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Antarctic circumpolar wave impact on marine biology: A natural laboratory for climate change study

Corinne Le Quéré, Laurent Bopp,¹ and Ina Tegen

Max Planck Institut für Biogeochemie, Jena, Germany

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[1] We use the observed variations in ocean surface chlorophyll, temperature and height caused by the Antarctic Circumpolar Wave (ACW) as a natural laboratory to determine how marine biology responds to changes in ocean stratification in the Southern Ocean. Interannual variations of surface chlorophyll ($\pm 5\%$) observed by SeaWiFS satellite during 1997–2001 vary in phase over the entire Southern Ocean in spite of large east-west dipoles in ocean dynamics. We suggest that this behavior is due to the regional predominance of light versus nutrient limitation over the most productive regions of the Southern Ocean. *INDEX TERMS*: 1615 Global Change: Biogeochemical processes (4805); 1640 Global Change: Remote sensing; 4572 Oceanography: Physical: Upper ocean processes; 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics; 1635 Global Change: Oceans (4203)

1. Introduction

[2] Biological productivity in the Southern Ocean is limited by the availability of nutrients (e.g. iron and silicate) and light for phytoplankton growth [Martin *et al.*, 1990; Mitchell *et al.*, 1991; Boyd *et al.*, 2000]. Nutrients are supplied to surface waters by atmospheric dust deposition, resuspension of coastal sediments and mixing with nutrient-rich deep waters. Light availability varies with the solar angle, cloud cover, and the stratification of the ocean surface. Ocean stratification is predicted to increase as a consequence of global warming [Sarmiento *et al.*, 1998; Bopp *et al.*, 2001]. If the ocean stratifies, less nutrients but more light will be available, driving opposite effects on biological productivity. The net impact is unknown. Here we use the four years of chlorophyll *a* (chl_a) observed by SeaWiFS satellite [Hooker and McClain, 2000; Moore and Abbott, 2000] to determine how biological productivity responds to changes in ocean stratification.

2. Analysis and Data Sources

[3] We used satellite observations of: (1) weekly Sea Surface Temperature (SST) interpolated on a 1×1 degree grid by Reynolds and Smith [1994], (2) 10 day maps of Sea Surface Height (SSH) from TOPEX/Poseidon supplied by the NOAA Laboratory for Satellite Altimetry on a grid of 1° of latitude by roughly 4° of longitude [Cheney *et al.*, 1994; Le Traon *et al.*, 1994] and (3) monthly surface chl_a from SeaWiFS level 3 data interpolated on a 0.7×0.7 degree grid generated by NASA Goddard Space Flight Center [Hooker and McClain, 2000]. Monthly averages were computed. Missing values were filled with a linear average of the nearest neighbor if not missing. Otherwise the value was not filled. For chl_a, remaining missing values were filled with the average of the nearest month if not missing. Otherwise the value

was not filled. This additional filling provided estimates mainly for winter months where chl_a concentrations are low and vary little from month to month. We computed primary production using surface chl_a and SST with the algorithm of [Behrenfeld and Falkowski, 1997]. This computation suggests that variations in chl_a (i.e. in biomass) in the Southern Ocean are mainly reflecting variations in primary production. Anomalies were computed by removing the 09/1997–08/2001 mean seasonal signal, and averaged in time using a 6 month running average.

3. Results and Discussion

[4] The ACW is a climatic perturbation observed in SST, SSH, sea ice extent, atmospheric pressure and wind stress [White and Peterson, 1996; Peterson and White, 1998]. It originates in the western subtropical Pacific and propagates eastward around the Southern Ocean. In 1997–1998, a warm SST/high SSH anomaly developed in the south Pacific (ca 120°W ; Figure 1) and was immediately followed by a cold anomaly half its size in 1999. At any one time during 1997–2000, SST and SSH anomalies formed two east-west dipoles with roughly the same sign in the east Pacific and Indian oceans and in the west Pacific and Atlantic oceans.

