chl-*a* and stratification variability in any of the subtropical basins, as well as a global spatial pattern of correlations showing very few subdomains with strong associations, primarily focused in the tropical Pacific. Essentially, the same results are obtained when stratification is assessed as $\rho_{200} - \rho_0$. A similar absence of evidence for a strong stratification control is observed when the daily chl-*a* fields are lagged to account for phytoplankton response to stratification variability or when the chl-*a* tendency is calculated by differencing the contemporaneous and lagged chl-*a* values. A wide range of metrics thus indicate that local, interannual stratification variability has not significantly impacted marine productivity over the observational record.

2.4. Alternatives to Local Stratification Control

[18] Why are interannual stratification and chl-*a* variability not locally correlated everywhere in our spatial domain? Predictions of long-term changes in marine productivity in response to interannual and decadal variability in stratification of low-latitude and mid-latitude waters reflect an assumption that the strength of nutrient fluxes into the surface layer on these timescales is determined by the local stratification. The absence of a strong historical interannual association between stratification and productivity, however, highlights two important considerations that undermine an argument for local stratification control of nutrient supply. The first is that stratification variability by itself does not predetermine the strength of vertical mixing; other processes that destroy the stratification and introduce mixing energy into the surface layer are also important. The dependence of nutrient supply on these factors is indicated by recent studies reporting correlations between subtropical productivity and variability in local buoyancy and wind forcing, both metrics from which the extent of vertical mixing can be inferred [Follows and Dutkiewicz, 2002; Ueyama and Monger, 2005; Henson *et al.*, 2009; Kahru *et al.*, 2010]. In all these studies, however, the correlative relationships between subtropical productivity and metrics for vertical mixing are at best moderately strong and able to explain only a small fraction of observed productivity variability. The analysis of time series station data in the subtropical North Atlantic and North Pacific by Lozier *et al.* [2011] and Dave and Lozier [2010] further demonstrates that metrics explicitly taking into account variability in vertical mixing, such as local mixed layer depth, are very weakly correlated with productivity variability. Variability in vertical mixing (or the metrics from which it is inferred) thus cannot be assumed to be the sole

