IMPACT OF THE SOUTHERN ANNULAR MODE ON THE SOUTHERN OCEAN CARBON CYCLE

N.S. Lovenduski[1], N. Gruber[1], A. Hawes[2], and D.W.J. Thompson[2]

[1]*Department of Atmospheric and Oceanic Sciences, University of California at Los Angeles, Los Angeles, CA 90095; nikki@atmos.ucla.edu, ngruber@igpp.ucla.edu*

[2]*Department of Atmospheric Sciences, Colorado State University, Fort Collins, CO 80523; amy@atmos.colostate.edu, davet@atmos.colostate.edu*

ABSTRACT

The Southern Annular Mode (SAM) is the leading mode of intraseasonal to interannual variability over the entire Southern Hemisphere, yet the impact of the SAM on the Southern Ocean carbon cycle is largely unknown. We investigate the impact of the SAM on surface wind, sea surface temperature (SST), chlorophyll concentration, and sea ice concentration on the basis of 8-day averaged satellite observations. We find that Southern Ocean circulation and biogeochemistry react quite sensitively to this mode of variability, potentially resulting in air-sea CO_2 flux anomalies. Since variations in atmospheric CO_2 congruent with the SAM are small, we hypothesize that the SAM produces anomalous air-sea fluxes of both natural and anthropogenic CO_2, which act to compensate each other.

INTRODUCTION

The SAM is characterized by a large-scale alternation of atmospheric mass between the mid- and high latitudes of the Southern Hemisphere, and is associated with a meridional shift in the atmospheric westerly winds [*Hartmann and Lo*, 1998]. 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]. Changes in circulation can affect phytoplankton abundance, biogeochemical cycling, and the air-sea CO_2 flux in this region, yet the impact of the SAM on them has only begun to be documented [see *Lovenduski and Gruber*, 2005].

The Southern Ocean plays a critical role in the global climate system, yet very little is known about how the Southern Ocean carbon cycle varies in response to climate variability and how it may be affected by climate change. The SAM may play a particularly important role in understanding secular variations in the global carbon cycle since it has exhibited a trend towards its positive phase over the past few decades [*Thompson et al.*, 2000; *Thompson and Solomon*, 2002].

RESULTS

The SAM index is defined by the leading principal component of the 700 mb geopotential height south of 20ºS in the atmosphere, such that positive SAM is associated with a strengthening of the zonal atmospheric pressure gradient. Surface wind fields from QuikSCAT indicate that positive phases of the SAM are associated with a poleward shift in the atmospheric westerly winds (Table 1), which creates anomalies in both poleward and equatorward Ekman transport (Figure 1). Using AVHRR SST and SeaWiFS chlorophyll concentration data, we find that this process is responsible for driving increased upwelling of cold, iron-rich water into the region south of the Antarctic Polar Front (APF; see Figure 1). As this water is also enriched in dissolved inorganic carbon, we hypothesize that positive phases of the SAM may be associated with enhanced natural CO_2 outgassing from this region. We also find evidence for increased convergence and downwelling in the vicinity of the Subtropical Front during positive phases of the SAM. Mode waters (e.g. Antarctic Intermediate Water, Subantarctic Mode Water) typically form in this region, and in doing so, uptake large amounts of anthropogenic CO_2 from the atmosphere. Since variations in atmospheric CO_2 congruent with the SAM are small, we hypothesize that increased mode water formation, and consequently increased anthropogenic CO_2 uptake, in this region during positive phases of the SAM may be balancing the enhanced natural CO_2 outgassing from the region south of the APF.

Additionally, we decompose the variability of each satellite product in space and time using empirical orthogonal function analysis. We find that the spatial patterns associated with the leading mode of variability inherent in each of the data sets are closely related to the spatial patterns associated with the regression of the data anomalies onto the SAM index. This indicates that the SAM is linked to Southern Ocean circulation and biogeochemistry variability on intraseasonal to interannual timescales.

Variable	Zone	Mean Value	Regression Coefficient associated with $1\sigma_{SAM}$	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 [ºC]	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

Table 1. Mean values and regression and correlation coefficients of the anomaly time series with the SAM index. Anomaly time series were averaged over 4 Southern Ocean zones, as defined by oceanic frontal boundaries. The Antarctic Zone (AZ) is the region between the Antarctic continent and the Antarctic Polar Front (APF), the Polar Frontal Zone (PFZ) is the region between the APF and the Subantarctic Front (SAF), the Subantarctic Zone (SAZ) is the region between the SAF and the South Subtropical Front (SSTF), and the Subtropical Zone (STZ) is the region between the SSTF and the North Subtropical Front (NSTF), as shown in Figure 1. From *Lovenduski and Gruber*, 2005.

CONCLUSIONS

Figure 1 summarizes our assessment of the impact of the SAM on the Southern Ocean carbon cycle. During positive phases of the SAM, we suspect that the anomalous upwelling of waters rich in dissolved inorganic carbon in the Antarctic Zone (AZ) is elevating the partial pressure of CO_2 in the surface waters. The resulting outgassing may, however, be mitigated by increased CO_2 solubility (cold SST) and biological productivity (high chlorophyll) in this region. Positive SAM increases convergence and downwelling in the Subantarctic Zone (SAZ), a mode water formation region in 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 (low chlorophyll) in this region. Overall, we therefore expect only a moderate level of air-sea CO_2 flux variability.

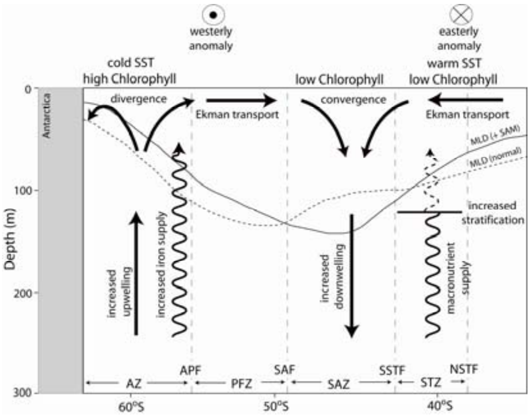

Figure 1. Schematic illustration of the upper ocean response to a positive phase of the SAM. From *Lovenduski and Gruber*, 2005.

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