GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L12712, doi:10.1029/2006GL028797, 2007

# Response of the global carbon cycle to human-induced changes in Southern Hemisphere winds

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Received 20 November 2006; revised 18 May 2007; accepted 30 May 2007; published 29 June 2007.

[1] An Earth System model is used to explore the response of the oceanic and terrestrial carbon sinks to strengthening and poleward shifting of the extratropical Southern Hemisphere winds, which is a robust feature of climate models' response to greenhouse gas forcing through the 20th and 21st centuries. We find that under time-varying $CO_2$ emissions poleward intensifying Southern Hemisphere winds act on average to slightly enhance the efficacy of both the oceanic and terrestrial carbon sinks, thus providing a small negative feedback on the atmospheric $CO_2$ concentration. Regionally, the effects of the changing winds on oceanic and terrestrial carbon uptake are more pronounced and partly of opposite sign. We further show that the magnitude and sign of global oceanic $CO_2$ uptake is also controlled by changes in mesoscale eddy activity, which has been suggested to increase in response to intensifying Southern Hemisphere winds. **Citation:** Zickfeld, K., J. C. Fyfe, O. A. Saenko, M. Eby, and A. J. Weaver (2007), Response of the global carbon cycle to human-induced changes in Southern Hemisphere winds, *Geophys. Res. Lett.*, *34*, L12712, doi:10.1029/2006GL028797.

## 1. Introduction

[2] Since the industrial revolution humankind has emitted large quantities of $CO_2$ into the atmosphere. Measurements of atmospheric $CO_2$ reveal, however, that less than half of these emissions remain in the atmosphere. This indicates that accumulation of anthropogenic $CO_2$ in the atmosphere is modulated by large natural sinks in the world ocean and terrestrial biosphere. Despite major advances in constraining the oceanic sink for anthropogenic $CO_2$ [*Sabine et al.*, 2004], uncertainties remain in the mechanisms governing oceanic $CO_2$ uptake. Estimates of anthropogenic $CO_2$ uptake by the ocean based on forward [*Caldeira and Duffy*, 2000; *Orr et al.*, 2001] and inverse [*Mikaloff Fletcher et al.*, 2006] models emphasize the Southern Ocean (SO) as a major sink region. The exchange of carbon dioxide across the air-sea interface in this region is related to the strong zonal winds there. In addition to having a direct effect on the air-sea carbon flux through the gas-transfer velocity, these winds drive the upwelling of deep waters south of the Antarctic Circumpolar Current (ACC). This upwelling provides for northward Ekman transport across the ACC, which is partly compensated by a southward eddy-induced flow. *Mignone et al.* [2006] (hereinafter referred to as M06) show that the strength of the zonal winds over the SO strongly controls the regional distribution of anthropogenic carbon uptake, while winds and mesoscale eddies together exert strong control over its magnitude. This finding is of interest in a climate change context since the strengthening and poleward shifting of the zonal winds at extratropical Southern Hemisphere (SH) latitudes is a robust feature of climate projections under increasing atmospheric concentrations of greenhouse gases (GHGs) [*Fyfe and Saenko*, 2006; *Fyfe et al.*, 2007]. In turn, zonal wind stress changes may affect the oceanic mesoscale eddy activity in the Southern Ocean, as indicated by eddy-permitting ocean models [*Hallberg and Gnanadesikan*, 2006].

[3] Here we investigate the effects of changes in SH winds on the oceanic and terrestrial carbon sink. To this end an Earth System model of intermediate complexity is driven with time-varying $CO_2$ emissions and time-varying surface winds over the SH derived from the latest series of coupled climate model simulations [*Fyfe and Saenko*, 2006; *Fyfe et al.*, 2007]. In our analysis, we focus on total rather than anthropogenic carbon since ocean circulation changes such as those induced by changes in SH winds can be expected to alter the oceanic sink of both anthropogenic and naturally occurring carbon.

