Impact of the Southern Annular Mode on Southern Ocean circulation and biology

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Received 15 February 2005; revised 2 May 2005; accepted 5 May 2005; published 8 June 2005.

[1] We investigate the impact of the Southern Annular Mode (SAM) on surface wind, sea surface temperature (SST), and surface chlorophyll concentration on intraseasonal to interannual timescales in the Southern Ocean using 8-day average satellite observations. Positive phases of the SAM are associated with enhanced westerly winds over the Antarctic Zone (AZ) and Polar Frontal Zone, driving increased equatorward Ekman transport and cold SST anomalies in these regions. Positive SAM is also associated with easterly wind and warm SST anomalies in the Subtropical Zone. South of the Antarctic Polar Front (APF), chlorophyll concentration anomalies are positively correlated with the SAM, however this correlation is negative north of the APF. We suggest that the positive correlation in the AZ is due to the increased supply of iron by upwelling, while the negative correlation north of the APF is caused by stronger light limitation as a consequence of deeper mixed layers. **Citation:** Lovenduski, N. S., and N. Gruber (2005), Impact of the Southern Annular Mode on Southern Ocean circulation and biology, *Geophys. Res. Lett.*, *32*, L11603, doi:10.1029/2005GL022727.

1. Introduction

[2] The SAM, or the Antarctic Oscillation, is the leading mode of climate variability on timescales from intraseasonal to interannual over the entire Southern Hemisphere [*Thompson and Wallace*, 2000]. It is characterized by a large-scale alternation of atmospheric mass between the mid- and high-latitudes, and is associated with a meridional shift in the atmospheric westerly winds [*Hartmann and Lo*, 1998]. These westerly winds are responsible for driving the circulation of the Southern Ocean, and it has been shown using general circulation models that wind shifts associated with the SAM alter Southern Ocean circulation patterns substantially [*Hall and Visbeck*, 2002; *Oke and England*, 2004; *Watterson*, 2000]. Changes in circulation can affect phytoplankton abundance and biogeochemical cycling in this region, yet the impact of the SAM on them has not yet been documented.

[3] The Southern Ocean plays a critical role in the global climate system. The strong wind-driven eastward flow of the Antarctic Circumpolar Current connects the Pacific, Atlantic, and Indian ocean basins. In addition, the Southern Ocean meridional overturning circulation contributes substantially to the global transport of climatically significant quantities such as heat, fresh water, nutrients, and anthropogenic CO_2 [*Rintoul et al.*, 2001; *Sarmiento et al.*, 2004]. Mode waters transfer these quantities from the surface into the interior of the oceans [*Banks et al.*, 2000] and ventilate the thermocline of the Southern Hemisphere subtropical gyres [*McCartney*, 1982]. Nearly 40% of global anthropogenic CO_2 uptake is associated with this pathway [*Sabine et al.*, 2004], substantially offsetting the outgassing of natural CO_2 [*Gloor et al.*, 2003]. However, very little is known about how this region responds to climate variability and how it may be affected by climate change.

[4] Given the paucity of in situ data in the Southern Ocean, satellite products provide us with one of the few means to investigate coherent variability over large spatial and temporal scales. This study takes advantage of satellite-derived wind speed and direction, SST, and chlorophyll-*a* concentration to examine the relationship between the SAM and Southern Ocean circulation and phytoplankton abundance on intraseasonal to interannual timescales.

2. Data Sources and Analysis

[5] We used satellite observations of: (1) daily wind speed and direction from QuikSCAT on a 25 km grid from 1999–2004, (2) 8-day averaged equal angle best SST from AVHRR Oceans Pathfinder (versions 4.1 and interim 4.1) on a 9 km grid from 1985–2003, and (3) 8-day averaged chlorophyll-*a* concentration from SeaWiFS on a 9 km grid from 1997–2004. Since oceanic chlorophyll concentration is approximately lognormally distributed [*Campbell*, 1995], the natural log transformation was applied to the SeaWiFS data and means were computed from the transformed data. The surface wind was averaged into 8-day periods, and all 3 data sets were interpolated to a 1° grid using a linear interpolation scheme. The data were deseasonalized by removing the climatological mean seasonal cycle computed by binning all data into 46 8-day bins and then taking the average. A linear trend was subtracted at each grid cell in order to remove any non-stationarity. Missing data were ignored in all calculations. The daily Antarctic Oscillation index from 1979–2004 was also averaged into 8-day periods, standardized by the standard deviation, and linearly detrended as above.

