Central role of Southern Hemisphere winds and eddies in modulating the oceanic uptake of anthropogenic carbon

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[1] Although the world ocean is known to be a major sink of anthropogenic carbon dioxide, the exact processes governing the magnitude and regional distribution of carbon uptake remain poorly understood. Here we show that Southern Hemisphere winds, by altering the Ekman volume transport out of the Southern Ocean, strongly control the regional distribution of anthropogenic uptake in an ocean general circulation model, while winds and isopycnal thickness mixing together, by altering the volume of light, actively-ventilated ocean water, exert strong control over the absolute magnitude of anthropogenic uptake. These results are provocative in suggesting that climate-mediated changes in pycnocline volume may ultimately control changes in future carbon uptake.
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1. Introduction

[2] 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 have been the subject of intense scientific debate. Recent convergence of several independent estimates of the contemporary ocean sink based on observational tracer data [*Bopp et al.*, 2002; *Plattner et al.*, 2002; *Takahashi et al.*, 2002; *McNeil et al.*, 2003], ocean forward model results [*Matsumoto et al.*, 2004] and a combination of the two via inverse techniques [A. R. Jacobson et al., A joint atmosphere-ocean inversion for surface fluxes of carbon dioxide, submitted to *Global Biogeochemical Cycles*, 2005, hereinafter referred to as Jacobson et al., submitted manuscript, 2005; S. E. M. Fletcher et al., Robust estimates of anthropogenic carbon uptake, transport, and storage by the ocean, submitted to *Global Biogeochemical Cycles*, 2005, hereinafter referred to as Fletcher et al., submitted manuscript, 2005] tightly constrains the amount of carbon entering the ocean today and would seem to similarly constrain the set of mechanisms governing this uptake. However, large differences in the regional attribution of sinks between forward and inverse models (Jacobson et al., submitted manuscript, 2005; Fletcher et al., submitted manuscript, 2005) as well as within the existing suite of forward models [*Orr*, 2002] belies this intuitive interpretation. Forward simulations alone differ in their estimates of the Southern Ocean sink by as much as 70%, according to an early comparison of ocean general circulation model (OGCM) results [*Orr et al.*, 2001] and by more than 200% in a more recent comparison involving a larger number of such models (K. Matsumoto, unpublished data, 2005).

[3] In this paper, we have chosen to explore the extent to which differences in wind forcing and eddy mixing at high southern latitudes can alter the magnitude and distribution of anthropogenic carbon uptake in an OGCM. This particular focus is motivated by compelling evidence that Southern Hemisphere winds and eddies profoundly impact the circulation and density structure of the global ocean [*Gnanadesikan*, 1999] and by the additional realization that both the isopycnal diffusion coefficient and the historical wind stress field over the Southern Ocean are poorly constrained at present, with two popular observational wind stress products used in existing model comparisons [e.g., *Matsumoto et al.*, 2004] differing in their estimates of the average stress by a factor of two in some regions of the extratropical Southern Hemisphere (see Table 1 and Figure 1). These considerations suggest that a significant fraction of the observed variability in carbon uptake between OGCMs may simply be an expression of uncertainty in the underlying physical circulation, derived in part from uncertainty in the high-latitude wind stress field and isopycnal diffusion coefficient.

2. Methods

[4] Here we use the third version of the Princeton/GFDL Modular Ocean Model (MOM) [*Pacanowski and Griffies*, 1999]. Except where noted, the model configuration is identical to the one used in other recent simulations of anthropogenic carbon storage [*Mignone et al.*, 2004]. In this study, the coefficient of diapycnal diffusion (Kv) is fixed at 0.15×10^{-4} m^2 sec^{-1} in the pycnocline in order to match observationally-derived estimates [*Ledwell et al.*, 1993, 1998]. To simulate the historical uptake of CO_2, we followed the OMCIP-2 protocol (O. Aumont and J. C. Orr, Abiotic how-to document, 2000, available at http://www.ipsl.jussieu.fr/OCMIP).

