Sensitivity of Southern Hemisphere circulation to LGM and 4×CO2 climates

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[1] This paper investigates the effect of Last Glacial Maximum (LGM) versus high CO2 world boundary condition on the Southern Hemisphere atmospheric circulation, in particular on the strength and latitudinal position of the near surface Southern Westerly Winds (SWW). PMIP2 and PMIP3 experiments, as well as the "abrupt 4×CO2" simulations from CMIP5, were analyzed. Robust findings include poleward expansion of the Mean Meridional Circulation (MMC) and intensified and poleward-shifted SWW in the 4×CO2 simulations (consistent with recent observations and 21st century climate change projections); and for the LGM, stronger and southward shifted northern hemisphere MMC, and weakened southern Hadley cell. However, six of the eight LGM simulations show a decrease in the SWW, the other two models simulate the opposite. A critical difference between the models is strong coupling between sea-ice extent, surface temperature gradients, SWW, and Ferrel cell in the two models with stronger and poleward-shifted SWW. Citation: Rojas, M. (2013), Sensitivity of Southern Hemisphere circulation to LGM and 4×CO2 climates, Geophys. Res. Lett., 40, 965-970, doi:10.1002/grl.50195.

1. Introduction

[2] The Southern Westerly Winds (SWW) are part of the surface expression of the tropospheric circulation in the Southern Hemisphere. They are a key component of the global climate system, affecting the precipitation over the Southern Hemisphere, the Antarctic Circumpolar Current, and the global carbon cycle. The annual cycle of the SWW results from the interplay between tropospheric meridional temperature gradients and sea-surface temperatures (SST) [e.g., Sampe et al., 2010]. Although the main hypotheses to explain glacial/interglacial CO₂ variations invoke the deep ocean, how exactly the CO_2 is stored during glacial periods and later outgassed at terminations remains elusive. The first model invoking an important role of the SWW in glacial/interglacial cycles was proposed by Imbrie et al. [1992], subsequently refined by Toggweiler et al. [2006] who developed a simplified numerical model, where equatorward-shifted SWW during extreme glacial conditions would have reduced the strength of ocean ventilation in the southern ocean (SO), inducing the characteristic minima in atmospheric CO₂ during glacial maxima. Poleward-shifted SWW during glacial terminations, on the other hand, would bring the core of the SWW into the latitude of the Drake Passage enhancing ocean ventilation and the release of CO₂ into the atmosphere, establishing a positive feedback into the de-glacial warming trend. Recent sedimentary (marine and terrestrial) data provide empirical support for the SWW-SO-CO₂ hypothesis during the onset of the last glacial termination [e.g., Skinner et al., 2010; Denton et al., 2010; Moreno et al., 2012] and during Marine Isotope Stage 3 [Anderson and Carr, 2010]. However, Earth System models of intermediate complexity with carbon cycle have tested this hypothesis and have consistently found that the effect of the changes in SWW wind stress on the upwelling and hence CO₂ outgassing is not enough to account for the CO₂ variations through the glacial-interglacial cycle [Menviel et al., 2008; Tschumi et al., 2008; Chikamoto et al., 2012] or find even a partially opposite signal [d'Orgeville et al., 2010] and hence do not confirm Toggweilers hypothesis. On the other hand, at the other extreme of the glacial/interglacial cycle, the current anthropogenic perturbed interglacial, there is a robust and consistent intensification and poleward shift of the storm tracks (and hence SWW) in observations [Wang et al., 2006; Bender et al., 2011] and climate change simulations [Yin, 2005; O'Gorman, 2010]. The increased strength of the SWW has been invoked as the cause of the decrease in ocean CO_2 uptake in the region [Le Quere et al., 2007]. Furthermore, several studies with state-of-the art ocean-biogeochemistry models attribute inter-annual and decadal variations, as well as twentieth century trend in CO₂ variations to SWW, through changes in the Southern Annular Mode (SAM) [Lenton and Matear, 2007; Treguier et al., 2010]. The positive trend observed in SAM in recent decades has forced the observed SWW strengthening and has been principally attributed to stratospheric ozone loss [Polvani et al., 2011]. The evidence of SWW response to modern interglacial condition and forcing on recent CO₂ variations suggests an asymmetric response of the Southern Hemisphere large-scale circulation to glacial/interglacial conditions that still needs to be addressed and remains in active debate.