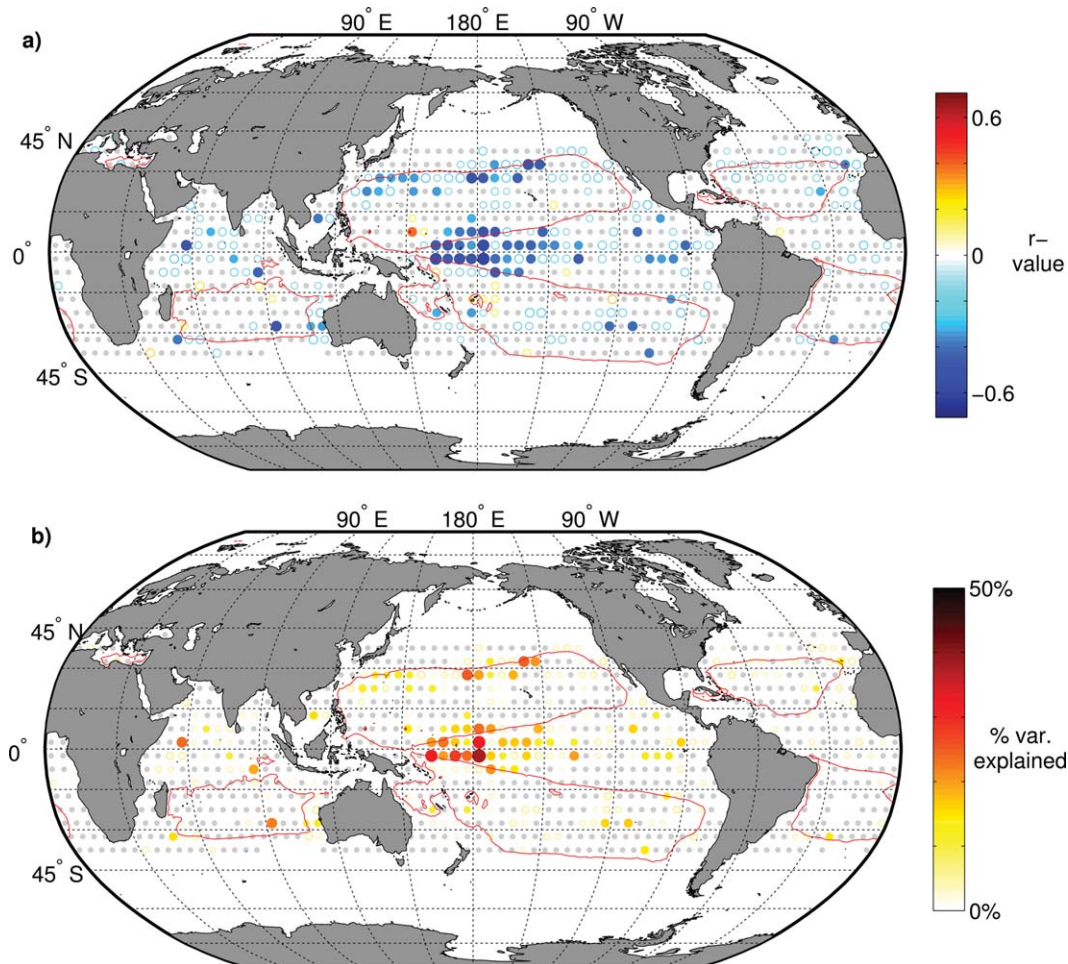


Figure 8. Correlations of detrended stratification and surface chl-*a* anomalies in $5^\circ \times 5^\circ$ subdomains. (a) The local, temporal correlations between anomalies in profile measurements of T_0-T_{200} and profile-captured chl-*a* data. The dots show subdomains in which there are at least 50 months of data (>80% of subdomains meet this criterion). The gray dots indicate nonsignificant correlations ($p \geq 0.05$). The colored dots indicate the significant correlations, with warmer colors reflecting a positive correlation (increasing stratification, increasing chl-*a*), and cooler colors reflecting a negative correlation (increasing stratification, decreasing chl-*a* and vice versa). The size of each dot is linearly scaled with the r value. Open circles indicate correlations that are significant but for which less than 10% of total chl-*a* variance is explained. (b) The percent of chl-*a* variance that can be explained by stratification variability in each subdomain. The size of each dot is linearly scaled with the r^2 value. In Figures 8a and 8b, the red lines delineate the climatological boundaries of the major oligotrophic regions.

predictor of interannual variability in nutrient supply and productivity in the subtropics.

[19] A second point with regard to local stratification control and the physical controls on nutrient supply, then, is that lateral inputs of nutrients from other locations may also be important. Previous studies have demonstrated the significant contributions of subsurface and surface horizontal advection to the climatological nutrient supply and biomass distributions in the subtropical North Atlantic [Williams and Follows, 1998; McClain *et al.*, 2004; Palter *et al.*, 2005] and to seasonal productivity variability in the subtropical North Pacific [Ayers and Lozier, 2010]. These horizontal processes, moreover, may also impact local stratification by producing lateral fluxes of heat. For example, horizontal convergence of cold, nutrient-rich waters might be expected to enhance biomass and also to weaken

local stratification by lowering temperatures at the surface. In other words, even in places where stratification and productivity are covarying in a manner that is consistent with the local stratification control model (weaker stratification/higher productivity and vice versa), the connection may not necessarily be causal. This masking effect may potentially play an important role in the one ocean region where our analysis uncovers strong negative correlations between stratification and productivity, the equatorial Pacific, which is a region that experiences substantial interannual changes in the horizontal transport of heat and nutrients.