[5] In order to explore the sensitivity of carbon uptake to the applied wind stress over the Southern Ocean, we forced the model with four different wind products, two of which, *Hellerman and Rosenstein* [1983, hereinafter referred to as HR] and ECMWF [*Trenberth et al.*, 1989, hereinafter referred to as EC], are based on observations, and two of

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Table 1. Diagnostics for the Two Sets of Simulations Discussed in the Text[a]

Model	Ai, m^2 sec^{-1}	Wind Stress, Pa	Pyc. Depth, m	Surface 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	0.05	445	9	103	16	15.3	21	20.1
HR	1000	0.11	524	23	119	19	15.6	34	28.3
EC	1000	0.20	651	40	141	29	20.5	54	38.1
EC-H	1000	0.30	756	63	172	42	24.3	79	46.0
HR-L*	300	0.05	521	12	114	17	15.3	26	22.4
HR*	1000	0.11	524	23	119	19	15.6	34	28.3
EC*	2000	0.20	552	35	121	19	15.6	41	33.8
EC-H*	4000	0.30	550	44	122	19	15.6	46	37.7

[a]The reported wind stress is the annual and zonal-mean at 50°S. Pycnocline depth is calculated according to Footnote 11 of *Gnanadesikan* [1999]. The surface transport is the net zonally-integrated northward transport above 50 m at 50°S, a reasonable proxy for the Ekman transport there. 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. The Southern Ocean (S.O.) is here defined as the region south of 40°S, and the fractional uptake and storage values are both calculated relative to the global C sink. Note that the values given for HR are identical to the values given for HR*. We reproduce the HR* values to facilitate visual comparison.

which are artificially-modified versions of these products. Although the ECMWF reanalysis is more recent, both have been used in OGCM simulations of historical anthropogenic uptake [e.g., *Matsumoto et al.*, 2004]. 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 resulting 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 and Figure 1).

[6] Our modeling strategy relies on a recently developed theory of the oceanic pycnocline [*Gnanadesikan*, 1999, hereinafter referred to as G99]. G99 invokes a buoyancy balance between light water ($\sigma_\theta < 27.4$) sinking in the north (after losing buoyancy) and returning either in the low-latitude pycnocline via diffusively-driven upwelling (parameterized by a diapycnal diffusion coefficient, Kv) or in high southern latitudes via Ekman-driven upwelling (linearly related to the average wind stress at Drake Passage latitudes, τ). The Ekman term is partially compensated by an eddy-driven return flow, parameterized by a Gent-McWilliams thickness mixing coefficient, Ai.

[7] If the ocean is currently in a "low-mixing" state favoring return flow in the Southern Ocean, then several distinct model versions can be developed that preserve both the depth of the low-latitude pycnocline and the *net* southern return flow. Since the Ekman-driven and eddy-driven transport terms oppose one another, this can be accomplished by increasing Ai whenever τ is increased or decreasing Ai whenever τ is decreased. If the net southern return flow is conserved and the low-latitude pathway remains unchanged, then the pycnocline depth itself will remain unchanged. However, increasing τ will necessarily increase the surface Ekman transport in all cases, even in those model versions in which the pycnocline depth, and hence pycnocline volume, is preserved. This is the key insight that allows us to separate volume-driven mechanisms of carbon uptake from transport-driven mechanisms.

[8] The standard value of Ai in our model is 1000 m^2 sec^{-1}, a value that straddles lower estimates derived from inverse methods [*Olbers and Wenzel*, 1989] and higher estimates based on sea surface height variability [*Holloway*, 1986]. Our choice yields roughly the observed pycnocline depth in the HR model when diapycnal diffusivity is chosen to match observations [*Ledwell et al.*, 1993, 1998]. As the wind forcing is altered, we may use G99 to estimate new values of Ai that will restore the pycnocline depth toward observed values. In HR-L, EC and EC-H, these values are 300, 2000, and 4000 m^2 sec^{-1}, respectively. (These so-called "compensated" versions are distinguished from the wind-only "uncompensated" versions by adding a "*" to the name; note however that HR* is identical to HR.) Average values of the pycnocline depth and Ekman transport for all of the model versions discussed here are given in Table 1 (see also Figures 2a and 2b).

3. Results and Discussion

[9] Anthropogenic fluxes and inventories for the model versions with altered winds, as well as for the versions with both altered winds and compensated density are given in Table 1 and shown in Figures 2c–2f. The cumulative anthropogenic flux distribution of the compensated runs (Figure 2d) yields some important insights into the mechanisms driving carbon uptake. As the wind forcing is

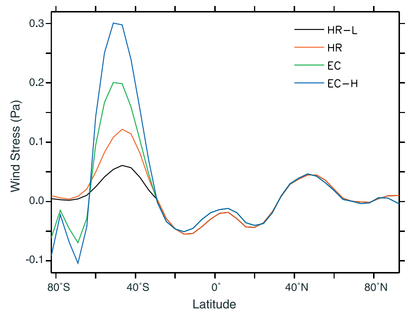

Figure 1. Annually and zonally-averaged wind stresses as a function of latitude for the wind products used in this study. Westerlies are shown as positive values.

