Ocean primary production and climate: Global decadal changes

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[1] Satellite-in situ blended ocean chlorophyll records indicate that global ocean annual primary production has declined more than 6% since the early 1980's. Nearly 70% of the global decadal decline occurred in the high latitudes. In the northern high latitudes, these reductions in primary production corresponded with increases in sea surface temperature and decreases in atmospheric iron deposition to the oceans. In the Antarctic, the reductions were accompanied by increased wind stress. Three of four low latitude basins exhibited decadal increases in annual primary production. These results indicate that ocean photosynthetic uptake of carbon may be changing as a result of climatic changes and suggest major implications for the global carbon cycle. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 1615 Global Change: Biogeochemical processes (4805); 1635 Global Change: Oceans (4203); 4806 Oceanography: Biological and Chemical: Carbon cycling. **Citation:** Gregg, W. W., M. E. Conkright, P. Ginoux, J. E. O'Reilly, and N. W. Casey, Ocean primary production and climate: Global decadal changes, *Geophys. Res. Lett.*, *30*(15), 1809, doi:10.1029/2003GL016889, 2003.

1. Introduction

[2] Ocean phytoplankton are responsible for approximately half the global biospheric net primary production [*Behrenfeld et al.*, 2001]. Long-term changes in ocean primary production can potentially have important consequences for the global carbon cycle. Global satellite observations of ocean chlorophyll, which are necessary to estimate global ocean primary production, have been available since 1979, but algorithm and processing incompatibilities have precluded time series analysis. Thus an evaluation of decadal changes in global ocean primary production has not previously been possible.

[3] Recently, the historical Coastal Zone Color Scanner (CZCS) record (1979–1986) has been reconstructed [*Gregg et al.*, 2002] to achieve compatibility with the modern Sea-viewing Wide Field-of-view Sensor (SeaWiFS; 1997-present). In addition, application of blending methodologies [*Gregg and Conkright*, 2001; *Gregg et al.*, 2002], where in situ data observations are merged with the satellite data, provide improvement of the residual errors of both the CZCS and SeaWiFS. These re-analyzed, blended satellite-in situ chlorophyll data records provide maximum compatibility and permit, for the first time, a quantitative analysis of the changes in global ocean primary production from the early-to-mid 1980's to the present.

2. Methods

[4] Modern methodologies for deriving chlorophyll from space have shown remarkable performance. *Eplee et al.* [2001] showed a mean ratio of SeaWiFS chlorophyll to in situ chlorophyll of 1.0056. *Behrenfeld et al.* [2001] indicated an average difference <6% root mean square. Blending satellite with in situ data can improve the accuracy an additional 4.4% in some basins, depending upon the number of in situ measurements and the size of the error in chlorophyll. Migration of these methodologies to the CZCS data set provides a consistent high quality data record spanning the two decades under investigation here.

[5] SeaWiFS Level-3 Version 4 ocean chlorophyll data were acquired from the Goddard Earth Sciences Distributed Active Archive Center (GES-DAAC) for the period Sep 1997 through Jun 2002. CZCS Level-1 data from Jan 1979 through Jun 1986 were also acquired from the GES-DAAC. The CZCS data set was re-analyzed for compatibility with the SeaWiFS archive [*Gregg et al.*, 2002], including recent algorithm modifications [*Stumpf et al.*, 2003]. Both data sets were blended with in situ data [*Gregg and Conkright*, 2001] from the NOAA/National Oceanographic Data Center (NODC) and the NASA SeaWiFS Bio-optical Archive and Storage System (SeaBASS).

[6] Global blended chlorophyll seasonal climatologies were used as inputs to the Vertically Generalized Production Model (VGPM) [*Behrenfeld and Falkowski*, 1997] to compute seasonal ocean primary production. This algorithm is widely used for ocean primary production estimates.

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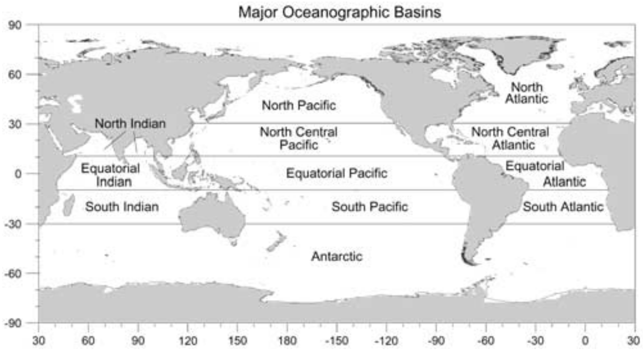

Figure 1. Boundaries for the 12 major oceanographic basins.