3. Conclusion

[20] Improvements in the spatial and temporal coverage of modern observational data provide an opportunity to

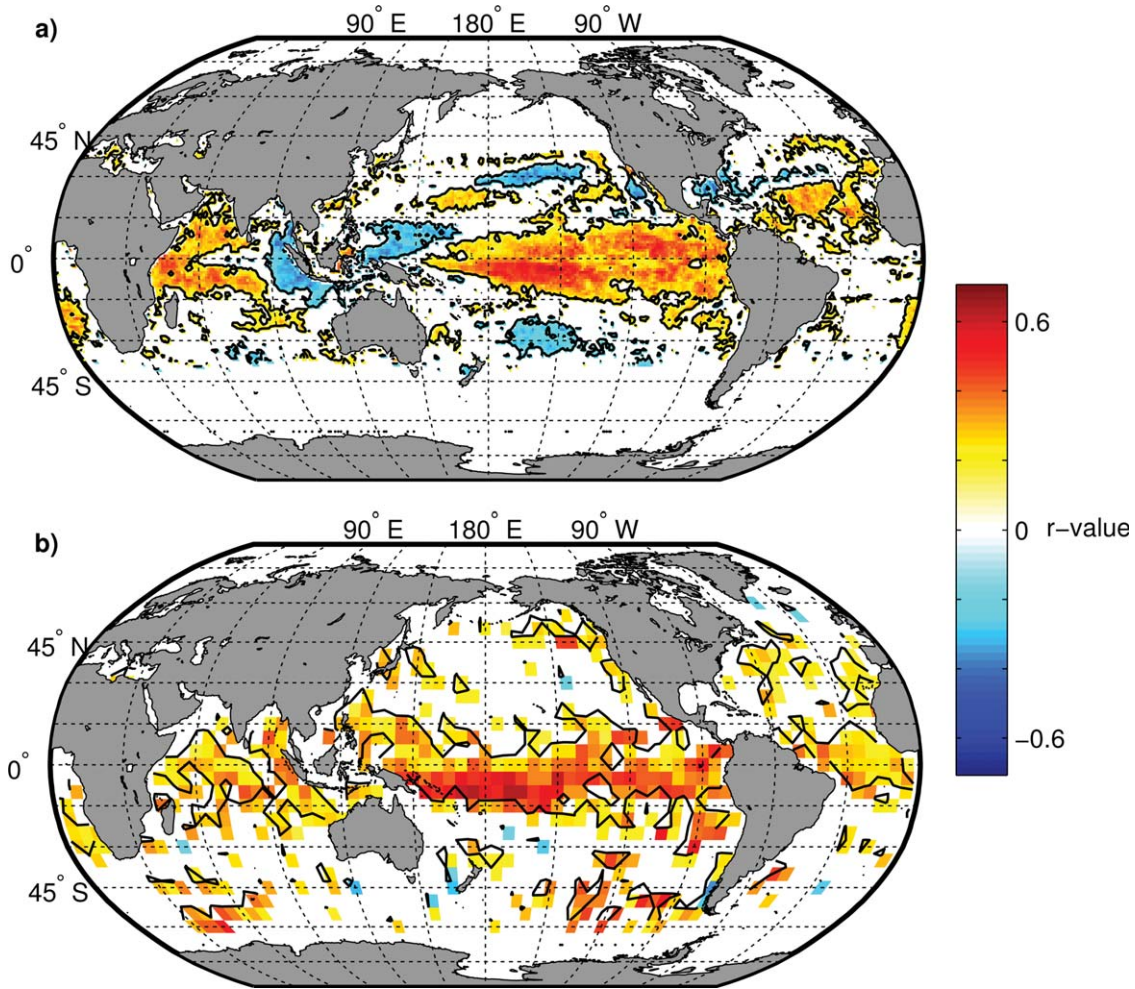


Figure 9. A comparison of detrended global and local chl-*a* anomalies. The map shows the temporal correlation of local variability in (a) SeaWiFS chl-*a* and (b) stratification (measured as $T_0 - T_{200}$) with time series constructed by averaging local anomalies over all waters equatorward of the climatological 15°C isotherm at each time step. Colored areas of the map indicate pixels where the correlation is statistically significant ($p < 0.05$). Warmer colors reflect a positive association (local chl-*a* or stratification is covarying with the globally averaged signal), whereas cooler colors reflect a negative association (local chl-*a* or stratification is anticorrelated with the global signal). The strongest positive correlative relationship is observed in the equatorial Pacific, while the subtropical basins are characterized by weak and mixed correlations.

test, at a global scale, a prevailing view regarding the environmental controls on marine primary productivity, namely that interannual variability in the vertical delivery of nutrients to primary producers is prescribed by changes in local stratification, and therefore that variability in stratification and productivity in the generally light-replete, low-latitude and mid-latitude ocean should be expected to exhibit a negative correlative relationship (stronger stratification/lower productivity and vice versa). Our analysis uses a range of metrics based on 13 years of in situ observations of stratification and contemporaneous satellite measures of ocean chl-*a* over the low-latitude and mid-latitude ocean to demonstrate that, although a significant negative correlation on interannual timescales is indeed observed for globally averaged data, this correlation breaks down at basin and smaller scales. Less than 8% of the ocean within the global domain for this study exhibits a statistically significant

correlation that is able to explain more than 10% of the observed variance in chl-*a*. In other words, local stratification variability does not appear to drive productivity variability on interannual scales over the modern observational record. The one region in which a strong, spatially coherent pattern of negative correlations is observed between stratification and chl-*a* variability is the equatorial Pacific, suggesting that strong associations in this region are responsible for the global correlations.

[21] Previous studies have also reported broad spatial patterns of opposing trends in stratification (inferred from reanalyzed hydrographic fields or SST data) and productivity across the global ocean, with the trends being determined from simple differences in property fields on either side of the time interval being analyzed. Our analysis applies a linear regression model to demonstrate that, although long-term trends in globally averaged stratification and chl-*a* are

observed in over half of the subdomains spanning the global domain, the spatial patterns of these trends are not well matched. Little more than a third of the global domain exhibits trends of opposite sign, and in only 4% of the global domain are the trends both opposite and statistically significant. An additional, intriguing feature of the long-term changes observed in our data set is the observation that stratification is trending downward across a significant portion of the global domain at the same time as SSTs are trending higher. Our analysis reveals that this is due to a faster rate of warming in the subsurface relative to the surface. This result challenges another fundamental assumption of the local stratification model, namely that warming of the upper ocean will result in increases in the strength of local stratification.

[22] Correlations of productivity variability with interannual and decadal-scale climate processes, ranging from ENSO to the Atlantic Multidecadal Oscillation, have been widely reported from both in situ studies [e.g., *Karl et al.*, 1995, 2001; *Dore et al.*, 2002; *Corno et al.*, 2007; *Bidigare et al.*, 2009] and from analyses of global fields [e.g., *Behrenfeld et al.*, 2006; *Martinez et al.*, 2009; *Boyce et al.*, 2010]. The correlations have generally been interpreted as reflecting a mechanistic connection between climate-driven changes in upper ocean heat content, local stratification and nutrient supply, a chain of causality that is directly challenged by the results of this study. Since these climate processes involve large-scale reorganizations of the atmospheric and oceanic circulation and their associated transports of heat and nutrients, not just changes in local stratification and mixing, we suggest that an examination of the role of nonlocal controls on heat and nutrient supply to the low-latitude and mid-latitude euphotic zone may provide promising avenues for future investigations of the environmental factors driving marine productivity variability.

Appendix A

A1. Data Description

[23] To assess interannual variability in upper ocean stratification, we use profile data obtained from the World Ocean Database (<http://www.nodc.noaa.gov/OC5/SELECTdb-search/dbsearch.html>). A total of 1,099,971 profiles have been retrieved, from five observing platforms: CTD data (38,856 profiles), moored buoys (341,332), ship-based ocean station data (19,730), profiling floats (443,173), and expendable bathythermographs (256,880). Temperature data are far more numerous than salinity data, so stratification is assessed as the temperature difference between the surface (0 m) and the subsurface (100, 150, or 200 m).

[24] To assess the spatial coverage of our hydrographic profile data, we use annual and monthly climatological fields from the World Ocean Atlas 2009 (WOA09, http://www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html) and monthly fields from the Simple Ocean Data Assimilation 2.1.6 reanalysis (SODA, <http://soda.tamu.edu>) [*Carton and Giese*, 2008]. Our analysis shows that stratification time series constructed by subsampling the WOA09 and SODA fields using the individual profile locations accurately capture the seasonal and interannual stratification

variability in each of the major subtropical basins, with coverage being somewhat better in the northern hemisphere (supporting information Figures S1 and S2). Our conclusion that the profile data adequately capture interannual variability is based on an assumption that the spatial gradients in the SODA fields are similar to that of the real ocean.

