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# Simulated impact of altered Southern Hemisphere winds on the Atlantic Meridional Overturning Circulation

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[1] Previous work has suggested that the strength and latitudinal position of the Southern Hemisphere (SH) mid-latitude westerly winds has an important impact on climate and the Atlantic Meridional Overturning Circulation (AMOC). We probe this hypothesis by conducting ensembles of experiments using the GFDL CM2.1 coupled ocean-atmosphere model with altered SH wind stress. We find, consistent with previous work, that enhanced (reduced) and poleward (equatorward) displaced SH westerly winds lead to an AMOC intensification (weakening). While the AMOC takes more than a century to respond fully to the altered SH winds, initial effects in the North Atlantic can occur within a few decades. The AMOC changes generate SST and surface air temperature responses in the North Atlantic and adjacent continental regions. In the Southern Hemisphere, the atmosphere responds to the altered ocean circulation with a further strengthening and poleward movement of the SH winds, thereby constituting a modest positive feedback. **Citation:** Delworth, T. L., and F. Zeng (2008), Simulated impact of altered Southern Hemisphere winds on the Atlantic Meridional Overturning Circulation, *Geophys. Res. Lett.*, *35*, L20708, doi:10.1029/2008GL035166.

## 1. Introduction

[2] The position and intensity of the mid-latitude Southern Hemisphere (SH) winds has emerged as an important influence on both the mean climate, including the Atlantic Meridional Overturning Circulation (AMOC), and in the response of the climate system to change [*Toggweiler and Samuels*, 1993; *McDermott*, 1996; *Gnanadesikan*, 1999; *Toggweiler et al.*, 2006; *Russell et al.*, 2006a; *Levermann et al.*, 2007]. The SH winds have a dominant influence on the circulation of the Southern Ocean, including ventilation [*Saenko et al.*, 2002] and the oceanic uptake of heat and carbon [*Mignone et al.*, 2006], and are an important component of the AMOC [*Kuhlbrodt et al.*, 2007]. Model-based projections of future climate change suggest that the SH winds will move poleward and amplify in response to projected changes in radiative forcing [*Kushner et al.*, 2001; *Fyfe and Saenko*, 2006]. This could have important implications for the oceanic uptake of carbon dioxide [*Russell et al.*, 2006b] and other aspects of ocean circulation [*Saenko*, 2007]. Evidence suggests that such a wind shift is already underway [*Gillett and Thompson*, 2003].

[3] In this work, we ask the following questions: (1) What is the impact of altered SH winds on the ocean circulation, especially the AMOC? (2) What subsequent impact does any altered ocean circulation have on the rest of the climate system, including the atmosphere? We address these questions by conducting ensembles of experiments with a coupled ocean atmosphere model in which SH wind stress anomalies are applied to the model ocean.

## 2. Model and Experimental Design

[4] We use GFDL's CM2.1 coupled ocean-atmosphere climate model [*Delworth et al.*, 2006]. The coupled model consists of atmosphere, ocean, land, and sea ice component models. The horizontal resolution of the atmospheric model is 2.5° longitude by 2.0° latitude, with 24 levels in the vertical. The horizontal resolution of the ocean model is 1° in the extratropics, with meridional grid-spacing in the Tropics gradually reducing to 1/3° near the Equator. The ocean model has 50 levels in the vertical, with 22 evenly spaced levels over the top 220 m. Atmosphere-ocean coupling occurs every two hours. The model does not employ flux adjustments. For further information and model output see http://nomads.gfdl.noaa.gov/CM2.X/.

[5] We make use of several types of experiments. The first is a 2000-year control experiment in which atmospheric constituents and external forcings are held constant at 1860 conditions. Output from this integration is used to provide a statistical description of unforced, internal variability in the model, as well as initial conditions for the forced experiments described next.

[6] We conduct perturbation experiments by applying anomalous wind stress patterns to the model ocean. In the coupled model, fluxes are exchanged between the atmosphere and ocean every two hours. In the perturbation experiments, when this flux exchange occurs we add an additional wind stress anomaly pattern to the ocean, thereby making the model ocean "feel" the altered SH winds. The amplitude and sign of this pattern are altered for various experiments, as described below. It is crucial to note that the atmosphere has no direct knowledge of these altered winds. The atmosphere is only impacted through any changes to the ocean that the wind stress anomalies induce.