[6] We investigate the impact of the SAM on circulation and biology using regression and correlation analysis. To maximize the statistical significance given the short and differing length of the records, we performed this analysis over the period of time for which the data sets overlap. We assume that the correlation is stationary, i.e. it is not changing with time. The statistical significance of all

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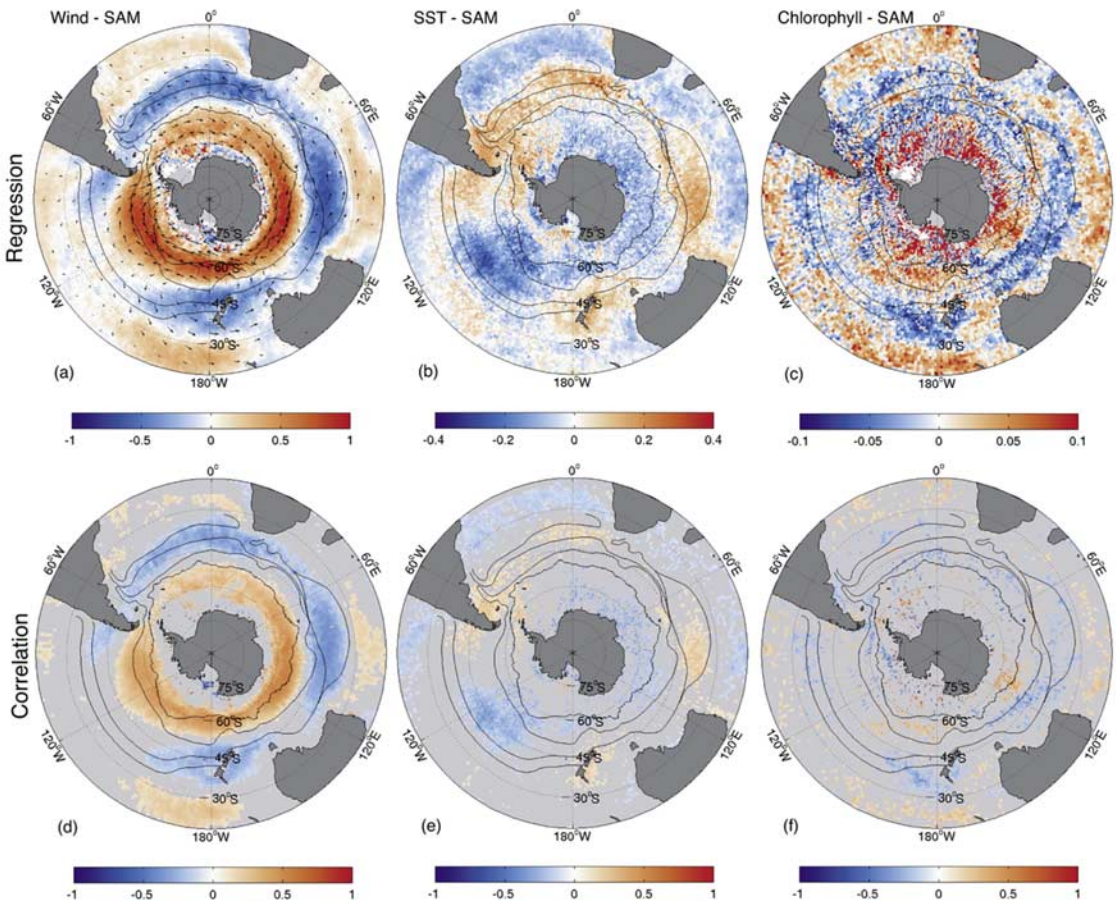

Figure 1. Maps of (a–c) regressions and (d–f) correlations between the SAM index and (a and d) wind speed and (a) direction, (b and e) SST, and (c and f) chlorophyll concentration. The regression coefficients indicate changes in the wind speed (m s^{-1}), SST (°C), and natural log of the chlorophyll concentration [ln(mg m^{-3})] corresponding to one standard deviation change in the SAM index. Only those correlation coefficients with significance ≥95% are shown. Black contours mark the location of the Southern Ocean fronts. From pole to equator these fronts are: Antarctic Polar Front [*Moore et al.*, 1999], Subantarctic Front, South Subtropical Front, and North Subtropical Front [*Belkin and Gordon*, 1996].

correlation coefficients was determined considering the autocorrelation present in our 8-day anomalies. This is accounted for by replacing the t statistic sample size, N, with an effective sample size, N_{eff}:

$$N_{\mathrm{eff}} = N\left(\frac{1 - r_1 r_2}{1 + r_1 r_2}\right) \quad (1)$$

where r_1 and r_2 are the lag-1 autocorrelation coefficients of the time series being correlated [*Bretherton et al.*, 1999].

3. Results and Discussion

[7] The SAM index is defined by the leading principal component of the 700 mb geopotential height south of 20°S in the atmosphere. Positive SAM is associated with negative pressure anomalies over Antarctica, positive pressure anomalies over the mid-latitudes, and a strengthening of the zonal atmospheric pressure gradient. We find that the anomalously strong pressure gradient during positive SAM acts to significantly strengthen the westerly winds at ~55°S, and to weaken the westerly winds (easterly anomaly) at ~35°S, by as much as 0.9 m s^{-1} in some regions (Figures 1a and 1d), confirming previous results [see *Hartmann and Lo*, 1998; *Limpasuvan and Hartmann*, 1999]. This poleward contraction of the westerlies during positive SAM persists throughout all seasons, but is strongest during austral summer.

[8] Figure 2 illustrates how the oceanic circulation is expected to change in response to the strengthening and shifting of the wind during positive SAM [see *Hall and Visbeck*, 2002]. Surface westerly wind anomalies generate northward Ekman transport anomalies in the Antarctic Zone (AZ), the region south of the Antarctic Polar Front (APF; ~55°S), and Polar Frontal Zone (PFZ), the region between the APF and the Subantarctic Front (SAF), enhancing the divergence and driving increased upwelling of water from below. Surface easterly wind anomalies produce southward Ekman transport anomalies in the Subtropical Zone (STZ), the region between the SAF and the Subtropical Front (STF). The increased convergence of water in the Subantarctic Zone (SAZ), the region between the SAF and STF, increases downwelling of water from the surface to depth. We therefore expect the anomalous Ekman transport to generate negative SST anomalies in the AZ and PFZ, and positive SST anomalies in the STZ (Figure 2).

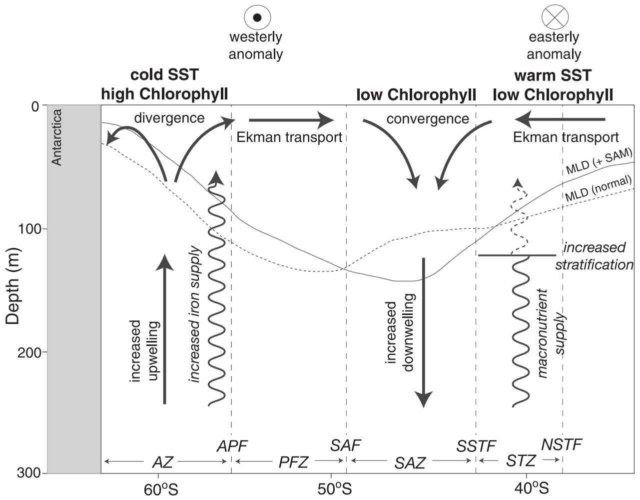

Figure 2. Schematic illustration of the upper ocean response to a positive phase of the SAM.