## 2. Methods

[4] We use the University of Victoria Earth System Climate Model (UVic-ESCM), version 2.8. It consists of a 19-layer ocean general circulation model with isopycnal mixing and a *Gent and McWilliams* [1990] (GM) parameterization of the effect of eddy-induced tracer transport. For diapycnal mixing it uses a horizontally constant profile of diffusivity, with values of about $0.3 \times 10^{-4}$ $m^2$ $s^{-1}$ in the pycnocline. The ocean model is coupled to a dynamic-thermodynamic sea-ice model and an energy-moisture balance model of the atmosphere [*Weaver et al.*, 2001]. The atmospheric model includes a parameterization of water vapour/planetary long-wave feedbacks, and the radiative forcing associated with changes in atmospheric $CO_2$ is included as a modification of planetary long-wave flux. The land surface and terrestrial vegetation are represented by a simplified version of the Hadley Centre's MOSES land-surface scheme coupled to the dynamic vegetation model TRIFFID [*Meissner et al.*, 2003]. MOSES/TRIFFID includes the $CO_2$ fertilization effect, i.e., it simulates a substantial terrestrial carbon sink in response to elevated atmospheric $CO_2$ levels. Ocean carbon is simulated by means of a OCMIP-type inorganic carbon-cycle model (J. Orr et al., Abiotic how-to document, 2000, available at http://www.ipsl.jussieu.fr/OCMIP) and a marine ecosystem

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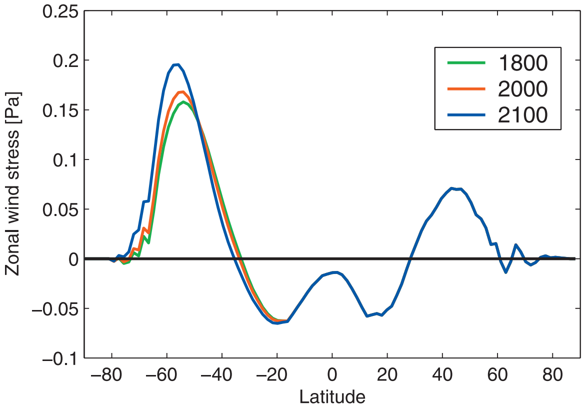

**Figure 1.** Annually and zonally averaged zonal component of wind stress used to force the UVic-ESCM. The anomalies relative to the control (1800) are computed as the mean of 12 global climate models employed for simulations in support of the IPCC AR4. The multimodel mean projects a 25% strengthening and a 3.5° poleward shift of the maximum annual mean zonal wind stress by 2100.

model solving prognostic equations for nutrients, phytoplankton, zooplankton and detritus [*Schmittner et al.*, 2005].

[5] To assess the sensitivity of the global carbon cycle to changes in SH winds, we force the model with wind-stress anomaly fields derived from multi-model-ensemble experiments performed in support of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (the data is available at http://www-pcmdi.llnl.gov). Over the historic period these models considered time-varying changes in anthropogenic GHGs and aerosols and in some cases changes in volcanic aerosols and solar forcing. For the period 1990 to 2100 they were forced by concentration of GHGs as given by the Special Report on Emissions Scenarios (SRES) [*Nakićenović and Swart*, 2000]. Here, we consider the projected changes in the SH winds from one such scenario (SRES A2) using results from 12 climate models. The models simulate a consistent strengthening and poleward shifting of the zonal wind stress over the SO through the 20th and 21st centuries [*Fyfe and Saenko*, 2006]. We add the time-varying mean SH wind stress anomalies derived by averaging over the 12 models to the prescribed climatological wind stress field (NCEP/NCAR; http://dss.ucar.edu/pub/reanalysis/ used by the UVic-ESCM in its standard configuration). The resulting zonal wind stress profiles for selected years are depicted in Figure 1. The corresponding wind speed data are also used in the model to obtain surface turbulent fluxes and to advect the atmospheric heat and moisture.