[7] The wind stress anomaly applied in the perturbation experiments is constant in time. Its latitudinal structure and amplitude are shown in Figure 1 by the brown circles, and are taken from the output of a simulation of the 22nd century using the CM2.1 model. (The full spatial structure is shown in Figure S1 in the auxiliary material[1]). This simulation uses the

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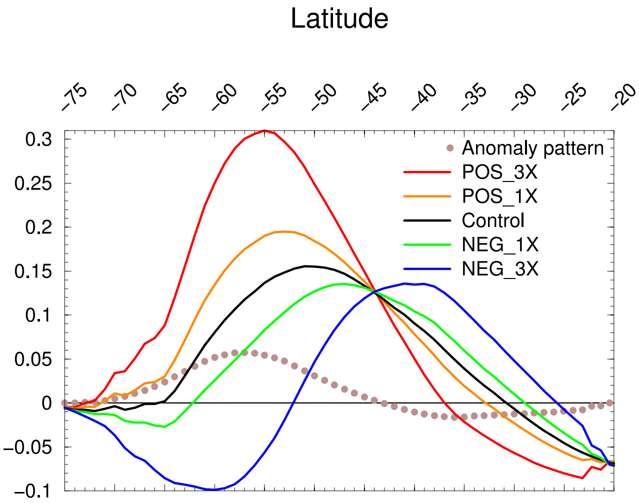

**Figure 1.** Zonal mean of the zonal wind stress in various experiments. The black line shows the control experiment. The brown circles denote the zonal mean of the zonal wind stress anomaly applied to the ocean in the various experiments; this anomaly pattern is multiplied by a scaling factor (+/−1, +/− 3) before being applied in addition to the wind stress calculated in the coupled model. The zonal mean of the zonal wind stress shown for each of the four perturbation experiments is then calculated as the time-mean of the zonal wind stress computed in the model plus the additional wind stress anomaly applied to the ocean in that experiment (the brown dotted curve multiplied by a scaling factor). Units are N m$^{-2}$.

SRES A1B scenario for forcing [*Intergovernmental Panel on Climate Change*, 2000], and represents one estimate of the future evolution of greenhouse gases and aerosols. Under this warming scenario, the SH winds intensify and shift poleward. This response is common among the models used for the recent IPCC AR4 assessment [*Fyfe and Saenko*, 2006]. We define our anomaly wind stress pattern by subtracting the wind stress from the control integration from the wind stress from model years 2181–2200.

[8] We conduct four ensembles of experiments, where each ensemble has three members that start from different years of the long control integration (specifically, years 951, 1001, and 1051). Each experiment is 200 years long. All results shown are ensemble means. The ensembles differ in the amplitude of the applied anomaly pattern. In ensemble "POS_1X" we add +1 times the flux anomaly defined above. In the second ensemble (POS_3X) we add the same flux pattern, but multiplied by a factor of 3. In the third ensemble (NEG_1X) we add the same flux pattern, but multiplied by a factor of −1. In the fourth ensemble (NEG_3X) we add the same flux pattern, but multiplied by a factor of −3. We show in Figure 1 the zonal mean of the zonal wind stress from the Control integration and the perturbation experiments. Shown are the sums of the wind stress computed in the various simulations plus the perturbation wind stress applied. The latitude of maximum zonal mean zonal wind stress felt by the ocean is 51°S in the Control integration. This changes to 53°S in the POS_1X experiment, and 55°S in the POS_3X experiment. In contrast, this occurs at 47°S in the NEG_1X experiment, and 41°S in the NEG_3X experiment.

## 3. Ocean Response to Altered SH Winds

[9] Previous work has suggested that changes in SH wind stress will impact the AMOC and oceanic heat transport [see, e.g., *Toggweiler and Samuels*, 1993; *McDermott*, 1996; *Gnanadesikan*, 1999; *Oke and England*, 2004; *Toggweiler et al.*, 2006; *Speich et al.*, 2007; *Toggweiler and Russell*, 2008]. Physically, enhanced SH winds induce a northward Ekman transport in the upper layers of the Southern Ocean, thereby enhancing the flow of water from the Southern Ocean into the Atlantic. This northward flow is balanced by a return southward flow at depth, with deep water exiting the Atlantic, thereby enhancing the AMOC. Intensified and poleward shifted SH winds act to enhance the upwelling of North

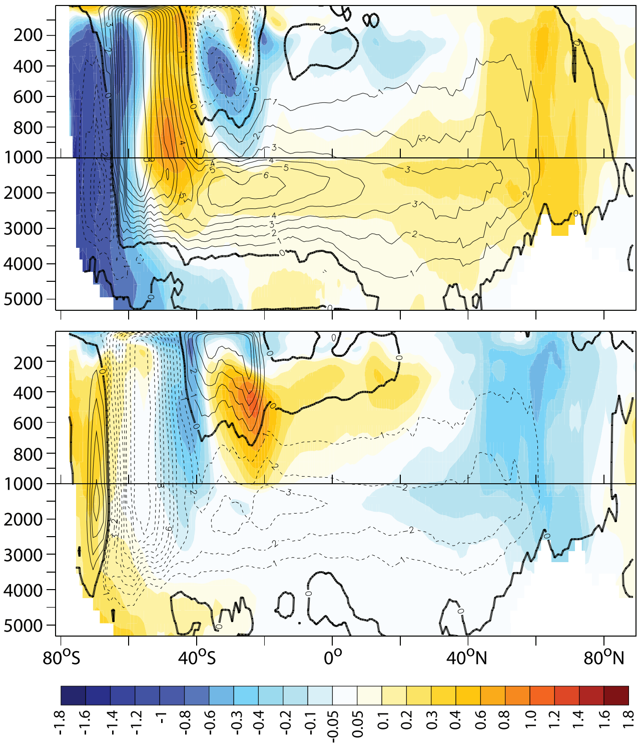

**Figure 2.** Zonal mean, annual mean temperature and meridional overturning circulation response to altered SH winds. Values plotted are time-means for years 101 to 200 after the perturbed SH winds are imposed, and represent differences between the ensemble mean of the perturbation experiments and the corresponding segments of the Control integration. The color shading shows the zonally averaged temperature response (units are K). The lines show the change in the global meridional overturning circulation (units are Sverdrups; 1 Sverdrup = $10^6$ m$^3$ s$^{-1}$). (For interpretation, anomalous flow moves clockwise around a local maximum in the streamfunction plotted; for the top panel this implies enhanced sinking at higher latitudes of the North Atlantic). (top) POS_1X minus control, indicating effects of poleward shifted SH winds. (bottom) NEG_1X minus control, indicating effects of equatorward shifted SH winds. Note that the vertical scale is amplified over the top 1000 meters.

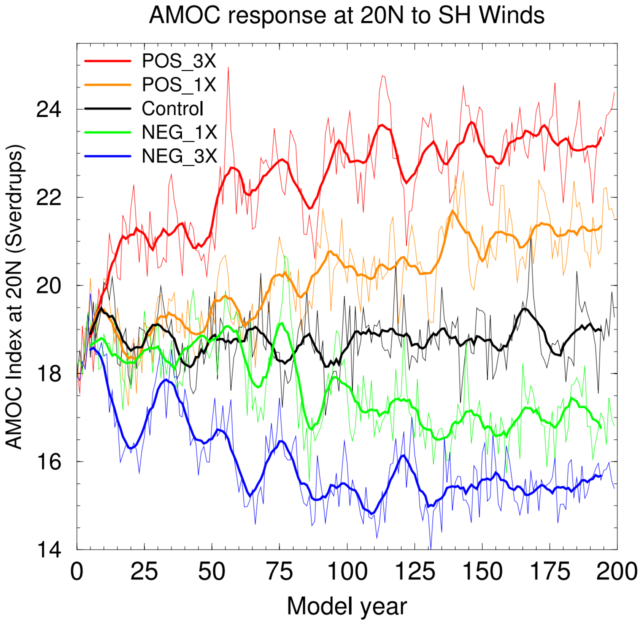

**Figure 3.** Response of the Atlantic Meridional Overturning Circulation (AMOC) to changes in wind stress over the Southern Ocean. The quantity plotted is the maximum value of the overturning streamfunction at 20°N in the North Atlantic. All values plotted are three member ensemble means. The Control, shown in black, indicates the average of the AMOC index over the three segments of the Control run corresponding to the perturbations runs (years 951–1150, 1001–1200, and 1051–1250). The thin lines denote time series of annual mean data for each experiment. The thicker solid lines denote 11 year running means. The colors indicate the various experiments: orange, POS_1X; red, POS_3X; green, NEG_1X; blue, NEG_3X.

Atlantic Deep Water (NADW) in the Southern Ocean, thereby increasing ocean ventilation [*Russell et al.*, 2006b].

[10] We show in Figure 2 the zonally averaged response of ocean temperature to the altered SH winds for the POS_1X and NEG_1X cases, along with changes in the global overturning streamfunction. The responses in the 3X cases (not shown) are similar in structure, but larger in amplitude. The physical relationship whereby altered SH winds impact the ocean appears clearly here. For the POS_1X case in the top plot, enhanced westerly winds between 50°S and 65°S drive a strong northward Ekman flow in the surface layers. This water subducts and moves northward in the subsurface layers, enhancing flow to the high northern latitudes where the water sinks. This leads to a strengthening of the AMOC, and enhanced southward flow below 2000 m from 60°S to 60°N (a global streamfunction is shown here, but the streamfunction changes in the Northern Hemisphere are primarily in the Atlantic).

[11] The poleward shifted SH winds move the oceanic upwelling further poleward in the SH, and increase the poleward penetration of warmer waters of subtropical origin, thereby warming the water column from 40°S to almost 60°S. Poleward of 60°S the water column cools, likely associated with enhanced vertical penetration of surface cooled waters. Changes in the NEG_1X ensemble have similar structure, but with opposite sign and smaller amplitudes. The simulated temperature changes in the POS_1X case are qualitatively consistent with observed warming in the Southern Ocean [*Gille*, 2002].

[12] We show in Figure 3 time series of the annual mean AMOC index at 20°N. The enhancement and poleward displacement of the SH winds in the "POS" experiments strengthens the AMOC, while the opposite is true for the weakened and equatorward shifted winds in the "NEG" experiments. The full adjustment to the wind stress anomalies takes at least one to two centuries, consistent with results of *Johnson and Marshall* [2004], although initial effects can be felt in the North Atlantic within a few decades of imposing the altered winds. The two "POS" experiments do not appear to have reached equilibrium at the end of 200 years, while the two "NEG" experiments appear to have equilibrated at reduced AMOC intensities by the end of the experiments.

[13] The response of SST is shown in Figure 4. In the mid to higher latitudes of the North Atlantic the SST changes are consistent with the AMOC changes – warming when the AMOC and oceanic heat transport is enhanced. For POS_1X, positive SST anomalies in the subpolar North Atlantic are around 0.5K, with local maxima exceeding 1.5K. SST anomalies in the subpolar North Atlantic have a similar structure with opposite sign for NEG_1X. For the POS_3X and NEG_3X cases (not shown) the patterns of SST changes in the subpolar North Atlantic are similar to

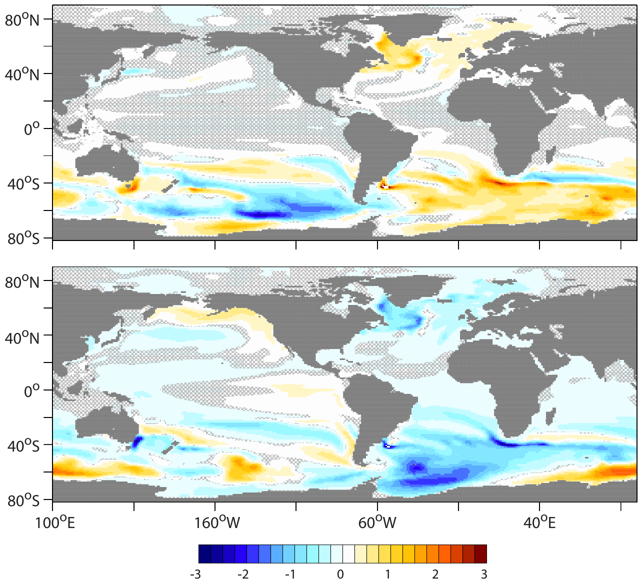

**Figure 4.** Sea surface temperature (SST) response to the altered SH wind stress. These are annual means, computed as the time means for years 101 to 200 after the addition of the SH wind stress anomalies. Units are K. Fields are computed by subtracting the SST fields in the control simulation from the ensemble mean SST fields from the perturbation experiment. Thus, positive values indicate a warming in response to the wind stress anomaly. Stippled regions indicate regions where the differences are not significant at the 1% level using a two sided t test. (top) POS_1X, indicating effect of poleward displaced SH winds. (bottom) NEG_1X, indicating effect of equatorward displaced SH winds.

the 1X cases, with enhanced amplitude – local SST changes can exceed 3K.