[3] In *Rojas et al.* [2009] (R09 from here onwards), from four PMIP2 LGM simulations, three simulated weaker winds during the LGM compared to the pre-industrial control, however with no significant shift in the mean position of the SWW. *Drost et al.* [2007] also came to a similar conclusion analyzing one LGM simulation (HadCM3) for the New Zealand region. A recent study by *Chavaillaz et al.* [2012] analyzes the PMIP3 LGM simulation in conjunction with the climate change CMIP5 RCP4.5. They describe the SWW in those simulations and find a

All Supporting Information may be found in the online version of this article.

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systematic poleward shift from PI to RCP4.5 warming but no systematic change from the LGM to PI warming. This paper re-evaluates the R09 study and widens the scope to understand the SWW and Southern Hemisphere circulation changes in the PMIP3 LGM and CMIP5 "abrupt 4xCO2" experiments ($4 \times CO2$ here onwards). The $4 \times CO2$ experiment is a simplified and more extreme analogue of climate change scenario simulations, which does not include the effects of aerosols and stratospheric ozone destruction.

2. Model Simulations

[4] Three types of experiments have been analyzed in this paper: the Last Glacial Maximum (LGM) as simulated by models that took part of the Paleo Modeling Intercomparison Project in its second phase (PMIP2, five models, *Braconnot et al.* [2007]: CCSM3, IPSL, HadCM3, MIROC3.2, and FGOALS) and PMIP3 (eight models, *Braconnot et al.* [2012]: CCSM4, IPSL, GISS, MIROC-ESM, MRI, CNRM, MPI, and COSMOS); the pre-industrial control simulation (PI); and the abrupt 4×CO2 experiment (seven models, CMIP5 experiment 6.3, *Taylor et al.* [2012]: CCSM4, IPSL, GISS, MIROC-ESM, MRI, CNRM, MPI). The abrupt $4\times$ CO2 is an experiment that starts from the PI control simulation and imposes an instantaneous quadrupling of atmospheric CO₂ concentration that is then hold fixed for 150 years [*Taylor et al.*, 2012]. Table S1 in the Supporting Information indicates the models used in this study and their resolution. Three of the models have PMIP2 and PMIP3 simulations (CCSM4, IPSL, and MIROC), where the effect on circulation of model development, including increased spatial resolution, can be assessed. Analyzed variables are monthly: winds, temperatures, precipitation and sea-ice extent, and sea-surface temperatures (SST) when available. Because SSTs are not available from all models, the SSTs gradient's effect on circulation is investigated by looking at air temperature gradients at the lowest level.

3. Results

3.1. Circulation

[5] Figure 1 shows the annual mean zonal wind at 850 hPa from the five PMIP2, eight PMIP3, and seven $4 \times CO2$ simulations. Solid contours (dashed) correspond to



Figure 1. Latitudinal cross section of annual mean zonal mean SWW speed at 850 hPa LGM and PI experiments: (a) PMIP2, (b) PMIP3, and (c) same as Figure 1b but for 4×CO2. Solid contours, PI; dashed contours, LGM/4xCO2; thin black line, NCEP/NCAR reanalysis.

the PI (LGM/ $4 \times CO2$) simulations, respectively. From the five PMIP2-LGM simulations, three simulate weaker winds, with no discernible shift in the latitude of the maximum winds. From the eight PMIP3-LGM simulations, six simulate weaker winds; some of them include a small equatorward shift. PMIP3 CCSM4 and MRI models (the two models with highest horizontal resolution) simulate the opposite: stronger and poleward-shifted SWW. On average, changes in the winds represent between 10 and 20% of the PI winds. On the other hand, Figure 1c indicates that in all the $4 \times CO2$ simulations, the winds show a significant increase and poleward shift that represents a 20-60% increase with respect to the PI simulations. As reference, the thin black line in Figure 1 corresponds to the NCAR/NCEP reanalysis wind [Kalnay et al., 1996]. Most of the models put their maximum wind too far equatorward. From PMIP2 to PMIP3, there is an improvement in the simulation of the SWW in the PI simulations (decreased strength and a poleward shift of the maximum wind location). However, the response of the SWW to LGM boundary conditions is the same in both versions. For example, CCSM4 simulates stronger and poleward-shifted winds in both PMIP2 and PMIP3 LGM simulations, compared to the PI. Given the results of SWW at 850 hPa seen in Figure 1b, for the rest of the analysis, I have taken a six (five) model mean for the LGM (4×CO2) simulations (MPI, MIROC, CNRM, GISS, IPSL, and COSMOS) and a two model mean (CCSM4 and MRI).