[6] We have performed six simulations for the 1800–2100 period: a control experiment (CTL), with all forcings held constant at 1800 levels, a WIND experiment, with changes in wind forcing over the SO evolving according to the multimodel ensemble mean, a GHG experiment, where fossil fuel and land-use $CO_2$ emissions follow historical estimates for the period 1800 to 1990 and the SRES-A2 scenario thereafter, and a GHG+WIND experiment, which includes both changes in wind and $CO_2$ forcing. In addition, guided by the results from eddy-permitting ocean models, we have conducted two experiments where we have tried to account for a more intense mesoscale eddy activity in the SO in response to the projected strengthening of SH winds. This was done by globally increasing the GM thickness mixing coefficient, $K_{GM}$, proportionally to the change in maximum wind stress, both with and without anthropogenic $CO_2$ emissions (the corresponding model experiments are referred to as GHG + WIND + EDS and WIND + EDS, respectively). The increase of $K_{GM}$ with time was obtained using the ratio $\tau_x(t)/K_{GM}(t) = \tau_x(0)/K_{GM}(0)$, where $\tau_x(t)$ is the maximum zonally averaged zonal wind stress in the SO at time $t$, and $\tau_x(0)$ and $K_{GM}(0)$ are the corresponding wind stress and GM coefficient in the CTL simulation. This results in an increase of $K_{GM}$ from the standard value of 800 $m^2$ $s^{-1}$ in CTL to a value of about 1100 $m^2$ $s^{-1}$ by 2100. Such a procedure makes the response of the mean isopycnal slope across the ACC and, hence, the mean transport of the current, consistent with the response to wind stress strengthening seen in eddy-permitting simulations [*Hallberg and Gnanadesikan*, 2006].

## 3. Results and Discussion

### 3.1. Oceanic Carbon Cycle

[7] In our analysis we focus on the effects of changing SH winds and eddies on uptake and storage of total, i.e. anthropogenic and naturally occurring carbon. The effect of the winds under pre-industrial and anthropogenic $CO_2$ conditions are separated by differencing the results of the WIND and CTL experiments and the results of the GHG + WIND and GHG experiments, respectively. Similarly, the combined effect of winds and eddies is obtained through the differences (WIND + EDS) − CTL and (GHG + WIND + EDS) − GHG. We show that if changes in the eddy activity in the SO are neglected, alteration of the SH winds has an opposite effect on oceanic carbon uptake and storage between cases with pre-industrial and elevated $CO_2$ concentrations. In the pre-industrial case, changes in winds lead to anomalous outgassing of carbon in the SO as compared to the control: by 2100 about 8 PgC are lost to the atmosphere (Figure 2, bottom left). In contrast, under elevated $CO_2$, from about 2020 on wind changes lead to a stronger uptake of carbon in the SO (which amounts to about 9 PgC in 2100). The region that dominates the difference in carbon uptake in the two cases is located around 60°S (Figures 2, top left, and 2, middle left) and is characterized by strong upwelling. This behavior of the carbon fluxes in the SO is reflected in global ocean carbon storage: under pre-industrial $CO_2$ altered winds lead to reduced carbon storage, whereas carbon storage slightly decreases and from about 2060 increases in the elevated $CO_2$ case. By 2100, ocean carbon is 12 PgC lower in the first and 5 PgC higher in the second case (Figure 3, bottom left). These globally integrated figures, however, hide significant regional differences: ocean carbon inventory decreases in the SO and increases in the low latitudes of both Hemispheres, this pattern being more pronounced in the pre-industrial case (Figures 3, top left, and 3, middle left). Note that changes in ocean carbon result mainly from changes in dissolved inorganic carbon (DIC). Changes in organic carbon are small and are neglected here.

[8] If concomitant changes in eddies are considered, the picture changes: alteration of the SH winds has a similar