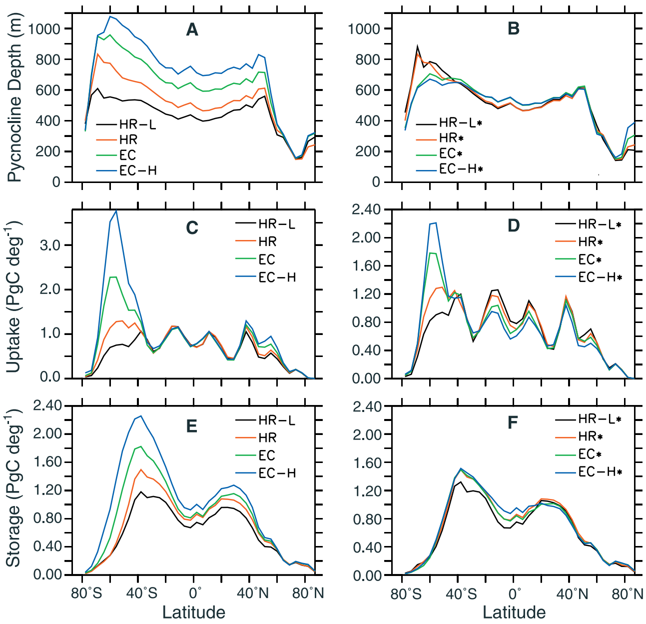

Figure 2. Key physical and carbon cycle diagnostics as a function of latitude. The left-hand column gives results for the uncompensated simulations, in which only winds vary, while the right-hand column gives results for the compensated runs, in which both winds and the parameter Ai vary in tandem to preserve pycnocline depth. (**A**,**B**) show zonally-averaged pycnocline depth as calculated in Footnote 11 of *Gnanadesikan* [1999]. (**C**,**D**) show zonally-integrated, cumulative (1765–2000) air-sea fluxes of anthropogenic carbon dioxide. (**E**,**F**) show zonally-integrated inventories of anthropogenic carbon in year 2000. Comparing (**E**) with (**A**) and (**F**) with (**B**) suggests that the pycnocline depth exerts strong control over the total carbon storage. Note that the scale in (**C**) is different from the other uptake and storage panels.

increased over the Southern Ocean, the cumulative uptake south of 40°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 inventory distributions in the same versions (Figure 2f) 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*). Curiously, this implies that in these simulations in which the changes in wind stress are compensated by changes in eddies, Ekman-driven flux increases in the Southern Ocean must be almost entirely compensated by flux decreases in the low and mid-latitudes. This nearly perfect offsetting is one clear indication that changes in surface transport *alone* cannot alter the global ocean CO_2 sink, although such changes can drastically alter the relative importance of regional sinks like the Southern Ocean.

[10] The non-compensated simulations offer a complimentary set of insights. The flux distributions in these models (Figure 2c) 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 40°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. In fact, uptake in low and mid-latitudes appears to be unaffected by Southern Ocean wind changes, implying that the additional uptake in these model versions must be accompanied by greater carbon storage in the ocean interior.

[11] A simple picture of carbon uptake and storage thus emerges from these seven simulations. The σ_θ = 27.4 surface effectively delineates the bowl of light, young, rapidly-ventilated water from the old abyssal water below. If diapycnal mixing is sluggish, as it is in our model and as it appears to be over much of the real ocean [*Ledwell et al.*, 1993, 1998], then communication between these regions remains limited, confining tracers with relatively recent atmospheric histories to the upper pycnocline (for experimental confirmation of this result, see *Sabine et al.* [2004]). As the depth of the pycnocline (light water volume) increases in the non-compensated high-wind runs, so does the capacity for carbon storage, allowing the additional carbon driven advectively out of the Southern Ocean to be sequestered there. Once in the interior, the carbon spreads isopycnally over large lateral areas, leading the inventory distribution to be significantly more uniform than the flux distribution, as seen in Figure 2 [cf. *Caldeira and Duffy*, 2000]. On the other hand, when the Ekman transport of carbon increases without a concomitant increase in light water volume (as in the compensated runs), then the capacity for storage remains limited, and the additional carbon is transported northward at the surface, rather than at depth. This additional surface transport results in higher CO_2 concentrations in low and mid-latitude surface waters and drives an effective outgassing there relative to models with less surface transport (i.e. the offsetting effect observed in Figure 2d).

[12] These results suggest distinct roles for transport-driven and volume-driven mechanisms. In particular, we see that the magnitude of the zonal wind stress at Drake Passage latitudes, by altering the magnitude of the northward Ekman volume transport and thus the residence time of carbon at the Southern Ocean surface, strongly controls the *regional distribution* of total carbon uptake in an OGCM (transport-driven mechanism), while the magnitude of the zonal wind stress *and* the value of the isopycnal diffusion coefficient, by altering the depth of the low-latitude pycnocline and thus the volume over which carbon can be stored, jointly control the *absolute magnitude* of total carbon uptake in an OGCM (volume-driven mechanism). Moreover, results from these seven model versions lead us to believe that the relationships between light water volume and total uptake and between Ekman transport and Southern Ocean uptake are approximately linear (Figure 3). These results differ somewhat from those of *Ito et al.* [2004], which indicate that the total Southern Ocean sink is not sensitive to the "residual circulation" (what we call the net southern return flow). Our results suggest that it is, or more precisely, that the

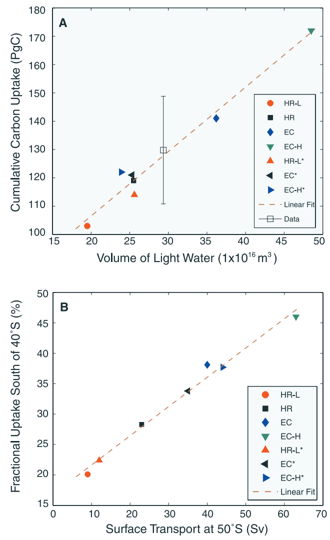

Figure 3. Key predictors of anthropogenic carbon uptake and storage in our model suite. (**A**) shows total cumulative anthropogenic carbon uptake (storage) as a function of light water volume (defined as the volume of water that lies above $\sigma_\theta = 27.4$). The R^2 of the regression is 0.97. The data point is derived from an estimate of cumulative carbon uptake (and associated errors) from *Sabine et al.* [2004] with a 10% model-derived correction added to account for uptake since 1994, and from an estimate of density derived from the temperature and salinity fields of *Levitus and Boyer* [1994]. The error in the latter is calculated by averaging two independent estimates (using 1994 and 2001 data), with the width of the square data marker representing the difference between them, which we take as a proxy for error due to interannual variation. (**B**) shows the fraction of uptake that occurs in the Southern Ocean (south of 40°S) as a function of surface Ekman transport (net northward transport above 50 m) at 50°S. The R^2 of this regression line is 0.99.

fractional uptake depends on the wind-driven component of the residual flow.

4. Implications

[13] Our results suggest that a significant component of the differences in total uptake and in the relative importance of the Southern Ocean observed in previous model intercomparison studies [*Orr*, 2002; *Orr et al.*, 2001] might be attributed to differences in surface wind forcing at high southern latitudes and to the parameterization of isopycnal diffusion [cf. *Ito et al.*, 2004]. These considerations suggest that improved observational constraints on the high-latitude wind stress field will markedly enhance our ability to attribute carbon uptake to different regions of the world ocean and to resolve outstanding questions about the role of the Southern Ocean sink.

[14] These results also suggest that our ability to accurately forecast changes and feedbacks in the global carbon cycle will require a deeper understanding of how future changes in winds, other surface boundary conditions and internal mixing will conspire to alter the volume of light water over which anthropogenic carbon can be stored. For example, winds over the Southern Ocean are known to have increased in the recent past [*Thompson and Solomon*, 2002] and are often predicted to increase in the future in response to anthropogenic forcing [e.g. *Kushner et al.*, 2001]. All else equal, our simulations suggest that such changes would increase both the relative importance of the Southern Ocean sink and the absolute magnitude of total anthropogenic uptake, the latter leading to a potentially significant negative feedback on the global carbon cycle. However, the potency of such a negative feedback depends critically on the strength of the coupling between Southern Hemisphere winds and pycnocline volume, which, in turn, depends on the extent to which changes in other surface boundary conditions and internal mixing oppose an Ekman-driven pycnocline volume increase. A preliminary analysis based on recent coupled model simulations [*Delworth et al.*, 2005] suggests a weaker dependence of volume changes on wind forcing, but further work with coupled models will be necessary to determine the true potency of this mechanism and its implications for the future carbon budget.

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