[25] To assess marine phytoplankton biomass, we use daily and monthly fields of chl-*a* concentrations from the SeaWiFS data set (<http://oceandata.sci.gsfc.nasa.gov/SeaWiFS/>). To assess rates of primary production, we use monthly fields of NPP estimated using the widely used Vertically Generalized Productivity Model (VGPM, <http://www.science.oregonstate.edu/ocean.productivity/>) [*Behrenfeld and Falkowski*, 1997].

A2. Linking Stratification and Chl-*a* Using Capture Radii

[26] Each hydrographic profile is matched with an average value for all the SeaWiFS pixels that lie within one baroclinic Rossby radius of the profile's location, a spatial area over which the profile measurement is considered representative. This averaging approach addresses concerns over potential biases created by single-point interpolations in ocean color fields with strong, small-scale heterogeneities (patchiness). The Rossby radius around each profile is calculated by interpolating values from a global climatology [*Chelton et al.*, 1998]. At very low latitudes ($<10^\circ\text{N}$ or S), the radii are sufficiently large such that overlap between profiles becomes an issue, and we cap their length to 100 km. To ensure that our profile observations are independent of each other (i.e., are sufficiently far apart in space and time so that they do not sample the same chl-*a* pixels), we eliminate any profile that lies within 2 days and 2 Rossby radii of a "higher priority" profile. In the case of a conflict, we define the higher priority profile as the one that has captured the greater amount of chl-*a* data. In this manner, we identify 485,434 independent profile measurements within our global domain. Our analysis demonstrates that the profile-captured chl-*a* values are able to accurately describe seasonal and interannual chl-*a* variability in the subtropical basins (supporting information Figures S3 and S4). In addition to pairing each profile with contemporaneous SeaWiFS data (within ± 1 day of each cast), we also use chl-*a* values after 6–8 days, a lag roughly corresponding to the expected response time of primary production to a change in local stratification. In addition, we calculate the chl-*a* "tendency" (i.e., the difference between lagged and contemporaneous values) to test for a chl-*a* response to a given stratification anomaly.

A3. Calculating Interannual Variability

[27] To avoid potential biases arising from changes in the spatial distribution of the profiles with time, we calculate local stratification and chl-*a* anomalies for each profile by subtracting values interpolated to the location of each profile from the corresponding WOA09 and monthly climatological SeaWiFS fields. The local anomalies are then grouped into $5^\circ \times 5^\circ$ subdomains spanning the global spatial domain (described in 2.1) and, if there are a sufficient

number of anomalies ($n > 10$), outliers are removed using a 2.3σ (99%) threshold. The remaining anomalies are spatially averaged within each 5° subdomain for each month of each year to produce time series of the average anomalies. To create time series for the comparisons of stratification and chl-*a* within each subtropical basin (see Table 1, Figures 5 and 6 in the main text), we also calculate the area-weighted average value for all the 5° subdomains at every month. Our results are robust for time series that are either unsmoothed or smoothed using 3 month or 5 month running means.

A4. Calculation of Trends and Spatial Correlations

[28] We calculate long-term trends in stratification and chl-*a* by applying a linear least squares regression model to the interannual time series for each property. The chl-*a* trends are robust regardless of whether they are calculated from the subdomain-averaged, profile-captured data (5°) or directly from the granular ($1/12^\circ$) satellite fields. Wherever a time series is identified as “detrended,” the linear trend has been subtracted from the data. Trends and temporal correlations are calculated using all 5° subdomains for which there are a sufficient number of measurements. The criteria applied here is for there to be at least 50 months of profile data, out of a total 160 months. Of 941 total subdomains within our global domain, 810 (~85%) meet this criterion. Of these 810 subdomains, 800 (99%) contain data that span at least 120 months (10 years). We note that the trends and correlations reported in this study do not change significantly when the criteria is reduced or increased by a factor of 2 (e.g., to 25 or 100 months, see supporting information Tables S1–S3). The spatial coverage of the data, however, does sharply decline for the more stringent criteria: a requirement of ≥ 50 months largely excludes subdomains in coastal and marginal waters near Southeast Asia, the Indonesian Archipelago and in the Caribbean, whereas a requirement of ≥ 100 months excludes large portions of the open ocean (including oligotrophic regions) in the Southern Hemisphere. Thus, to preserve adequate spatial coverage in these waters, we selected the criteria of ≥ 50 months.