[9] Our satellite-based analysis confirms these expectations by showing that a positive SAM is associated with a significant decrease in SST in the AZ and PFZ, and a significant increase in SST in the STZ (Figures 1b, 1e, and 3 and Table 1). As is the case for the westerly wind, this SST response is most pronounced during austral summer. The SST response pattern is nearly zonally symmetric, the exception being the Pacific sector (~100°W–160°W), where a positive SAM is associated with negative SST anomalies across all 4 Southern Ocean zones (Figure 1b). This response may be associated with other climate variations that overwhelm the impact of SAM but have some correlation with Southern Ocean circulation, e.g. ENSO [*Garreaud and Battisti*, 1999] and its connection to the Antarctic Dipole Pattern [*Liu et al.*, 2002], and the Antarctic Circumpolar Wave [*White and Peterson*, 1996].

[10] In the AZ, SAM and chlorophyll are positively correlated, and regression coefficients often exceed 0.1 mg m^{-3} per standard deviation (Figure 1c). Conversely, the remaining 3 Southern Ocean zones tend to experience a decrease in chlorophyll concentration during positive phases of the SAM (Figure 3 and Table 1). While this negative response dominates north of the APF, it is not entirely zonally symmetric. The strongest response is found in the SAZ south of Australia where regression coefficients can be as large as −0.06 mg m^{-3} per standard deviation, corresponding to 34% of the mean chlorophyll value in this region. Elsewhere, correlations are relatively low and often not statistically significant (Figure 1f). We attribute this low level of significance primarily to the shortness of the record and the non-uniform chlorophyll coverage due to high incidence of cloud cover (e.g. $\overline{N_{\mathrm{eff,AZ}}} \simeq 30$; $\overline{N_{\mathrm{eff,SAZ}}} \simeq 90$).

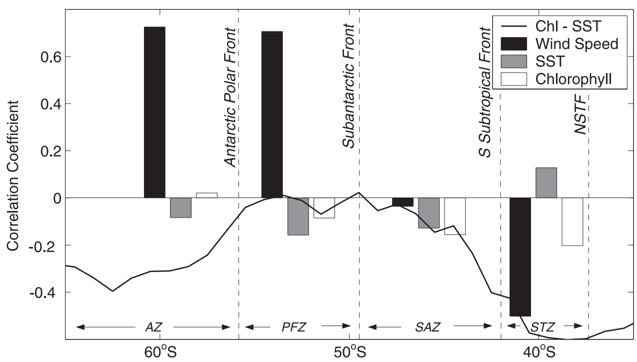

Figure 3. The correlation coefficient of the SAM index with the average time series of wind speed, SST, and chlorophyll concentration anomalies. The anomaly time series were averaged over various regions in the Southern Ocean, defined by the Southern Ocean fronts. Overlain is the correlation coefficient of the zonal-mean SST and chlorophyll concentration anomalies.

Table 1. Mean Values and Regression and Correlation Coefficients of the Mean Anomaly Time Series With the SAM Index[a]

Zone	Mean Value	Regression Coefficient Associated With 1σ_{SAM}	Correlation With SAM Index
		Wind Speed [m s^{-1}]	
AZ	10.0	0.45	0.73
PFZ	10.8	0.39	0.71
SAZ	10.1	−0.02	−0.04
STZ	8.9	−0.03	−0.50
		SST [°C]	
AZ	−0.4	−0.024	−0.08
PFZ	4.3	−0.041	−0.16
SAZ	9.6	−0.028	−0.13
STZ	14.8	0.032	0.13
		Chlorophyll [mg m^{-3}]	
AZ	0.2029	0.0020	0.02
PFZ	0.1876	−0.0061	−0.09
SAZ	0.1748	−0.0075	−0.16
STZ	0.1770	−0.0120	−0.20

[a]Regression coefficients correspond to one standard deviation change in the SAM index.