Although there are many other algorithms, variability among them associated with chlorophyll, the main driver for decadal changes in primary production, is very small [*Campbell et al.*, 2002] Seasons were based on the Northern Hemisphere convention, beginning with January through March representing winter. Seasonal analyses were chosen to minimize the effects of data gaps in the CZCS record. The seasonal primary production estimates were integrated to derive annual estimates. The primary production estimates were derived at 1 degree spatial resolution, and coastal regions (bottom depth <200 m) were excluded. Only co-located observations of chlorophyll from CZCS and SeaWiFS were used in the analysis. Also, data poleward of 45° latitude were excluded in boreal spring and summer for the Antarctic, and in boreal autumn and winter in the Atlantic and Pacific to reduce biases associated with poor CZCS sampling in these regions and seasons. Consequently, global annual primary production estimates here are lower than previous estimates [*Behrenfeld et al.*, 2001].

[7] Other inputs to the VGPM are Sea Surface Temperature (SST), daylength, and photosynthetically available radiation (PAR). SST and shortwave radiation data records were obtained from the National Center for Environmental Prediction (NCEP), coincident with the CZCS and SeaWiFS records. The shortwave radiation was converted into PAR (moles quanta m^{-2} s^{-1}, over the spectral range 350–700 nm). Decadal changes in SST and PAR had negligible influence on VGPM.

[8] Iron deposition data were taken from a model of mineral dust deposition [*Ginoux et al.*, 2001] and converted to iron assuming a solubility of 2%, and iron content of 5% for a clay fraction, and 1.2% for 3 silt fractions. Only data from 2000–2002 were available to represent the SeaWiFS era, and only data from 1981–1986 were available to represent the CZCS era.

[9] We analyzed SST, surface scalar wind stresses, precipitation, shortwave radiation, sea level pressure, relative humidity, precipitable water, atmospheric iron deposition, aerosol optical depths, and ice cover as potential climatic variables affecting decadal ocean primary production. Only SST, iron deposition, and wind stresses appeared to correspond with the basin-scale changes in primary production and are the only ones shown.

[10] We segregrated the oceans into 12 major oceanographic basins (Figure 1) to evaluate basin-scale annual ocean primary production along with climate change variables. Basin means were area-weighted and only co-located CZCS and SeaWiFS data were used for the comparison. Lower limits for the North Atlantic, North Pacific, and Antarctic were set to 30° N and S to capture the sub-polar frontal zones.

3. Results and Discussion

[11] Global annual ocean primary production has decreased from the CZCS era (1979–1986) to the present by 6.3% ($P < 0.05$; Table 1). SeaWiFS-era (1997–2002) annual primary production was estimated as 42.5 Pg C y^{-1}, compared to 45.3 Pg C y^{-1} for the CZCS era (1979–1986).

[12] The decadal decline in global ocean annual primary production corresponded with an increase in global SST of 0.2°C ($P < 0.05$) over the same time period. Warmer ocean temperatures increase stratification of the surface mixed layer, which inhibits the entrainment of nutrients from below to support ocean primary production [*Sarmiento et al.*, 1998]. In addition, atmospheric iron deposition to the global oceans decreased by 25% over the two observational time segments ($P < 0.05$). Iron is an important micronutrient for phytoplankton and primary production in major parts of the global oceans [*Falkowski et al.*, 1998].

[13] Most of the decrease in global annual primary production occurred in the high latitudes (Figure 2). Combined, the high latitudes losses were 2.0 Pg C y^{-1}, which accounted for 70% of the global decline in photosynthetic carbon uptake. This represented basin-wide decreases of 7, 9, and 10% in the North Atlantic, North Pacific, and Antarctic, respectively, over the two decadal time segments (Table 1). Concurrently, the North Atlantic and North Pacific experienced major increases in SST: 0.7 and 0.4°C respectively (Figure 2). These reductions in primary production and accompanying increases in SST may be related via increased stratification and reduced nutrient supply, as described above. Although increased temperature and shallower mixed layers can lead to increased chlorophyll in early spring in these basins, more severe nutrient exhaustion reduces concentrations in late spring and summer [*Gregg and Conkright*, 2002] and results in reduced annual primary production. Similar long-term reductions in primary production (along with decreasing availability of nutrients) have been observed in the North Pacific by other investigators [*Ono et al.*, 2002].