[6] Figure 2 shows latitude versus height meridional temperature gradients, as they are related to midlatitude tropospheric circulation. Also shown is the zonal mean, winter mean sea-ice extent, and surface temperature gradient in the smaller panels as lines and bars, respectively. For the LGM, in the Southern Hemisphere, all models simulate reduced mid- to high-troposphere meridional temperature gradients, between about 20 and 50°S, and increased gradients over Antarctica. CCSM4 and MRI simulate increased surface and lower tropospheric temperature gradients between 40 and 60°S and further equatorwards extended sea ice (55°S versus 65°S for the LGM), whereas the six-model mean has slightly decreased surface temperature gradients and less extended sea ice (just to about 55° S). For the 4×CO2 simulations, all models indicate increased temperature gradients up to 60°S, and decreased south of 60°S, compared to PI, i.e., opposite meridional temperature gradients to LGM. There are no significant differences between the fivemodel and two-model means in the 4×CO2 simulations. For the northern hemisphere, the temperature gradient changes depend more on season, but in the annual mean, LGM temperature gradient increase over PI and tend to decrease in 4×CO2 over PI. Temperature gradient differences are robust as measured by small standard deviation from the mean in most regions (shown in Supporting Information Figure S1).

[7] The meridional mass stream function of the models was calculated, depicting the zonal mean mean meridional circulation (MMC), and shown in Figure 3. In the annual mean, the MMC in the Southern Hemisphere is characterized by a strong and latitudinally extended $(5^{\circ}N-30^{\circ}S)$ southern branch of the Hadley cell, a midlatitude Ferrel cell $(30-65^{\circ}S)$, with a strong midlatitude jet that extents from the upper troposphere down to the surface, and a polar cell south of $65^{\circ}S$ (Figures 3a and 3d). In the northern hemisphere, the northern branch of the Hadley cell is less



Figure 2. Annual mean meridional temperature gradients. (a, c, e, g) White lines, PI temperature contours; black contours, PI meridional temperature gradients; shaded, LGM(4×CO2)-PI temperature gradients. (b, d, f, h) 1000 hPa temperature gradients. Bars: winter sea-ice extent; red whisker indicates the minimum and maximum sea-ice extents. (a, b) Six-model mean LGM-PI, (c, d) two-model mean LGM-PI, (e, f) five-model 4×CO2–PI, and (g, h) two-model 4×CO2-PI. Note that for easier interpretation, northern hemisphere absolute values of temperature gradients are shown. Six(five)- and two-model separations due to differing response in LGM SWW.



Figure 3. Mean Meridional Circulation (colored, scaled by 10×10 kg/s) and zonal mean wind in contours: black contour, PI; purple contour, LGM and 4×CO2. Positive (negative) colors indicate clockwise (counterclockwise) circulation. (a) Six-model mean annual mean PI, (b) six-model mean LGM-PI, (c) five-model mean 4×CO2-PI, (d) two-model mean PI, (e) two-model mean LGM-PI, and (f) two-model mean 4×CO2-PI. S denotes stronger, and W weaker. Six(five)- and two-model separations due to differing response in LGM SWW.

extended than its southern counterpart $(5-30^{\circ}N)$, and there is a weaker midlatitude Ferrel cell with a weaker tropospheric jet. Figures 3b and 3e depict the differences in the MMC between the LGM and PI, and in purple (black) contours, the LGM (PI) zonal mean winds. The six-model mean shows a decreased Ferrel cell that coincides with the decreased intensity of the midlatitude jet. The southern branch of the Hadley cell is also less intense and meridionally contracted compared to the PI Hadley cell, and the polar jet is intensified (not shown). Hence, in the Southern Hemisphere, the midlatitude jet that forms at the southern flank of the Hadley cell is decreased. In contrast, although CCSM4 and MRI also simulate a less intense and extended Hadley cell, they simulate a somewhat stronger Ferrel cell and hence intensified midlatitude jet throughout the troposphere, whose lower troposphere manifestation is shown in Figure 1. In the northern hemisphere, all models simulate a southward shift of the MCC (northern Hadley cell and Ferrel cell), with a mixed signal in change of strength that is coherent with the changes in meridional temperature gradients seen in Figure 2. On the other hand, for the $4\times$ CO2 simulations, there is a robust response (no significant difference between five- and two-model means) that includes a weaker and poleward expanded Hadley cell and a stronger circulation at the poleward flank of the Southern Hemisphere Ferrel cell that is coincident with the stronger and poleward-shifted midlatitude jet. In the northern hemisphere, there is weakening of the MCC that coincides with the decrease in the temperature gradients seen in Figure 2.

