Climate Variability and Southern Ocean Carbon Uptake

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Since the beginning of the industrial revolution, anthropogenic emissions of carbon dioxide (CO_2) have increased atmospheric CO_2 concentrations, driving increases in global atmospheric temperature. Only about half of the anthropogenic CO_2 emissions have remained in the atmosphere, while the remainder have been absorbed by natural carbon sinks: the ocean and the terrestrial biosphere. Modeling studies suggest that nearly half of the global oceanic anthropogenic CO_2 uptake has occurred in the Southern Ocean (Mikaloff Fletcher et al., 2006). As such, the Southern Ocean is an important regulator of atmospheric CO_2 and the global climate system.

The physical circulation of the Southern Ocean governs the exchange of CO_2 across the air-sea interface. South of the Antarctic Circumpolar Current (ACC), the circulation is characterized by divergence and upwelling of deep water to the surface. The upwelled deep water is enriched in dissolved inorganic carbon (DIC), and given the inefficient DIC uptake via the biological pump, the high latitude Southern Ocean tends to lose natural CO_2 to the atmosphere (Figs. 1a, 3; Mikaloff Fletcher et al., 2007). North of the ACC, subduction and mode water formation lead to substantial oceanic uptake of natural carbon from the atmosphere. This pattern of oceanic release and uptake of natural carbon is overlain by a pattern of uptake of anthropogenic CO_2, which is largest north of the ACC (Khatiwala et al., 2009). The resulting pattern of the contemporary CO_2 fluxes is thus the superposition of these two component fluxes, with reduced outgassing south of the ACC relative to pre-industrial times, and enhanced uptake north of the ACC (Gruber et al., 2009).

The Southern Ocean sink for atmospheric CO_2 has exhibited significant interannual to multi-decadal variability over the past few decades. Coarse-resolution physical and biogeochemical ocean models yield large interannual variability in high-latitude sea-air fluxes of natural CO_2 (Fig. 2; Lenton and Matear, 2007; Lovenduski et al., 2007; Verdy et al., 2007). Studies based on ocean models (Lovenduski et al., 2008) and the inversion of atmospheric CO_2 data (Le Quéré et al., 2007) have revealed a significant multi-decadal trend in sea-air fluxes of natural CO_2 over the past 30 to 50 years (Fig. 2) that has substantially weakened the Southern Ocean's capacity to absorb CO_2 from the atmosphere. It has been suggested that a large fraction of this variability is driven by the Southern Annular Mode (SAM).

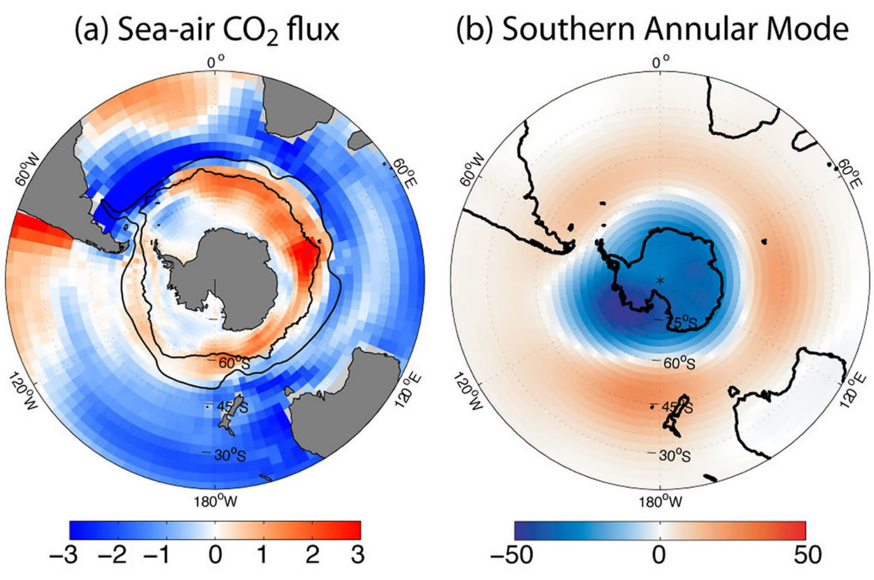
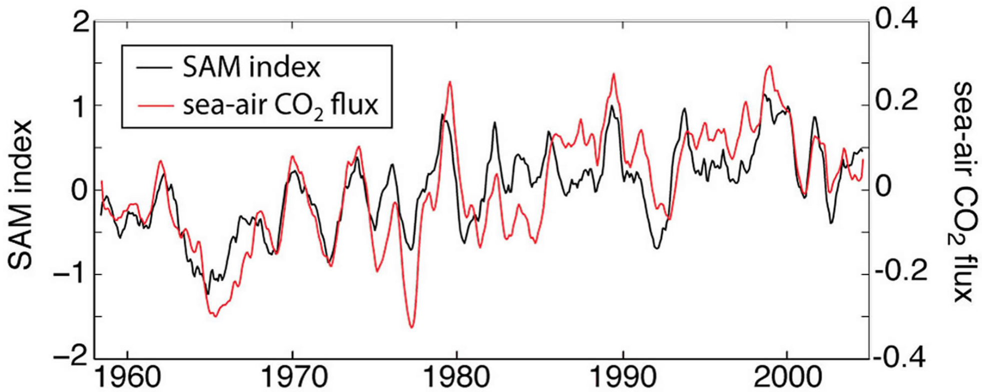