Table 1. Percent change in ocean primary production (SeaWiFS-CZCS) by basin and surface area of basins (10^7 km^{-2}) where data from both SeaWiFS and CZCS were sampled

Basin	Area	Change
N. Atlantic	1.83	−6.7%
N. Pacific	2.32	−9.3%
N. Central Atlantic	1.53	−7.0%
N. Central Pacific	3.22	−5.8%
N. Indian	0.46	13.6%
Eq. Atlantic	1.15	6.9%
Eq. Pacific	3.72	−3.0%
Eq. Indian	1.37	8.8%
S. Atlantic	1.20	−3.8%
S. Pacific	2.69	−14.0%
S. Indian	1.77	−4.2%
Antarctic	8.28	−10.4%
Global	29.73	−6.3%

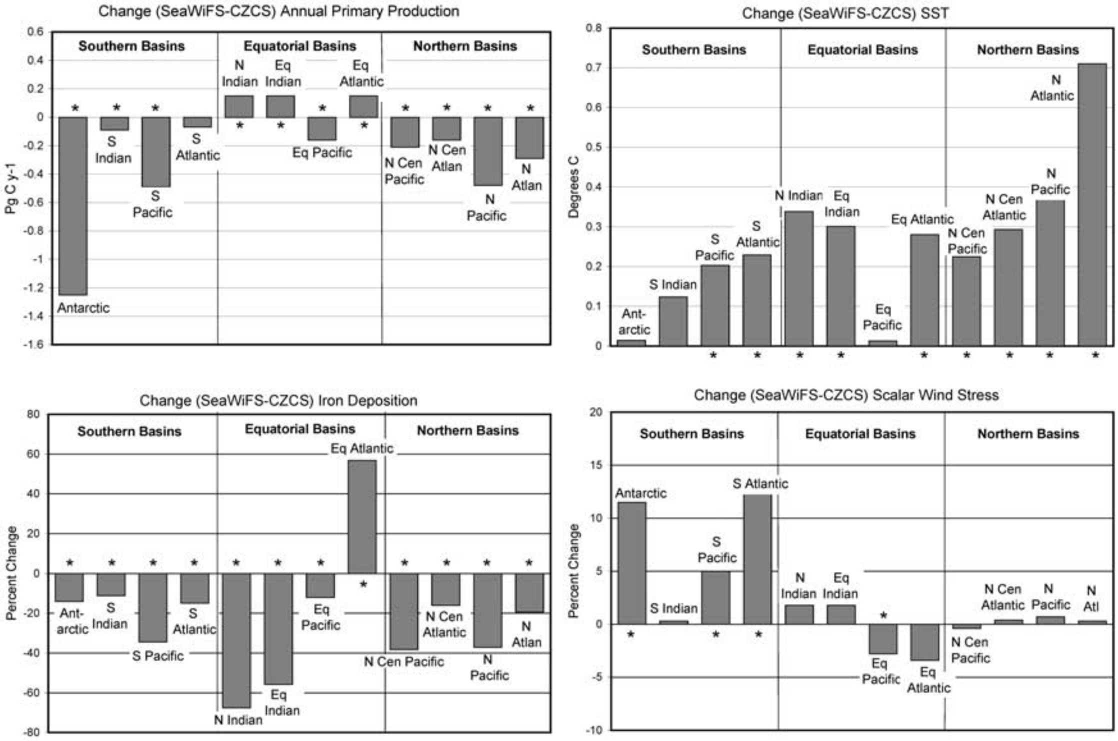

Figure 2. Differences between SeaWiFS (1997–2002) and CZCS (1979–1986) in the 12 major oceanographic basins. Differences are expressed as SeaWiFS-CZCS. Top left: Annual primary production (Pg C y^{-1}). An asterisk indicates the difference is statistically significant at $P < 0.05$. Top right: SST (degrees C). Bottom left: iron deposition (%). Bottom right: mean scalar wind stress (%).

The reduced primary production observed here was also accompanied by decreases in iron deposition over the two decadal segments, of 19% and 37% respectively in the North Atlantic and Pacific (Figure 2). The eastern portion of the North Pacific is limited by iron [*Shiomoto et al.*, 1998].

[14] Decreases in primary production in the Antarctic basin were not associated with significant warming over the two decadal time segments (Figure 2). However, mean scalar wind stresses were much higher in recent years (Figure 2), as indicated by a 12% increase from the early 1980's. The Southern Ocean operates much differently than its Northern high latitude counterparts. In most of the basin, mixed layers are deep year-round [*Monterey and Levitus*, 1997] and macro-nutrients (nitrate, phosphate, and silica) are available even during the maximum growing season. Except where the basin is iron-limited, light availability governs primary production. Increased wind mixing will deepen the surface mixed layer and decrease the amount of light available for photosynthesis. Decreases in iron deposition (Figure 2) further suppress primary production in the iron-limited portions of the basin.

[15] The South Pacific exhibited a reduction of 0.5 Pg C y^{-1} in primary production (Figure 2), which represented a 14% basin-wide decline (Table 1). This reduction corresponded with a decrease of nearly 35% in atmospheric iron deposition. Iron has been reported to be limiting in the South Pacific [*Behrenfeld and Kolber*, 1999].