3.2. LGM Southern Hemisphere Sea Ice

[8] The full LGM boundary conditions, which include large ice sheets in both hemispheres, result in a contracted tropical MMC and a southward shift of the northern



JJA LGM tas grad, max uwind at 850hPa and 80% seaice b CCSM4



Figure 4. (a) PMIP3 80% winter (JJA) sea-ice extent in colors. Black line: Estimated LGM winter sea ice, drawn from *Fraser et al.* [2009]. Right: Maps of surface temperature gradients (colored contours), latitude of 80% winter (JJA) sea-ice extent (purple line). Blue line: latitude of maximum zonal wind at 850 hPa, from (b) CCSM4 and (c) MIROC.

hemisphere MMC, i.e., the Midlatitude Ferrel cell and northern Hadley cell. This is better seen in the seasonal difference (in northern hemisphere winter in particular; Figure S2). However, in the Southern Hemisphere circulation, six models simulate a weaker Ferrel cell and SWW, and two models a stronger Ferrel cell and SWW. Figure 2 indicates that a critical difference between the six-model mean and two-model mean is the surface and lower troposphere temperature gradient between 40 and 60°S, and an important equatorward extent of sea ice in the two-model mean. To evaluate these differences, Figure 4a shows the LGM winter 80% sea-ice cover in the PMIP3 models, together with a qualitative reconstruction by Fraser et al. [2009]. CCSM4 and MRI both reproduce closer the reconstructed LGM sea-ice extent, at most longitudes, except around the Ross Sea. Indeed, the four models that simulate stronger SWW during the LGM (CCSM3 and FGOALS in PMIP2, and CCSM4 and MRI in PMIP3) have in common a very strong sea-ice extent response. Sea-ice reconstructions in the Southern Hemisphere are limited and with important uncertainties [Gersonde et al., 2005; Fraser et al., 2009]. Therefore, within the southern ocean sea-ice extent uncertainties, it is difficult to disregard any of the simulated sea-ice extent, except perhaps of the models with extremely little changes in sea-ice extent. Furthermore, Figures 4b and 4c shows for two models (CCSM4 and MIROC to exemplify two differing responses) maps of surface temperature gradients (colors), latitude of 80% sea-ice extent (purple line), and the latitude of maximum zonal winds (blue lines). There is a strong coupling of all three variables in CCSM4 (and MRI as well, Figure S3), whereas in the other six models, the maximum SWW winds are largely decoupled from sea ice and the surface temperature gradient (as exemplified by the MIROC model in the figure, other models shown in S3).

4. Discussion and Conclusion

[9] At the time of R09, there were four PMIP2-LGM simulations available, and they did not show a significant shift in the position of the SWW. It was suggested that (low) resolution could hinder the atmosphere to properly respond to the LGM forcing. This suggestion can be discarded in the light of CMIP5/PMIP3 results. All the CMIP5 models are able to simulate shifts in the meridional mean circulation of the Southern Hemisphere, as seen here in the $4 \times CO2$ simulations.