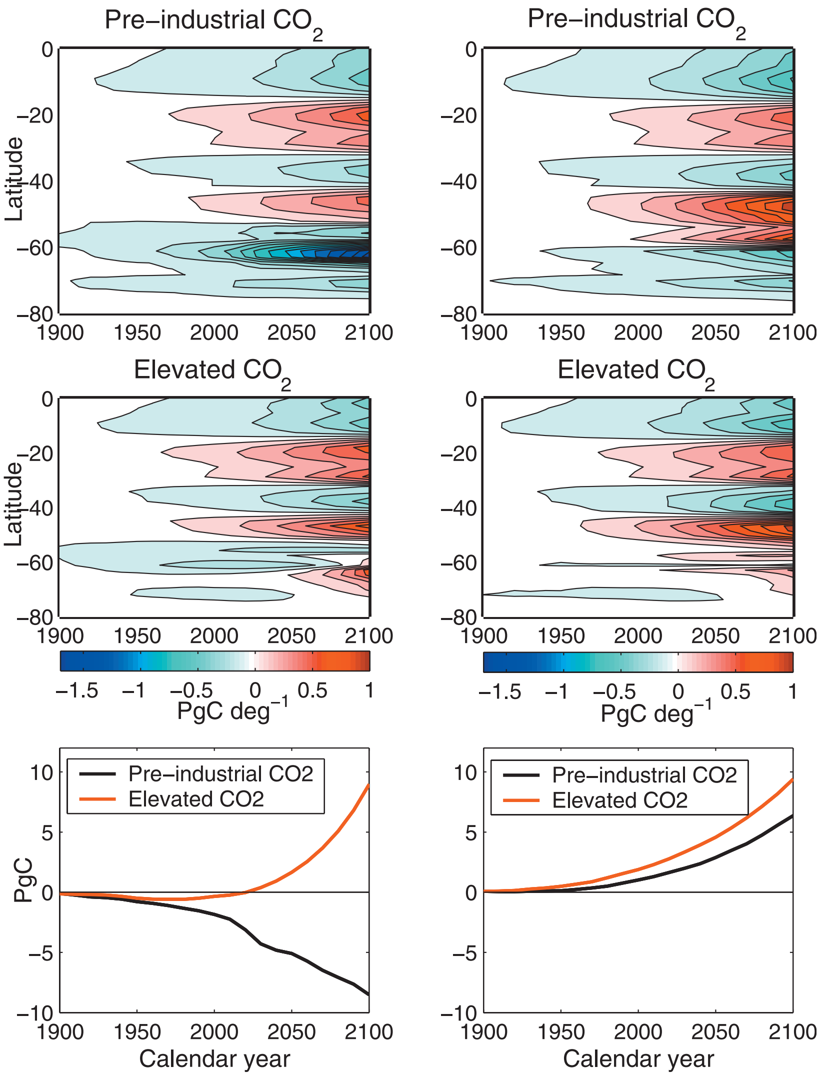

**Figure 2.** Effect of changes in winds on cumulative zonally-integrated air-to-sea carbon flux in the Southern Hemisphere over the time period 1900–2100 under (top) pre-industrial and (middle) elevated CO$_2$ concentrations. Figures 2 (top left) and 2 (middle left) display the wind effect without concomitant changes in eddies. Figures 2 (top right) and 2 (middle right) display the wind effect with concomitant changes in eddies. (bottom) The cumulative carbon flux integrated over the Southern Ocean (80°S–40°S). Note that the globally integrated cumulative flux is equal to the globally integrated carbon inventory displayed in Figure 3 (bottom).

effect on carbon uptake and storage under both pre-industrial and elevated CO$_2$ concentrations. As shown in Figure 2 (bottom right), under pre-industrial CO$_2$ altered winds and eddies lead to an increase in CO$_2$ uptake in the SO relative to CTL (reaching about 7 PgC in 2100). The change in sign in the cumulative flux is due to a reduced outgassing south of 55°S and increased uptake north of 55°S (Figure 2, top right). Accordingly, global carbon storage decreases much less in the experiment with winds and eddies relative to CTL than in the experiment with altered winds alone (−2 PgC vs. −13 PgC in 2100; cf. Figure 3, bottom). Under anthropogenic CO$_2$ emissions, the effect of changing eddies is similar: outgassing is reduced south of 55°S, whereas uptake is increased north of 55°S (Figure 2, middle right). As a result, SO cumulative carbon uptake is stronger in the case with eddies and winds than in the case with winds alone. This is reflected in the global carbon storage, which is higher through the 20th and first half of the 21st centuries in the experiment including changes in eddies. Note that even though $K_{GM}$ increases globally, the effects on carbon storage outside the Southern Ocean are small.

[9] The dominant effects of wind changes on SO carbon uptake can be explained by invoking a simple model of the SO meridional overturning circulation [*Gnanadesikan*, 1999; *Saenko and Weaver*, 2003]. In this model it is assumed that in the upper SO at Drake passage latitudes the principal components of flow are the northward Ekman transport driven by the winds and a southward return transport associated with the mesoscale eddies. The residual of these two flows gives a net subduction of light water north of the ACC, which is ultimately supplied by the deep water upwelling south of the ACC. If changes in the eddy induced flow are neglected, stronger winds lead to stronger subduction and hence stronger deep water upwelling. Since

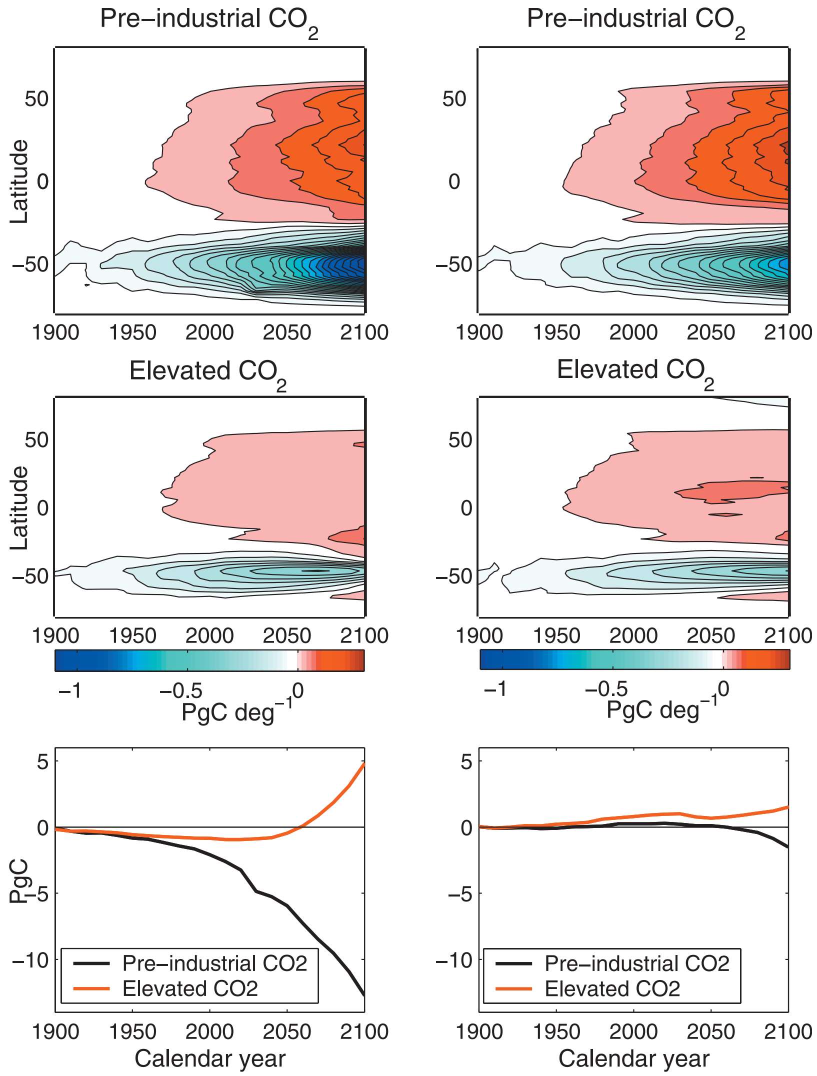

**Figure 3.** Effect of changes in winds on zonally-integrated water column inventories of dissolved inorganic carbon over the time period 1900–2100 under (top) pre-industrial and (middle) elevated CO$_2$ concentrations. Figures 3 (top left) and 3 (middle left) display the wind effect without concomitant changes in eddies. Figures 3 (top right) and 3 (middle right) display the wind effect with concomitant changes in eddies. (bottom) The globally integrated carbon inventories.