A5. Differences With Previous Studies Examining Stratification and Productivity

[29] This study builds on previous assessments of stratification and productivity variability (most notably by Behrenfeld *et al.* [2006] and Martinez *et al.* [2009], hereinafter B06 and M09) by applying an improved test of the local stratification control model. Briefly, our approach differs from that of B06 and M09 in five main ways: (1) we examine the period 1997–2010, whereas B06 examine the period 1997–2004 and M09 examine the period 1979–2002, (2) we test for a local correlation between stratification and productivity by matching individual profiles with contemporaneous and colocated values of chl-*a*, whereas B06 present a correlation of stratification and productivity time series constructed from spatially averaged data, (3) our trends are calculated using linear regression models, whereas B06 and M09 calculate difference fields on either

side of a time interval, (4) we use actual, in situ stratification measurements from hydrographic profiles, whereas B06 assess stratification using gridded fields of ocean properties from the SODA ocean reanalysis and M09 infer stratification from satellite SST fields, and (5) we assess stratification as T_0-T_{200} (B06 use $\rho_{200}-\rho_0$) and infer productivity from the satellite chl-*a* data (B06 use modeled “VGPM” NPP fields). We use T_0-T_{200} since temperature measurements far outnumber salinity measurements in the profile data set and thus provide superior spatial and temporal coverage, although we note that substituting $\rho_{200}-\rho_0$ from profile data produces essentially the same results. We choose chl-*a* data over VGPM data, which incorporate SST information and thus are not completely independent from the stratification data.

[30] We note, however, that our results are not entirely contradictory to those of B06, who show that time series of spatially averaged NPP-stratification and SODA-stratification are strongly negatively correlated over their study domain for the period 1997–2004 (see Figure 2b in B06). We also observe this strong negative correlation when our stratification and chl-*a* data are similarly averaged over the global domain (see Figure 6g). The main difference between the analysis presented here and that of B06, then, lies in its interpretation of this result. This paper demonstrates that the global correlation is not spatially representative, but instead driven by a strong association in the equatorial Pacific region.

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References

- Ayers, J. M., and M. S. Lozier (2010), Physical controls on the seasonal migration of the North Pacific transition zone chlorophyll front, *J. Geophys. Res. Oceans*, 115, C05001, doi:10.1029/2009JC005596.
- Behrenfeld, M. J., and P. G. Falkowski (1997), Photosynthetic rates derived from satellite based chlorophyll concentration, *Limnol. Oceanogr.*, 42(1), 1–20.
- Behrenfeld, M. J., R. T. O'Malley, D. A. Siegel, C. R. McClain, J. L. Sarmiento, G. C. Feldman, A. J. Milligan, P. G. Falkowski, R. M. Letelier, and E. S. Boss (2006), Climate-driven trends in contemporary ocean productivity, *Nature*, 444(7120), 752–755, doi:10.1038/nature05317.
- Bidigare, R. R., F. Chai, M. R. Landry, R. Lukas, C. C. S. Hannides, S. J. Christensen, D. M. Karl, L. Shi, and Y. Chao (2009), Subtropical ocean ecosystem structure changes forced by North Pacific climate variations, *J. Plankton Res.*, 31(10), 1131–1139, doi:10.1093/plankt/fbp064.
- Bopp, L., P. Monfray, O. Aumont, J.-L. Dufresne, H. Le Treut, G. Madec, L. Terray, and J. C. Orr (2001), Potential impact of climate change on marine export production, *Global Biogeochem. Cycles*, 15(1), 81–99, doi:10.1029/1999GB001256.
- Boyce, D. G., M. R. Lewis, and B. Worm (2010), Global phytoplankton decline over the past century, *Nature*, 466(7306), 591–596, doi:10.1038/nature09268.
- Boyd, P. W., and S. C. Doney (2002), Modeling regional responses by marine pelagic ecosystems to global climate change, *Geophys. Res. Lett.*, 29(16), doi:10.1029/2001GL014130.
- Carton, J. A., and B. S. Giese (2008), A reanalysis of ocean climate using simple ocean data assimilation (SODA), *Mon. Weather Rev.*, 136, 2999–3017, doi:10.1175/2007MWR1978.1.
- Cermeño, P., S. Dutkiewicz, R. P. Harris, M. Follows, O. Schofield, and P. G. Falkowski (2008), The role of nutricline depth in regulating the