Figure 1. (a) Annual-mean observed sea-air CO_2 flux (mol m-2 yr-1). Positive values indicate CO_2 outgassing. Data from Takahashi et al. (2009). Black contours indicate the position of the Antarctic Polar Front and Subantarctic Front, the two main cores of the ACC. (b) Regression of 700 mb geopotential height anomalies onto the SAM index (m).

The SAM is the dominant mode of atmospheric climate variability in the extratropical Southern Hemisphere, and is characterized by an oscillation of atmospheric mass between the mid- and high latitudes. Positive and negative phases of the SAM are associated with meridional shifts in the westerly winds (Fig. 1b; Thompson and Wallace, 2000). Observations show a positive trend in the SAM over the past 30 years, synchronous with a poleward intensification of the westerly winds (Thompson et al., 2000).

A substantial component of Southern Ocean circulation and sea-air

Figure 2. Integrated Southern Ocean (<35oS) sea-air flux of natural CO_2 (red; Pg C yr-1), as estimated by a coarse-resolution ocean GCM, and the standardized SAM index (black). Both time series have been smoothed with a 12-month running average. Adapted from Lovenduski et al. (2007).



CO_2 flux varies in phase with the SAM. Positive phases of the SAM (poleward-intensified westerlies) are correlated with an increase in northward Ekman transport and meridional overturning, inducing anomalous upwelling of water in the region south of the ACC (Hall and Visbeck, 2002). Since these upwelled waters are enriched in natural DIC, model-based studies show enhanced outgassing of natural CO_2 from the Southern Ocean during a positive SAM (Fig. 2; Lovenduski et al. 2007), while anthropogenic fluxes remain largely unchanged. Simulations of coarse-resolution ocean general circulation models (GCMs) suggest that the multi-decadal trend in the SAM has led to a long-term increase in the rate of meridional overturning, driving an increase in the upwelling and equatorward transport of DIC-rich waters, and a trend toward outgassing of natural CO_2 (Figs. 2, 3; LeQuéré et al. 2007; Lovenduski et al. 2008) while again, the anthropogenic CO_2 fluxes appear not to be affected.