[11] In order to better understand the biological response to circulation changes associated with the SAM, we investigate the relationship between chlorophyll concentration and SST anomalies in the Southern Ocean. At latitudes typically associated with the AZ, anomalies of chlorophyll concentration and SST are negatively correlated (Figure 3), suggesting that when cold, nutrient-rich water upwells, phytoplankton abundance tends to increase. Since biological productivity in this region of the Southern Ocean is thought to be limited by micronutrients [*Boyd et al.*, 2000], this negative chlorophyll-SST correlation may be related to iron supply from below. There is little correlation between anomalies of chlorophyll and SST in the SAZ (Figure 3). Since this region is characterized by deep mixed layers [*Kara et al.*, 2003], this lack of correlation could indicate that biological productivity in this region is limited by light. In the subtropical waters within and equatorward of the STZ, biological production is limited by macronutrients (Figure 3) and stratification is dominated by temperature [*Pollard et al.*, 2002].

[12] The biological response to the SAM can be explained by considering the consequences of the circulation changes (Figure 2). We propose that during positive SAM the increase in phytoplankton abundance in the AZ is driven by the anomalous upwelling of iron, while the decrease in chlorophyll concentration in the SAZ is caused by deeper mixed layers and increased light limitation. We note that nonlinear effects such as photoadaptation could be confounding correlations in the SAZ. The decrease in chlorophyll concentration in the STZ during positive

SAM can be explained by warmer than normal SST (Figures 1b and 3) and increased stratification, leading to reduced macronutrient supply in this region.

[13] On the basis of a suite of remotely sensed products, we suggest the following sequence of events in response to a positive phase of the SAM (Figure 2): The poleward shift of the surface westerly winds creates anomalies in both poleward and equatorward Ekman transport, driving increased upwelling of cold, iron-enriched water into the AZ, and increasing convergence and downwelling in the SAZ. The former process slightly increases the phytoplankton abundance in the AZ, while the latter processes deepens the mixed layer and decreases the chlorophyll concentration in the SAZ. In the STZ, increased stratification from warm SST anomalies reduces macronutrient supply and decreases chlorophyll concentration.

4. Impact on Carbon Cycle

[14] Can we use these relationships to deduce something about the impact of the SAM on the air-sea CO_2 flux in the Southern Ocean? During positive phases of the SAM, we suspect that the anomalous upwelling of waters rich in dissolved inorganic carbon in the AZ is elevating the partial pressure of CO_2 in the surface waters. The resulting anomalous outgassing may, however, be mitigated by increased CO_2 solubility and biological productivity in this region. Positive SAM increases convergence and downwelling in the mode water formation regions of the Southern Ocean, possibly accelerating the pathway for the subduction and equatorward transport of anthropogenic CO_2. However, the anomalous uptake of CO_2 may be offset by decreased biological production in this region. Overall, we therefore expect only a moderate level of air-sea CO_2 flux variability.

5. Conclusions

[15] Despite the relatively short length and sometimes sparseness of the observation record, we have demonstrated that statistically significant relationships between the satellite observations and the SAM exist. These relationships can be interpreted with a conceptual model (Figure 2), which suggests a substantial response of ocean circulation and biology to variations in the SAM.

[16] Several studies have drawn our attention to the trend toward positive SAM over the past 30 years, which may be linked to climate change and ozone depletion in high latitudes [*Thompson et al.*, 2000; *Thompson and Solomon*, 2002]. The impact of this trend on ocean circulation and the global carbon cycle is poorly understood, but could be indicative of how this system might respond to future climate change.

[17] **Acknowledgments.** The QuikSCAT level 3 ocean wind vector data and the AVHRR Oceans Pathfinder sea surface temperature data were obtained from the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at NASA JPL in Pasadena, CA (http://podaac.jpl.nasa.gov). The SeaWiFS level 3 chlorophyll data were obtained from the Distributed Active Archive Center (DAAC) at NASA Goddard in Greenbelt, MD (http://daac.gsfc.nasa.gov). The daily Antarctic Oscillation index was provided by the NOAA/NCEP Climate Prediction Center in Camp Springs, MD (http://www.cpc.ncep.noaa.gov). This work was supported by NASA through grants NAG5-12528 and NNG04GH53G and by the Caltech President's Fund through NASA contract NAS7-1407. We thank D. Thompson for many stimulating discussions.

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