- ocean carbon cycle, *Proc. Natl. Acad. Sci. USA*, 105(51), 20344–20349, doi:10.1073/pnas.0811302106.
- Chelton, D. B., R. A. deSzoeke, M. G. Schlax, K. El Naggar, and N. Siwertz (1998), Geographical variability of the first Baroclinic Rossby radius of deformation, *J. Phys. Oceanogr.*, 28, 433–460, doi:10.1175/1520-0485(1998)028<0433:GVOTFB>2.0.CO;2.
- Corno, G., D. M. Karl, M. J. Church, R. M. Letelier, R. Lukas, R. R. Bidigare, and M. R. Abbott (2007), Impact of climate forcing on ecosystem processes in the North Pacific Subtropical Gyre, *J. Geophys. Res.*, 112(C4), doi:10.1029/2006jc003730.
- Dave, A. C., and M. S. Lozier (2010), Local stratification control of marine productivity in the subtropical North Pacific, *J. Geophys. Res.*, 115, C12032, doi:10.1029/2010JC006507.
- Doney, S. C. (2006), Oceanography—Plankton in a warmer world, *Nature*, 444(7120), 695–696, doi:10.1038/444695a.
- Dore, J. E., J. R. Brum, L. M. Tupas, and D. M. Karl (2002), Seasonal and interannual variability in sources of nitrogen supporting export in the oligotrophic subtropical North Pacific Ocean, *Limnol. Oceanogr.*, 47(6), 1595–1607.
- Duarte, C. M., and J. Cebrian (1996), The fate of marine autotrophic production, *Limnol. Oceanogr.*, 41(8), 1758–1766.
- Falkowski, P. G., R. T. Barber, and V. Smetacek (1998), Biogeochemical controls and feedbacks on ocean primary production, *Science*, 281(5374), 200–206, doi:10.1126/science.281.5374.200.
- Follows, M., and S. Dutkiewicz (2002), Meteorological modulation of the North Atlantic spring bloom, *Deep Sea Res. II: Top. Stud. Oceanogr.*, 49(1–3), 321–344, doi:10.1016/S0967-0645(01)00105-9.
- Gregg, W. W., N. W. Casey, and C. R. McClain (2005), Recent trends in global ocean chlorophyll, *Geophys. Res. Lett.*, 32, L03606, doi:10.1029/2004GL021808.
- Henson, S. A., J. P. Dunne, and J. L. Sarmiento (2009), Decadal variability in North Atlantic phytoplankton blooms, *J. Geophys. Res.*, 114, C04013, doi:10.1029/2008JC005139.
- Henson, S. A., Sarmiento, J. L., Dunne, J. P., Bopp, L., Lima, I., Doney, S. C., John, J., and Beaulieu, C. (2010), Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity, *Biogeosciences*, 7, 621–640, doi:10.5194/bg-7-621-2010.
- Irwin, A. J., and M. J. Oliver (2009), Are ocean deserts getting larger?, *Geophys. Res. Lett.*, 36, L18609, doi:10.1029/2009GL039883.
- Kahru, M., S. T. Gille, R. Murtugudde, P. G. Strutton, M. Manzano-Sarabia, H. Wang, and B. G. Mitchell (2010), Global correlations between winds and ocean chlorophyll, *J. Geophys. Res.*, 115, C12040, doi:10.1029/2010JC006500.
- Karl, D. M., R. Letelier, D. Hebel, L. Tupas, J. Dore, J. Christian, and C. Winn (1995), Ecosystem Changes in the North Pacific Subtropical Gyre Attributed to the 1991–92 El-Nino, *Nature*, 373(6511), 230–234, doi:10.1038/373230a0.