Recent literature questions whether coarse-resolution ocean GCMs can simulate an appropriate Southern Ocean meridional overturning circulation (MOC) response to the SAM (Böning et al., 2008; Hogg et al., 2008). Mesoscale eddies, believed to play a central role in Southern Ocean heat and momentum balance, are not explicitly resolved, but rather are parameterized in such models. During positive phases of the SAM, the Ekman-driven increase in the strength of the MOC may be compensated by a wind-induced increase in the southward eddy fluxes, such that there is little net change in the residual MOC. If SAM variability has only a moderate impact on the rate of meridional overturning, one would expect only a small anomaly in CO_2 outgassing during positive phases of the SAM. Similarly, the trend in natural sea-air CO_2 flux (Fig. 2) would likely be substantially reduced relative to that predicted by coarse-resolution models. Resolving this issue will require improved parameterization of eddy advection in coarse-resolution ocean GCMs (Farneti and Gent, 2011; Gent and Danabasoglu, in press), eddy-resolving simulations of the Southern Ocean carbon cycle (Lovenduski et al., in prep.), and enhanced physical and biogeochemical observations of the Southern Ocean.

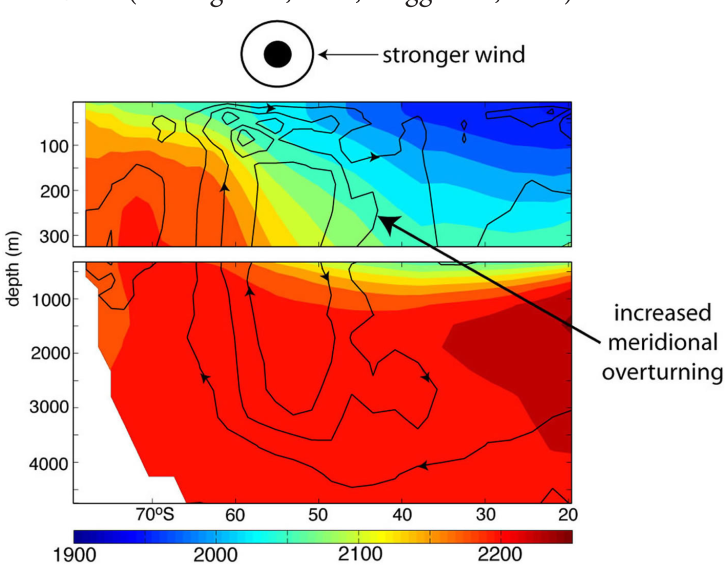


Figure 3. Annual-mean, zonal-mean DIC concentration (colors; mol kg-1), and the 30-year trend in the meridional overturning streamfunction (contours), as estimated by a coarse-resolution ocean GCM. Adapted from Lovenduski et al. (2008).

Relatively sparse sampling of physical and biogeochemical properties in the Southern Ocean has hampered the investigation of circulation and carbon uptake variability from an observational perspective. However, a few studies of long-term biogeochemical changes have recently emerged in the literature. Using historical measurements of the partial pressure of CO_2 in the surface ocean, Metzl (2009) and Takahashi et al. (2009) documented a multi-decadal decrease in Southern Ocean CO_2 uptake rates. On the basis of historical radiocarbon measurements in Drake Passage, Sweeney et al. (in prep.) provide evidence for a positive trend in the rate of meridional overturning over the last three decades. While these results appear to support those produced from coarse-resolution modeling studies, there remains a critical need for additional observational studies in this region.

The future evolution of the Southern Ocean carbon sink will depend on the future state of the climate system, which remains difficult to quantify. Simulations of future climate from coupled models consistently predict a positive trend in the SAM, warmer surface ocean temperatures, and enhanced precipitation in the Southern Ocean region over the coming century (Meehl et al., 2007). While the SAM trend is likely to lead to more vigorous overturning (Sigmond et al., 2011), the warming and freshening of the Southern Ocean surface is expected to increase stratification (Sarmiento et al., 1998). Accurate predictions for the future evolution of the Southern Ocean carbon sink therefore require understanding how both SAM and stratification changes impact carbon cycling and sea-air CO_2 exchange in this region (Lovenduski and Ito, 2009).

Given the importance of the Southern Ocean for the global carbon cycle and climate system, it is critical that we develop a sustained physical and biogeochemical observational program for the Southern Ocean, and that we continue to improve modeling efforts in this region.

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