[5] Surface chl_a observed by SeaWiFS does not show this east-west dipole: it varies in phase over the entire Southern Ocean (Figure 1). In spite of this different behavior, chl_a and SSH anomalies are strongly correlated regionally (Figure 2). Correlations are positive in the west Pacific ($r = +0.60$) where chl_a increases when the SSH is high, negative in the east Pacific ($r = -0.74$), positive in the Atlantic ($r = +0.79$) and negative in the Indian ocean ($r = -0.40$; Figure 2). In all basins, chl_a varies by 5% for every cm SSH anomaly. Correlations between chl_a and SST anomalies are in the same direction but are smaller. These correlations are similar when only a sub-set of the data is used, suggesting that results are not an artifact of the length of the time series, of biases due to possible drift in satellite measurements or of the comparison of satellites with different treatment of cloud cover. These correlations suggest that changes in chl_a are directly related to changes in SSH, but that the dominant process varies regionally.

[6] To understand which process dominates, we must first identify what are the dynamic variations which are reflected by SSH anomalies. SSH anomalies are caused by changes in the density of the water column due to surface heat or water fluxes or to advection. Here we assume that surface heat fluxes or advection of waters of a different temperature are the most important processes affecting changes in SSH in the Southern Ocean. This means that low SSH/cold SST anomalies would be indicative of denser surface waters and thus increased ocean mixing (i.e. destratification); high SSH/warm SST of lighter waters and thus increased ocean stratification.

[7] This assumption is based on three independent pieces of evidence. First, the SSH response to observed wind forcing agrees in amplitude and in phase with quasi-geostrophic dynamics [Jacobs and Mitchell, 1996] which indicates that a high SSH anomaly reflects the thermal expansion of the ocean due to surface heating and thus increased stratification. Second, time-series observations at KERFIX [Jeandel *et al.*, 1998] oceanographic

¹Now at The Laboratoire des Sciences du Climat et de l'Environnement, 91191 Gif-sur-Yvette, France.

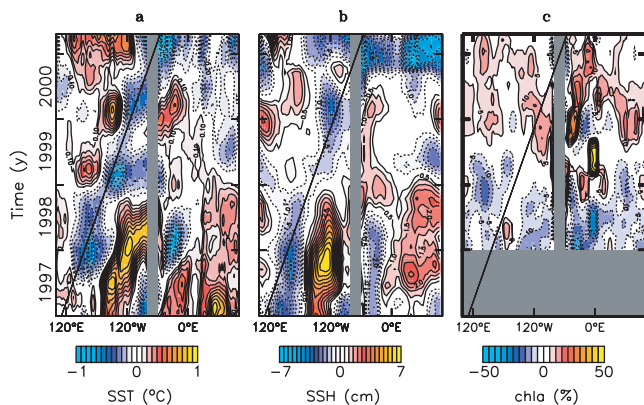


Figure 1. Satellite-derived anomalies in the Southern Ocean. Sea surface temperature (SST; a) from different instruments ($^{\circ}\text{C}$) [Reynolds and Smith, 1994], sea surface height (SSH; b) from TOPEX/Poseidon (cm) [Cheney et al., 1994; Le Traon et al., 1994], and surface chlorophyll (chl_a; c) from SeaWiFS [Hooker and McClain, 2000; Moore et al., 1999] level 3 gridded product (%) averaged between 45°S and 55°S . Surface chl_a is shown in percent because of the large spatial heterogeneity of the mean chl_a concentration. The black line follows the speed of propagation of the ACW and is identical in all figures. The gray area shows missing data or the presence of a continent. Computation of the anomalies is described in the Analysis and Data Sources Section. The anomalies were smoothed horizontally with an 8° running average.

station (50°S , 68°E) in the Indian ocean during 1991–1995 showed a high SSH of 2.6 cm and warm SST of $+0.5^{\circ}\text{C}$ in 1992 compared to 1994 [Park et al., 1998]. From local observations of the vertical density profile, we compute a 50 m shoaling of the mixed layer depth (i.e. increased stratification) in 1992 compared to 1994, where the mixed layer depth is defined by the shallowest depth at which the density exceeds the surface value by 0.125 g cm^{-3} . Third, results from a global ocean model of roughly 1.5×2