[10] Toggweiler and Russell [2008] put forward a conceptual model, in which the atmospheric circulation has a symmetric response to low and high CO₂ concentrations, such as for the LGM and twentieth century warming. For LGM conditions, the meridional temperature gradients decrease compared to the pre-industrial situation, and hence the tropical circulation contracts, and the midlatitude jets move equatorwards. For anthropogenic CO₂ increase, the tropospheric meridional temperature gradient would increase, widening the tropical circulation and hence shift the jets and SWW poleward. Also arguing for a crucial atmospheric role in the response to cold versus warm climate forcing is Lee et al. [2011]. They performed a Heinrich event-type northern hemisphere cooling experiment that is transmitted via the atmospheric MCC into the Southern Hemisphere and results in an intensification and poleward shift of the SWW. The analysis performed in this paper shows that the conceptual model of Toggweiller and Russel is an over simplification and that more elements play a role in determining atmospheric circulation response to low (cold) versus high CO₂ (warm) forcing. The tropical contraction (expansion) to LGM $(4 \times CO2)$ forcing is found in the models, but in the northern hemisphere, there are important seasonal differences, and in the Southern Hemisphere, the coupling with the ocean needs to be included. In CCSM4 and MRI, over the Southern Hemisphere, there is a strong coupling between surface temperature gradients, sea-ice extent, and latitude of maximum SWW winds, whereas in the other six models, these variables are largely decoupled. It remains to be investigated whether this coupling is a response to a forcing that is transmitted via atmospheric teleconnections (like in Toggweiler and Russell [2008] or Lee et al. [2011]), or if ocean thermodynamics changes the sea-ice extent, forced via changes in the thermohaline circulation for example. Finally, although the carbon cycle response to the simulated SWW is not investigated here, one can hypothesize that both LGM configurations found in PMIP3 models-weaker and somewhat equatorward-shifted SWW, or stronger SWW but large sea-ice extent response—could produce less CO₂ outgassing. Further work to evaluate the response of ocean thermodynamics on sea-ice extent, as well as better constraining LGM sea-ice extent, is required. The debate is still open.

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References

- Anderson, R. F., and M.-E. Carr (2010), Uncorking the Southern Ocean's Vintage CO2, Science, 328(5982), 1117–1118.
- Bender, F. A.-M., V. Ramanathan, and G. Tselioudis (2011), Changes in extratropical storm track cloudiness 1983–2008: Observational support for a poleward shift, *Clim. Dynam.*, 38(9-10), 2037–2053.
- Braconnot, P., B. Otto-Bliesner, S. Harrison, S. Joussaume, J. Y. Peterchmitt, A. Abe-Ouchi, M. Crucifix, E. Driesschaert, T. Fichefet, and C. D. Hewitt (2007), Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum—Part 1: Experiments and large-scale features, *Clim. Past*, 3(2), 261–277.
- Braconnot, P., S. P. Harrison, M. Kageyama, P. J. Bartlein, V. Masson-Delmotte, A. Abe-Ouchi, B. Otto-Bliesner, and Y. Zhao (2012), Evaluation of climate models using palaeoclimatic data, *Nat. Clim. Change*, 2, 417–424, doi:10.1038/nclimate1456.
- Chavaillaz, Y., F. Codron, and M. Kageyama (2012), Southern westerlies in LGM and future (RCP4.5) climates, *Clim. Past Discuss.*, under review. Chikamoto, M. O., A. Abe-Ouchi, A. Oka, R. Ohgaito, and A.
- Chikamoto, M. O., A. Abe-Ouchi, A. Oka, R. Ohgaito, and A. Timmermann (2012), Quantifying the ocean's role in glacial CO2 reductions, *Clim. Past*, 8(2), 545–563.
- Denton, G. H., R. F. Anderson, J. R. Toggweiler, R. L. Edwards, J. M. Schaefer, and A. E. Putnam (2010), The last glacial termination, *Science*, 328(5986), 1652–1656.
- d'Orgeville, M., W. P. Sijp, M. H. England, and K. J. Meissner (2010), On the control of glacial-interglacial atmospheric CO2 variations by the Southern Hemisphere westerlies, *Geophys. Res. Lett.*, 37(21), L21,703.