the carbon fluxes at the air-sea interface are governed, in part, by the difference in CO$_2$ partial pressure (pCO$_2$), in the case with constant CO$_2$ concentrations stronger upwelling of deep, DIC-rich water leads to a larger pCO$_2$ in the ocean south of about 55°S and hence outgassing of CO$_2$, which is only partly compensated by CO$_2$ uptake anomaly north of 55°S. With anthropogenic emissions, accumulation of CO$_2$ in the atmosphere acts to nearly offset the higher ocean pCO$_2$. Due to this effect and stronger uptake north of 55°S the wind forcing acts to increase SO carbon uptake from about 2020 on.

[10] If stronger wind stress leads to a concomitant increase in eddy activity, the flow induced by these eddies acts to compensate the northward Ekman transport. As a consequence, upwelling of deep water is reduced compared to the case without changes in eddies, which leads to reduced outgassing of carbon south of 55°S under pre-industrial CO$_2$. Under elevated CO$_2$ concentrations, reduced upwelling implies stronger SO carbon uptake through the 20th and early 21st centuries. Additional experiments indicate that changes in the wind speed also affect the air-sea flux of CO$_2$, whereas changes in ocean biology do not play a significant role (the latter account for an increase in global cumulative CO$_2$ uptake of about 1 PgC by 2100 under pre-industrial CO$_2$).

[11] The evidence that under anthropogenic CO$_2$ emissions poleward intensifying SH winds act to decrease carbon storage in the SO may seem to contradict results of earlier studies (e.g., M06) which showed an increase in carbon storage there. Note, however, that these studies addressed changes in storage of anthropogenic carbon, whereas we consider changes in total (i.e., anthropogenic + natural) carbon. For the sake of comparison, the effects of altered winds on anthropogenic fluxes and inventories can be obtained by subtracting the effects on natural carbon (as given by the difference WIND − CTL) from the effects on total carbon [i.e. (GHG + WIND) − GHG]. This yields an increase in anthropogenic carbon storage in the SO by about 23 PgC in 2100, thus reconciling our results with those of

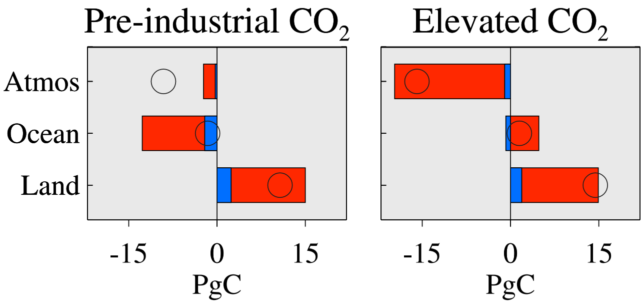

**Figure 4.** Effect of changing winds on atmosphere, ocean, and land carbon under (left) pre-industrial and (right) elevated $CO_2$ concentrations in 2000 (blue bars) and 2100 (red bars). The open circles indicate the results of the experiments with concomitant changes in winds and eddies in 2100.

M06 (Figure S1 of the auxiliary material).[1] This increase in storage is partly compensated by a decrease around the equator and in the mid-latitudes of the Northern Hemisphere by about 5 PgC, giving a global anthropogenic storage of 18 PgC in 2100. If the effect of eddies is taken into account, global storage of anthropogenic carbon increases little relative to the case without changes in winds (by about 4 PgC in 2100). Qualitatively, this is in agreement with results of M06. They suggest that the depth of the low-latitude pycnocline and hence the volume of light, actively-ventilated water, which is controlled by winds and eddies together, determines the magnitude of anthropogenic carbon uptake. In our model, the mean slope of isopycnals across of the ACC, and hence the depth of the pycnocline north of the current, is also effectively controlled by the wind stress in the SO and by the value of $K_{GM}$; however, the depth of the low-latitude pycnocline is less affected (not shown). Therefore, we find that the model, the residual overturning in the SO, rather than changing depth of the low-latitude pycnocline, controls the magnitude of anthropogenic carbon uptake in the ocean, by supplying/removing DIC-rich water to/from the ocean surface.

### 3.2. Global Carbon Budget

[12] How do changes in ocean carbon uptake translate into atmospheric $CO_2$ concentrations? If less carbon is stored in the ocean, one might expect higher atmospheric $CO_2$ concentrations, and vice versa. However, changes in the SH winds also affect the spatial pattern of Precipitation - Evaporation in the SH. This, in turn, alters the terrestrial (i.e. soil and vegetation) carbon pools. In our model, poleward intensifying winds lead to increased precipitation over South Africa, southeastern South America and Australia. In response, the global terrestrial carbon pool increases by about 15 PgC in 2100 (Figure 4), the main reason being increased net primary productivity. Therefore, even though ocean carbon content is about 12.7 PgC lower in the experiment with changing winds than in the control, atmospheric carbon decreases by 2.3 PgC. A similar figure arises under rising $CO_2$ concentrations: changes in winds lead to an increase in terrestrial carbon by 14.9 PgC in 2100. As in this case oceanic carbon uptake is stronger (by 4.8 PgC), atmospheric $CO_2$ concentrations are about 20 PgC lower in the experiment with changing winds. Qualitatively, this picture is preserved if an increase in mesoscale eddy activity is considered. The largest difference arises under pre-industrial $CO_2$, where concomitant changes in eddies act to significantly reduce the negative ocean carbon storage anomaly (Figure 3, bottom). As a result, atmospheric $CO_2$ is reduced by about 9 PgC in the case with changing eddies as compared to a reduction of about 2 PgC in the case with changing winds alone.

[13] Overall, with or without changes in eddy activity, the effect of wind changes is small if related to the increase in atmospheric $CO_2$ from 1800 to 2100 in the GHG + WIND experiment (1269 PgC): changes in SH winds decrease the airborne fraction of carbon by 1.5% in 2100 with changing winds alone and by 1.2% in the experiment with changing winds and eddies; the corresponding estimates for, e.g., year 2030 are 0.8% and 1.5%. To put these numbers into perspective: the total climate-carbon cycle feedback (i.e. the feedback that arises when all $CO_2$-induced climate effects are included) simulated by the current generation of models is positive and ranges from about 3% to 22% in 2100 [*Friedlingstein et al.*, 2006].

## 4. Conclusions

[14] The results presented in this paper indicate that the magnitude of the global oceanic carbon sink is affected both by changes in SH winds and mesoscale eddies. As the eddy field is heavily parameterized in the current generation of coupled climate models, and models with parameterized eddies have been shown to respond differently to wind forcing compared to models with explicit eddies [*Hallberg and Gnanadesikan*, 2006], our results highlight the need to use models with finer resolution or better sub-grid-scale parameterizations to assess the magnitude of the oceanic carbon sink. Moreover, our findings indicate that ocean circulation changes such as those induced by changes in SH winds affect the sink of anthropogenic and naturally occurring carbon alike. We suggest that attempts to understand the role of the oceanic carbon sink under climate change should focus upon changes in total carbon, as this is the quantity that will ultimately determine the radiative forcing of the atmosphere. We find that the strengthening and poleward shift of the SH winds, by affecting the hydrological cycle in the SH, alters the terrestrial carbon pool. In our model, to 2100 this alteration is even larger than changes in the global ocean carbon sink. This emphasizes the necessity to take into account changes in the terrestrial biosphere when making inferences about the effects of changing winds on atmospheric $CO_2$ concentrations. Overall, our results suggest that under anthropogenic $CO_2$ emissions the negative feedback of SH wind changes on atmospheric $CO_2$ is small (on the order of a few percent). This result is independent of the relative role of winds and eddies in determining the circulation in the SO.

[15] **Acknowledgments.** We would like to thank Jim Christian, Ken Denman, and two anonymous reviewers for helpful comments on the manuscript. This research was supported by NSERC and CFCAS operating grants, including the CFCAS Polar Climate Stability Research Network

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2006GL028797.

grant. We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy.

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