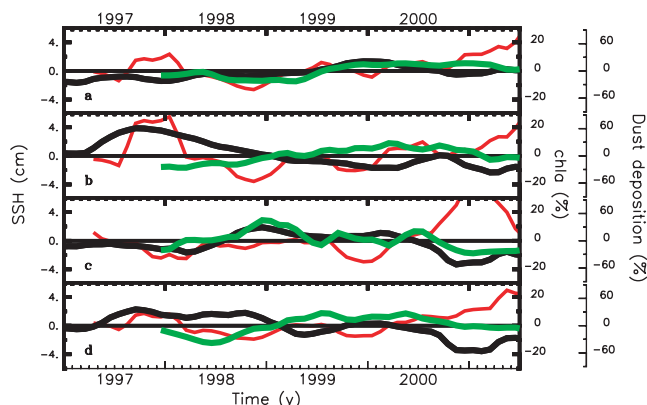


Figure 2. Time series by regional basins. Anomalies of SSH (black line; in cm), chl_a (green line; in %) and dust deposition (red line; in %) averaged between 45°S and 55°S for the west Pacific (a; 110°E – 160°W), the east Pacific (b; 160°W – 80°W), the Atlantic (c; 70°W – 0°E) and Indian (d; 0°E – 110°E) oceans. The correlation r and statistical significance (in parenthesis) between SSH and chl_a is by sector respectively (a) $+0.60$ (85%), (b) -0.74 (90%), (c) $+0.79$ (95%) and (d) -0.40 (80%). The correlation between dust and chl_a is positive and significant only in the west Pacific with $r = 0.52$ (85%). The statistical significance of these correlations was estimated according to Student t -test and considering the auto-correlation of the time-series.

degree resolution [Madec and Imbard, 1996] including specific parameterization of vertical mixing [Gaspar et al., 1990] and forced by re-analyzed winds and fluxes for 1979–1997 [Le Quéré et al., 2000] always show an increased ocean stratification when there is warming in the Southern Ocean, except along the Antarctic continent where the water fluxes from ice melting and freezing are important.

[8] A regional map of chl_a-SSH correlation shows that the chl_a increases when ocean mixing increases (i.e. chl_a-SSH correlation is negative) in the east Pacific and west Indian oceans, and over most of the region north of 40°S (Figure 3). Such a relationship is to be expected if biological productivity is predominantly limited by nutrients coming from below. This result corroborates current knowledge of nutrient limitation in the Southern Ocean. North of 40°S , phosphate and nitrate concentrations diminish rapidly to near zero values. Nutrient limitation is also expected at these low latitudes because of the high availability of light due to shallow mixing depth and to the higher solar angle. Between 40°S and 50°S silicate concentrations are low [Levitius et al., 1993], whereas iron concentrations are low south of 50°S [Löscher et al., 1997] in regions far away from continental dust sources.

[9] The predominance of nutrient limitation in the west Indian ocean is consistent with the KERFIX time series observations where lower chl_a concentrations were observed in 1992 when the ocean was more stratified than in 1994 [Jeandel et al., 1998]. Model results at this station also reach similar conclusions [Pondaven et al., 2000].

[10] Chl_a increases when the ocean stratifies (i.e. chl_a-SSH correlation is positive) generally over the most productive regions of the Southern Ocean: the south west Atlantic ocean (west of 20°W , 55°S – 40°S), south of Africa (15°E – 30°E , 45°S – 40°S), and south of Australia (110°E – 170°W , 55°S – 45°S ; Figure 3). Such a relationship can occur if biological productivity is predominantly controlled by light availability, by dust input from the atmosphere or by temperature. We assume that the re-suspension of coastal sediments diminishes when the ocean stratifies and thus cannot account for variability in these regions. Productive regions are mostly down-current of continental shelves or down-wind of atmospheric dust sources and may receive plenty of nutrients on average [Fung et al., 2000; Kohfeld and Harrison, 2001]. This result is also not in contradiction with the recent iron fertilization experiment in the south east Indian ocean [Boyd et al., 2000].