[14] The patterns of SST changes in the Southern Ocean are more complicated and evolve over time (not shown). Several factors determine the SST changes. The altered winds in the POS_1X case lead to a warming of the upper 3000 m of the water column from 40°S to 60°S, associated with a poleward shift in the ocean circulation, and increased upwelling of warm, salty North Atlantic deepwater. This contributes to a general increase of SST. However, the enhanced westerly winds also create an enhanced Ekman transport in the surface layers; this tends to cool the surface layer. In addition, there are changes in transport associated with boundary currents. For example, the wind stress anomaly modulates the latitudinal position of the Aghulas current. A more poleward position of the winds allows more Indian Ocean water to enter the Atlantic, with a local maximum in the surface warming in the vicinity of the Aghulas current. An additional factor influencing SST changes is that the Antarctic Circumpolar Current (ACC) changes in response to the winds. For the POS_1X case, the ACC increases by approximately 30%, from 130 Sverdrups (Sv; 1 Sv = $10^6$ $m^3$ $s^{-1}$) to 170 Sv. The current results present a more complicated picture than that shown by *Levermann et al.* [2007], possibly due to differences in forcing, simulation length, or model design. These differences need to be better understood.

## 4. Atmospheric Response to Altered SH Winds

[15] In our experimental framework we can assess the impact of wind-stress induced ocean changes on the atmosphere. For the POS_1X case, sea level pressure (SLP) is substantially lower over the high latitudes of the Southern Hemisphere during DJF, consistent with a further enhancement and poleward movement of the SH westerlies (see Figure S2). There are also increases in SLP in the Southern Hemisphere midlatitudes. If we define the feedback as the enhancement of the zonal stress in the coupled model relative to the imposed stress anomaly, we conclude there is a small positive feedback (approximately 5%). The SLP for the NEG_1X case is generally of opposite sign. The SLP responses with 3X forcing (not shown) have similar spatial structures as the 1X cases, but with larger amplitudes and more regions that are statistically significant.

## 5. Summary and Discussion

[16] We have used a state of the art coupled ocean-atmosphere model to probe the climate system response to altered Southern Hemisphere (SH) winds. In our experiments, we force the model ocean with changes in wind stress corresponding to the simulated wind shift between the end of the 22nd century and preindustrial conditions. The climate system then adjusts to these changes.

[17] We find that changes in the SH winds have a clear impact on the Atlantic Meridional Overturning Circulation (AMOC). For example, a 2° poleward shift in the winds, accompanied by a 0.04 N $m^{-2}$ increase in the maximum zonal wind stress, increases the AMOC by 2 Sv after 200 years. This is accomplished by changes in Ekman transport in the upper layers of the Southern Ocean, inducing a southward flow at depth in the Atlantic (below 2000 m) and enhanced upwelling in the Southern Ocean of North Atlantic Deep Water (see Figure 2). There is also enhanced downward motion near the coast of Antarctica.

[18] We also find a small positive atmospheric feedback to the SH wind forcing changes. The poleward shift and strengthening of the SH winds induces a 1–2 hPa reduction of SLP over high latitudes of the Southern Hemisphere, consistent with enhanced SH zonal winds.

[19] These results have implications for a variety of climate change issues. For example, most models project a weakening of the AMOC in response to global warming. These results suggest that the SH wind shifts that accompany global warming and changes in stratospheric ozone would tend to oppose that weakening, although the effect in this model is modest. For example, it takes approximately 80 years for the SH wind shift in the POS_1X case to significantly strengthen the AMOC at 20°N. Conversely, equatorward shifted winds would weaken the AMOC, and this could be of relevance for glacial climates.

[20] While the coupled model used was one of the best models used in the recent IPCC AR4 assessment for the AMOC [*Schmittner et al.*, 2005] and the Southern Ocean [*Russell et al.*, 2006a], this model has relatively coarse resolution, is fairly viscous, and has weaker ocean currents than observed. Experiments such as those described here need to be repeated in models with higher resolution, lower viscosity, and generally more energetic flows that include features such as mesoscale eddies. It is possible that the amplitudes of the responses and feedbacks described here, as well as the response time scales, could be dependent upon such model characteristics.

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