- Karl, D. M., R. R. Bidigare, and R. M. Letelier (2001), Long-term changes in plankton community structure and productivity in the North Pacific Subtropical Gyre: The domain shift hypothesis, *Deep-Sea Res. II*, 48(8–9), 1449–1470, doi:10.1016/S0967-0645(00)00149-1.
- Levitus, S., J. I. Antonov, T. P. Boyer, R. A. Locarnini, H. E. Garcia, and A. V. Mishonov (2009), Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems, *Geophys. Res. Lett.*, 36, L07608, doi:10.1029/2008GL037155.
- Lozier, M. S., A. C. Dave, J. B. Palter, L. M. Gerber, and R. T. Barber (2011), On the relationship between stratification and primary productivity in the North Atlantic, *Geophys. Res. Lett.*, 38, L18609, doi:10.1029/2011GL049414.
- Martinez, E., D. Antoine, F. D’Ortenzio, and B. Gentili (2009), Climate-driven basin-scale decadal oscillations of oceanic phytoplankton, *Science*, 326(5957), 1253–1256, doi:10.1126/science.1177012.
- McClain, C. R., S. R. Signorini, and J. R. Christian (2004), Subtropical gyre variability observed by ocean-color satellites, *Deep Sea Res. II: Top. Stud. Oceanogr.*, 51(1–3), 281–301, doi:10.1016/j.dsr2.2003.08.002.
- Palter, J. B., M. S. Lozier, and R. T. Barber (2005), The effect of advection on the nutrient reservoir in the North Atlantic subtropical gyre, *Nature*, 437(7059), 687–692, doi:10.1038/nature03969.
- Polovina, J. J., E. A. Howell, and M. Abecassis (2008), Ocean’s least productive waters are expanding, *Geophys. Res. Lett.*, 35, L03618, doi:10.1029/2007GL031745.
- Riebesell, U., A. Kortzinger, and A. Oschlies (2009), Sensitivities of marine carbon fluxes to ocean change, *Proc. Natl. Acad. Sci. U. S. A.*, 106(49), 20,602–20,609, doi:10.1073/pnas.0813291106.
- Sarmiento, J. L., and N. Gruber (2006), *Ocean Biogeochemical Dynamics*, 503 pp., Princeton Univ. Press, Princeton.
- Sarmiento, J. L., et al. (2004), Response of ocean ecosystems to climate warming, *Global Biogeochem. Cycles*, 18(3), GB3003, doi:10.1029/2003GB002134.
- Schmittner, A. (2005), Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation, *Nature*, 434(7033), 628–633, doi:10.1038/nature03476.
- Ueyama, R., and B. C. Monger (2005), Wind-induced modulation of seasonal phytoplankton blooms in the North Atlantic derived from satellite observations, *Limnol. Oceanogr.*, 50(6), 1820–1829.
- Vantrepotte, V., and F. Melin (2009), Temporal variability of 10-year global SeaWiFS time-series of phytoplankton chlorophyll a concentration, *ICES J. Mar. Sci.*, 66(7), 1547–1556, doi:10.1093/icesjms/fsp107.
- von Schuckmann, K., and Le Traon, P.-Y. (2011), How well can we derive Global Ocean Indicators from Argo data? *Ocean Sci.*, 7, 783–791, doi:10.5194/os-7-783-2011.
- von Schuckmann, K., F. Gaillard, and P.-Y. Le Traon (2009), Global hydrographic variability patterns during 2003–2008, *J. Geophys. Res.*, 114, C09007, doi:10.1029/2008JC005237.
- Williams, R. G., and M. J. Follows (1998), The Ekman transfer of nutrients and maintenance of new production over the North Atlantic, *Deep Sea Res. I: Oceanogr. Res. Papers*, 45(2–3), 461–489.