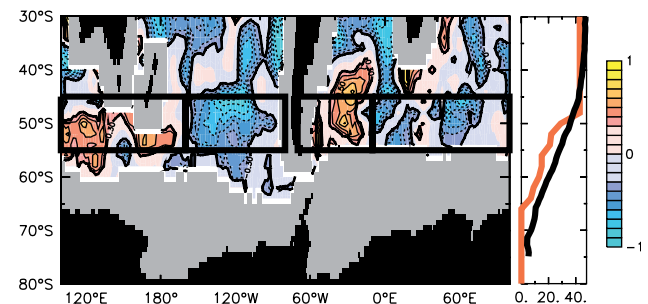


Figure 3. Map of the temporal correlation (09/1997–12/2001) between SSH and chl_a anomalies computed over each grid box of $2 \times 2^{\circ}$. Contours every 0.1 for correlations greater than ± 0.3 . The correlation is positive (red) where chl_a increases with ocean stratification and negative (blue) where it increases with ocean mixing (see text). The right panel shows the average number of good months used from the original SeaWiFS level 3 data (black line) and for the anomalies computed as in Analysis and Data Sources Section and smoothed with a running average of 8° of longitude and 5° of latitude (red line). The temporal and spatial smoothing are necessary to clearly identify the different zones of limitation. SSH anomalies South of 60°S are assumed identical to those at 60°S . Black boxes represent the areas selected for Figure 2.

Indeed, if iron is added without changing the ocean stratification, biological productivity will increase. On the other hand, if iron is added as a consequence of changes in ocean stratification, biological productivity may respond differently because of changes in temperature, light availability or associated atmospheric dust input.

[11] We estimated the direct impact of temperature on biological productivity using the algorithm of *Behrenfeld and Falkowski* [1997] with constant and varying SST. Temperature variations account for less than 10% of the primary production over most of the Southern Ocean except in the south Atlantic where it accounts for ~30% of the total signal. Changes in light availability or changes in atmospheric dust deposition must be considered to explain the changes in biological productivity.

[12] The changes in dust deposition cannot be assessed directly using satellite Total Ozone Mapping Spectrometer (TOMS) [*Herman et al.*, 1997] because the contribution of soil dust aerosol to the total aerosol load is small in the Southern Ocean. To assess interannual variations in the supply of aeolian dust to the ocean surface we used a global model of dust emission and deposition [*Tegen et al.*, 2002]. The atmospheric dust particles were transported in the TM3 offline tracer-transport model [*Heimann*, 1995; *Denning et al.*, 1999] driven by daily NCEP re-analyzed meteorological fields [*Kalnay et al.*, 1996] to simulate dust deposition over the years 1997 through 2001. This model reproduces well interannual dust changes for most regions of the world, even though it underestimates dust emissions in some regions [*Tegen et al.*, 2002]. Our results and sensitivity tests suggest that dust deposition in the Southern Ocean is modulated to a first order by variations of dust sources over the former Lake Eyre basin in central Australian. Dust is then advected eastwards or south-eastwards depending on the direction of the winds. There is a weak positive correlation between dust deposition and chl_a anomalies only in the west Pacific (Figure 3) which suggests that the modulations of dust deposition reinforce variations in light availability to produce anomalies in chl_a. In the other basins however, dust deposition anomalies do not line up with chl_a anomalies.

[13] Based on our analysis, changes in temperature and dust cannot explain most of the observed chl_a variability in productive regions of the Southern Ocean. The availability of light must therefore be dominant. When the ocean stratifies, phytoplankton organisms are on average closer to the ocean surface and have more time to use the solar radiation entering the ocean. Between 40°S and 65°S, 40% of the ocean area and 44% of the total primary production appear dominated by light limitation. Because of the dipoles in ocean stratification created by the passage of the ACW [*Jacobs and Mitchell*, 1996; *Le Quéré et al.*, 2000], and of the opposite processes controlling the variability in primary production in the different basins, chl_a varies in phase throughout the Southern Ocean between 40°S and 65°S with a mean amplitude of ±5%, corresponding to variations in primary production of ±0.3 Pg C y⁻¹.

4. Conclusions

[14] Our analysis suggests that the response of primary production to a generalized stratification of the Southern Ocean such as that predicted under global warming [*Sarmiento et al.*, 1998; *Bopp et al.*, 2001] would lead to large spatial redistribution with productive regions becoming more productive and poor regions more sterile. This conclusion is based on simple assumptions regarding the inference of ocean stratification and biological productivity from SST, SSH and chl_a observed by satellite. Although this analysis is limited by the fact that satellite observations only view the top few meters of the ocean, this observational-based analysis provides a powerful tool for understanding processes regulating marine biology.

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- C. Le Quéré, L. Bopp, and I. Tegen, Max Planck Institut für Biogeochemie, Postfach 100164, D-07701 Jena, Germany.