- Drost, F., J. Renwick, B. Bhaskaran, H. Oliver, and J. McGregor (2007), A simulation of New Zealand's climate during the Last Glacial Maximum, *Quaternary Sci. Rev.*, 26(19–21), 2505–2525.
- Fraser, C. I., R. Nikula, H. G. Spencer, and J. M. Waters (2009), Kelp genes reveal effects of subantarctic sea ice during the Last Glacial Maximum, *Proc. Natl. Acad. Sci.*, 106(9), 3249.
- Gersonde, R., X. Crosta, A. Abelmann, and L. Armand (2005), Seasurface temperature and sea ice distribution of the Southern Ocean at the EPILOG Last Glacial Maximum—A circum-Antarctic view based on siliceous microfossil records, *Quaternary Sci. Rev.*, 24(7–9), 869–896.
- Imbrie, J., E. Boyle, S. Clemens, A. Duffy, W. Howard, G. Kukla, J. Kutzbach, D. G. Martinson, A. C. Mix, B. Molfino, J. Morley, L. Peterson, N. G. Pisias, W. Prell, M. E. Raymo, N. Shackleton, and J. R. Toggweiler (1992), On the structure and origin of major glaciation cycles, *Paleoceanography*, 7(6), 701–70,738.
- Kalney, E. et al. (1996), The NCEP/NCAR 40-year re-analysis project, Bull. Am. Meteorol. Soc., 77, 437–471.
- Le Quere, C., C. Rodenbeck, E. T. Buitenhuis, T. J. Conway, R. Langenfelds, A. Gomez, C. Labuschagne, M. Ramonet, T. Nakazawa, N. Metzl, N. Gillett, and M. Heimann (2007), Saturation of the Southern Ocean CO2 sink due to recent climate change, *Science*, 316(5832), 1735–1738.
- Lee, S.-Y., J. C. H. Chiang, K. Matsumoto, and K. S. Tokos (2011), Southern Ocean wind response to North Atlantic cooling and the rise in atmospheric CO2: Modeling perspective and paleoceanographic implications, *Paleoceanography*, 26(1), PA1214.
 Lenton, A., and R. J. Matear (2007), Role of the Southern Annular Mode
- Lenton, A., and R. J. Matear (2007), Role of the Southern Annular Mode (SAM) in Southern Ocean CO2 uptake, *Global Biogeochem. Cy.*, 21, GB2016, doi:10.1029/2006GB002714.
- Menviel, L., A. Timmermann, A. Mouchet, and O. Timm (2008), Climate and marine carbon cycle response to changes in the strength of the Southern Hemispheric westerlies, *Paleoceanography*, 23(4), PA4201.
- Moreno, P. I., R. Villa-Martínez, M. L. Cardenas, and E. A. Sagredo (2012), Deglacial changes of the southern margin of the southern westerly winds revealed by terrestrial records from SW Patagonia (52S), *Quaternary Sci. Rev.*, 41(C), 1–21.
- O'Gorman, P. (2010), Understanding the varied response of the extratropical storm tracks to climate change, *Proc. Natl. Acad. Sci.*, 107, doi: 10.1073/pnas.1011547107.
- Polvani, L. M., D. W. Waugh, G. J. P. Correa, and S.-W. Son (2011), Stratospheric ozone depletion: The main driver of twentieth-century atmospheric circulation changes in the Southern Hemisphere, *J. Climate*, 24(3), 795–812.
- Rojas, M., P. Moreno, M. Kageyama, M. Crucifix, C. Hewitt, A. Abe-Ouchi, R. Ohgaito, E. C. Brady, and P. Hope (2009), The Southern Westerlies during the last glacial maximum in PMIP2 simulations, *Clim. Dynam.*, 32(4), 525–548.
- Sampe, T., H. Nakamura, A. Goto, and W. Ohfuchi (2010), Significance of a Midlatitude SST frontal zone in the formation of a storm track and an eddy-driven Westerly jet, J. Climate, 23(7), 1793–1814.
- Skinner, L. C., S. Fallon, C. Waelbroeck, E. Michel, and S. Barker (2010), Ventilation of the deep Southern Ocean and deglacial CO2 rise, *Science*, 328(5982), 1147–1151.
- Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc.*, 93(4), 485–498.
- Toggweiler, J. R., and J. Russell (2008), Ocean circulation in a warming climate, *Nature*, 451(7176), 286–288.
- Toggweiler, J. R., J. L. Russell, and S. R. Carson (2006), Midlatitude westerlies, atmospheric CO₂, and climate change during the ice ages, *Paleoceanography*, 21(2), PA2005.
- Treguier, A., J. Le Sommer, J. Molines, and B. De Cuevas (2010), Response of the Southern Ocean to the southern annular mode: Interannual variability and multidecadal trend, J. Phys. Oceanogr., 40(7), 1659–1668.
- Tschumi, T., F. Joos, and P. Parekh (2008), How important are Southern Hemisphere wind changes for low glacial carbon dioxide? A model study, *Paleoceanography*, 23, PA4208, doi:10.1029/2008PA001592.
- Wang, X. L., V. R. Swail, and F. W. Zwiers (2006), Climatology and changes of extratropical cyclone activity: Comparison of ERA-40 with NCEP-NCAR reanalysis for 1958–2001, J. Climate, 19(13), 3145–3166.
- Yin, J. H. (2005), A consistent poleward shift of the storm tracks in simulations of 21st century climate, *Geophys. Res. Lett.*, 32(18), L18,701.