THE ROLE OF SOUTHERN HEMISPHERE WINDS IN CONTROLLING THE OCEANIC UPTAKE AND STORAGE OF ANTHROPOGENIC CARBON DIOXIDE

B.K. Mignone[1], A. Gnanadesikan[2], J. L. Sarmiento[3] and R. D. Slater[3]

[1]*Department of Geosciences, Princeton University, Princeton, NJ 08544; bmignone@princeton.edu*

[2]*National Oceanographic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory, Princeton, NJ 08542; gnana@princeton.edu*

[3]*Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ 08544; jls@splash.princeton.edu; rdslater@splash.princeton.edu*

ABSTRACT

Physical processes in the Southern Ocean are known to profoundly impact the global carbon cycle, but this region is one of the most difficult to simulate consistently in ocean general circulation models (OGCMs). Here we show that Southern Hemisphere winds, by altering the volume of light, actively-ventilated ocean water as well as the relative contribution to this volume from Ekman transport, exert strong control over both the magnitude and distribution of anthropogenic carbon uptake in an OGCM. These results are provocative in suggesting that climate warming, by increasing the magnitude of the wind stress at high southern latitudes, may act as a negative feedback on the global carbon cycle.

INTRODUCTION AND MODELING PROTOCOL

Although the atmospheric accumulation of anthropogenic carbon dioxide (CO_2) is known to be modulated by large natural sinks in the world ocean and terrestrial biosphere, the exact processes driving these sinks has been the subject of some debate. Using a familiar OGCM [*Pacanowski and Griffies*, 1999], we show here that the magnitude of the zonal wind stress over the Southern Ocean largely controls both the total ocean uptake of anthropogenic carbon and the regional distribution of this uptake. These results should help to explain some of the observed differences between OGCMs [*Orr*, 2002] that have so far prohibited a consistent and plausible mechanistic attribution.

In this study, we used the third version of the Princeton/GFDL Modular Ocean Model (MOM) [*Pacanowski and Griffies*, 1999] and adopted a previously described model configuration [*Mignone et al.*, 2004] and modeling protocol [*Aumont and Orr*, 2000]. In order to explore the sensitivity of global carbon uptake to the applied wind stress over the Southern Ocean, we ran the model with four different wind fields, two of which, Hellerman and Rosenstein (henceforth HR) and ECMWF (henceforth EC), are actual data products (see references in *Mignone et al.* [2004]) and two of which are artificially-modified versions of these products. Our artificial modifications to HR and EC were made to explore the effects of more extreme wind stress values over the Southern Ocean. The first of these (henceforth HR-L) is identical to HR, except south of 30° S, where the zonal stress was everywhere decreased by 50%. The second (EC-H) is identical to EC, but with stresses *increased* by 50% everywhere south of 30° S. The annually and zonally-averaged Drake Passage wind stress in EC-H is roughly six times greater than the maximum value in HR-L [Table 1].

RESULTS AND DISCUSSION

Previous modeling studies have shown that comparable changes in Southern Hemisphere winds can profoundly alter the large-scale circulation and density structure of the global ocean [*Gnanadesikan*, 1999]. Since both transport and stratification changes can presumably drive equally significant changes in carbon uptake, we have utilized a recently developed theory of the oceanic pycnocline [*Gnanadesikan*, 1999] to decouple the physical mechanisms driving uptake. One result of this theory is that, by jointly altering the magnitudes of the Southern Hemisphere wind stress and the lateral eddy diffusivity, several distinct model versions can be developed that preserve both the depth of the low-latitude pycnocline and the *net* southern return flow, while allowing the Ekman transport out of the Southern Ocean to vary (leading to the so-called "compensated" versions, labeled with a "*" in Table 1). Conversely, changing the winds, while leaving the lateral diffusivity unchanged allows both the Ekman transport and pycncocline depth to vary together (the so-called "uncompensated" versions without a "*" in Table 1).