[16] The low latitude basins, in contrast to the high latitudes, showed increases in primary production from the CZCS era to the present (Figures 2 and 3). An exception was the equatorial Pacific, which exhibited a decrease. The equatorial Atlantic increases (0.15 Pg C y^{-1}, or 7%) were located near the mouth of the Congo River, where record floods have been observed recently [*Le Comte*, 1999]. Increased discharge provides nutrients to stimulate primary production. The remote sensing contaminant chromophoric dissolved organic carbon is also present in tropical river discharges but it is partially corrected by the blended analysis.

[17] The increases in the North and Equatorial Indian were 0.15 Pg C y^{-1} each, representing 14 and 9% increases, respectively (Table 1). The largest increases occurred along the western portion of the Arabian Sea (Figure 3). Although basin-wide annual wind stresses did not show a statistical change in the two time segments, increases were observed in the western Arabian Sea, corresponding to the increases in primary production, which suggests enhanced upwelling.

[18] In the North Central Pacific near Hawaii, surface warming/increased stratification has been linked to increased primary production, associated with an ecosystem shift to smaller phytoplankton species, including nitrogen-fixing groups, for the period 1968–1997 [*Karl et al.*, 2001]. Our analyses showed a modest decrease for the basin mean (Figure 2). A reduction in iron deposition here, as suggested by our results, can potentially compensate the changes associated with species shifts, as nitrogen-fixers in the oceans may be iron-limited [*Falkowski*, 1997].

4. Implications for the Ocean Carbon Cycle

[19] These results have major implications for the global carbon cycle. The high latitude oceans typically represent a

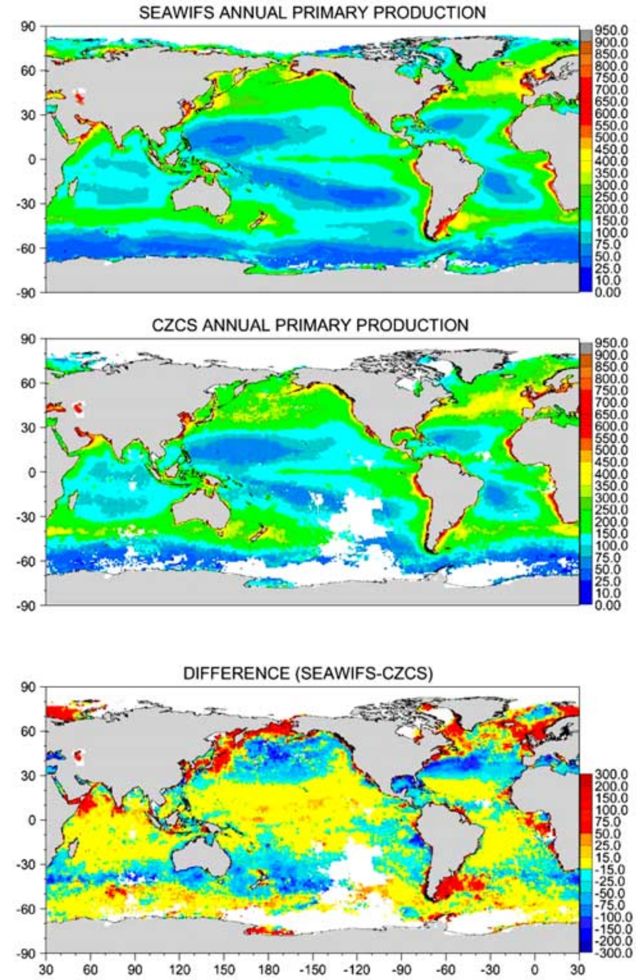

Figure 3. Primary production distributions for the SeaWiFS era (1997-mid-2002), the CZCS era (1979-mid-1986), and the difference. Units are g C m^{-2} y^{-1}. White indicates missing data.

net sink of atmospheric carbon [*Archer et al.*, 2000]. These regions are dominated by diatoms [*Marañon et al.*, 2000], which typically grow and sink faster than other phytoplankton groups, and thus can represent an important carbon transfer mechanism to the deep oceans. The reduction in primary production may represent a reduced sink of carbon here via the photosynthetic pathway since the early 1980's. The low latitudes, conversely, represent a source of carbon to the atmosphere [*Takahashi et al.*, 1997]. Increased production in the Equatorial and North Indian basins and the Equatorial Atlantic may suggest reduced carbon flux to the atmosphere here through increased ocean photosynthetic uptake.

[20] The relationship between the change in basin-scale annual primary production and climatic trends is mostly consistent with model predictions and established relationships, although a conclusive link is not demonstrated here. It is not clear whether these changes represent a long-term trend or whether they are related to decadal-scale oscillatory events such as the Pacific Decadal or North Atlantic Oscillation.

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