The anthropogenic fluxes and inventories corresponding to these model versions are also given in Table 1. As the wind forcing is increased over the Southern Ocean in the compensated versions, the cumulative uptake south of 40º S increases dramatically from 26 Pg C in HR-L* to 46 Pg C, in EC-H*, or from roughly 22% of the total uptake to 38% of the total uptake. However, a closer look at the inventories in the same versions reveals that these large flux changes are not accompanied by significant inventory changes. In fact, the model with the highest inventory (EC-H*) stores 122 Pg C, only 5% more carbon than the model with the lowest inventory (HR-L*). The uncompensated simulations offer a complimentary set of insights. The flux distributions in these models show a similar dependence of Southern Ocean uptake on Southern Hemisphere winds, with the high-wind version (EC-H) taking up 46% of the total uptake south of 40º S and the low-wind version (HR-L) taking up 20%. However, a closer inspection of the flux distributions in this case reveals that the additional Southern Ocean uptake in the non-compensated high-wind versions is not similarly offset by decreased uptake elsewhere in the ocean. This implies that the additional uptake in these model versions must be accompanied by greater carbon storage in the ocean interior.

The main result that follows from these simulations can be stated compactly: In a world in which diapycnal mixing is small, Southern Hemisphere winds control *total* anthropogenic carbon uptake *indirectly* by altering the volume of actively-ventilated light water but control the *distribution* of global carbon uptake *directly* by altering the Ekman transport out of the Southern Ocean. We suggest that the strong sensitivity to winds seen here offers the best hope yet of reconciling differences in observed uptake between various OGCMs. In particular, our results suggest that a large component of the differences in total uptake and in the relative importance of the Southern Ocean observed in previous model inter-comparison studies [*Orr*, 2002] may be attributed to differences in surface wind forcing at high southern latitudes. Furthermore, if anthropogenic changes in climate due to greenhouse gas (GHG) increases project onto existing modes of variability like the Southern Annual Mode (SAM), then our results suggest that such changes may negatively feedback on the carbon cycle, by increasing the wind stress over the Southern Ocean and consequently enlarging the volume over which carbon can be stored.

Table 1. Diagnostics for the two sets of simulations discussed in the text. The reported wind stress is the annual and zonal-mean at 50ºS. Pycnocline depth is calculated according to Footnote 11 of *Gnanadesikan* [1999]. The Ekman transport is the net zonally-integrated northward transport above 50 m at 50ºS. The global C sink is the cumulative globally-integrated air-sea flux of anthropogenic carbon between 1765-2000, or equivalently, the total anthropogenic carbon inventory in year 2000, and the Southern Ocean (S.O.) is here defined as the region south of 40ºS.

Model	Ai (m^2 sec^{-1})	Wind stress (Pa)	Pyc. depth (m)	Ekman transport (Sv)	Global C sink (Pg C)	S.O. C storage (Pg C)	% S.O. storage	S.O. C uptake (Pg C)	% S.O. uptake
HR-L	1000	0.5	445	9	103	16	15.3	21	20.1
HR	1000	1.1	524	23	119	19	15.6	34	28.3
EC	1000	2.0	651	40	141	29	20.5	54	38.1
EC-H	1000	3.0	756	63	172	42	24.3	79	46.0
HR-L*	300	0.5	521	12	114	17	15.3	26	22.4
HR*	1000	1.1	524	23	119	19	15.6	34	28.3
EC*	2000	2.0	552	35	121	19	15.6	41	33.8
EC-H*	4000	3.0	550	44	122	19	15.6	46	37.7

REFERENCES

Aumont O. and J. C. Orr (2000), *Abiotic how-to document* (http://www.ipsl.jussieu.fr/OCMIP).

Gnanadesikan A (1999), A simple predictive model for the structure of the oceanic pycnocline, *Science*, 283, 2077-2079.

Mignone, B. K., J. L. Sarmiento, R. D. Slater and A. Gnanadesikan (2004), Sensitivity of sequestration efficiency to mixing processes in the global ocean, *Energy*, 29, 1467-1478.

Orr, J. C. (2002), *Global Ocean Storage of Anthropogenic Carbon*, Inst. Pierre Simon Laplace, Gif-Sur-Yvette, France.

Pacanowski, R. C. and S. M. Griffies (1999), *The MOM 3 Manual, Alpha Version*, NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ.