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The wind-driven, subtropical gyres and the solubility pump of CO_2

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[1] Using a suite of abiotic, ocean-atmosphere, carbon cycle models we demonstrate that the representation of the ventilated thermocline leads to a significant enhancement of the sensitivity of atmospheric pCO_2 to subtropical surface ocean properties. In particular, we study an idealized sector, ocean circulation and abiotic carbon cycle model with a coupled atmospheric reservoir and examine the solubility pump of CO_2 in the subtropical oceans. We compare solutions for atmospheric pCO_2 when driven only by buoyancy forces to those with both buoyancy and wind stress forcing. Introducing the wind stress leads to the formation of a subtropical gyre and the warm lens of the ventilated thermocline. This lens is depleted in carbon relative to the surrounding waters since its properties are inherited from the warm, subtropical surface ocean. It is undersaturated in carbon since subduction quickly follows the strong cooling in the western boundary current before equilibration with the overlying atmosphere can occur. Plausible wind stress patterns increase atmospheric pCO_2, relative to the case without wind forcing, and double the sensitivity of atmospheric pCO_2 to perturbations of the low latitude surface carbon system properties. We suggest that it is the resolution of the ventilated thermocline in global, three-dimensional, ocean circulation models that enhances their sensitivity of atmospheric pCO_2 to warm surface water properties relative to highly idealized box models. *INDEX TERMS:* 4255 Oceanography: General: Numerical modeling; 4271 Oceanography: General: Physical and chemical properties of seawater; 4572 Oceanography: Physical: Upper ocean processes; 4532 Oceanography: Physical: General circulation; 4806 Oceanography: Biological and Chemical: Carbon cycling; *KEYWORDS:* subtropical gyre, CO_2, ocean-atmosphere, carbon cycle, wind stress

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1. Introduction

[2] We examine the role of the wind-driven subtropical ocean circulation in modifying the solubility pump of carbon and influencing the partitioning of carbon between the atmosphere and ocean reservoirs. Much focus has been given to the possible role of the high latitude oceans as an agent change for atmospheric CO_2, particularly on glacial/interglacial timescales (see, for example, the review by *Sigman and Boyle* [2000]). In the 1980s, several independent box model studies highlighted the strong sensitivity of atmospheric pCO_2 to perturbations of the high latitude surface ocean properties, in particular a biological drawdown of high-latitude surface nutrients [*Sarmiento and Toggweiler*, 1984; *Knox and McElroy*, 1984; *Siegenthaler and Wenk*, 1984]. In contrast, these models also indicated that atmospheric pCO_2 may be quite insensitive to changes in low-latitude surface ocean properties. In those models, perturbations to the properties of the shallow, low-latitude surface layer have a negligible long-term impact atmospheric pCO_2. However, these conclusions have been questioned due to inconsistencies with more complex, ocean general circulation and carbon cycle models. These show a weaker response of pCO_2 to high-latitude nutrient drawdown [*Archer et al.*, 2000] and a much more significant influence of the warm surface water properties [*Bacastow*, 1996; *Broecker et al.*, 1999; *Archer et al.*, 2000]. This work focuses on understanding the latter point.

[3] *Broecker et al.* [1999] compare the sensitivities of several carbon cycle box models and ocean general circulation models (GCMs) with carbon cycle parameterizations finding a significantly stronger response of atmospheric pCO_2 to perturbations of the low-latitude surface waters in the GCMs than in the more idealized box models. *Archer*

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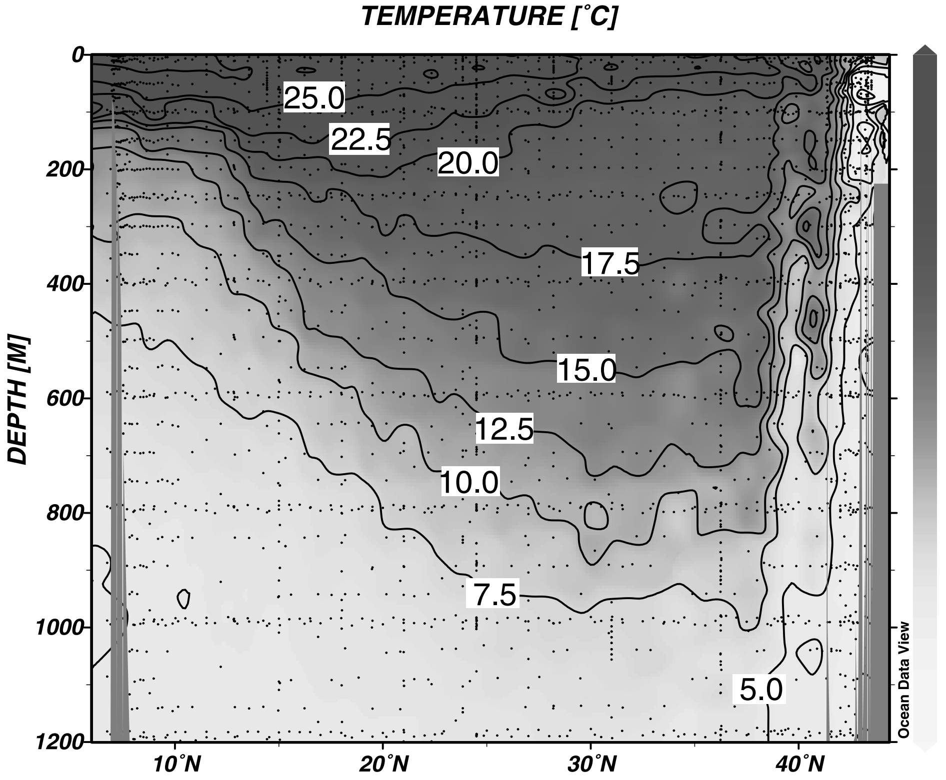

Figure 1. Temperature (°C) section in the North Atlantic along 50°W from WOCE line A20.

et al. [2000] show that this difference may be related to the solubility pump of carbon and that the contrasting behavior is not simply an artifact of model resolution. Using a two-dimensional abiotic ocean-atmosphere carbon model, with a prescribed ocean overturning circulation, they argue that the box models may be brought into closer agreement with the GCMs if vertical mixing between low-latitude surface and deep boxes is sufficiently strong. The authors examine the possibility that numerical dispersion, due to discretization effects, in general circulation models might lead to unrealistically high diapycnal mixing rates. However, their experiments with an isopycnal general circulation model, where diapycnal mixing may be very precisely controlled, do not support this explanation. Alternatively, *Broecker et al.* [1999] noted that the relative volumes of water masses ventilated at lower and higher latitudes is different in GCMs and box models which may lead to these differences.

[4] Here we suggest and examine the hypothesis that the enhanced importance of the warm surface waters in the general circulation models is due to the action of the wind-driven ocean gyres and ventilation of the main thermocline. These processes are coarsely resolved in three-dimensional ocean carbon cycle models but are not generally explicitly represented in highly idealized box models. We illustrate and test this hypothesis using a simplified, basin-scale, ocean-atmosphere carbon cycle model.

2. Wind-Driven Gyres

[5] The action of the wind on the ocean basins leads to the formation of the cyclonic, subpolar and anticyclonic, subtropical gyres. In the subtropical gyres, Ekman pumping and lateral flow through the sloping winter mixed layer base, close to the subtropical-subpolar boundary, lead to the subduction of relatively warm surface waters and maintains the ventilated thermocline [*Iselin*, 1939; *Stommel*, 1979; *Marshall et al.*, 1993]. The dynamics of the subtropical gyres and the ventilation process have been extensively studied and reviewed [see, e.g., *Pedlosky*, 1996; *Price*, 2001]. The waters of the subtropical thermocline are renewed on timescales of a decade or more, as revealed by transient tracers such as tritium-helium [e.g., *Sarmiento et al.*, 1982; *Jenkins*, 1987; *Van Scoy et al.*, 1991]. Following subduction, these waters are shielded from the atmosphere and their properties reflect the relatively warm, carbon depleted surface waters from which they were formed (modified by the remineralization of organic matter). Figure 1 illustrates the meridional temperature structure in the North Atlantic subtropical gyre. The warm lens of the ventilated thermocline penetrates to depths of more than 1000 m. Similar gyre features exist in all the ocean basins.

2.1. Carbon in the Subtropical Thermocline

[6] The relatively shallow water masses associated with subduction and mode water formation represent a significant reservoir of carbon in the ocean-atmosphere system. A subtropical thermocline 500 m thick and extending over half the ocean's surface area represents a carbon reservoir of the order of 2000 Pg C. This is several times the atmospheric reservoir though much smaller than that of the ocean's deep waters (about 35,000 Pg C). Variations in the surface properties in regions of subduction and mode water for-

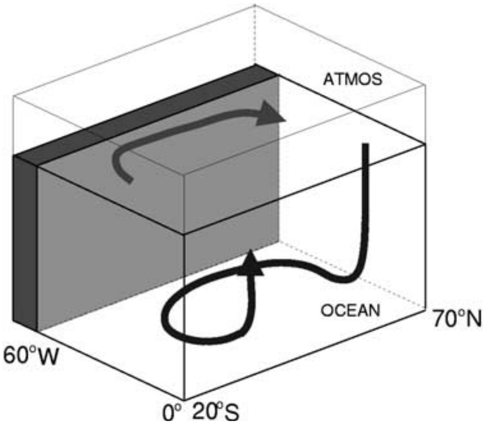

Figure 2. Schematic depiction of the sector carbon model.

mation will modulate the carbon content of in this shielded volume of water, affecting atmospheric $p\mathrm{CO}_2$ on the timescales of ventilation. In addition, climate variability will modulate the volume and ventilation rate of the subtropical thermocline and the associated carbon reservoir.

3. Abiotic Carbon Cycle Model

[7] To examine the hypothesis that water masses associated with the wind-driven ocean gyres increase the sensitivity of atmospheric $p\mathrm{CO}_2$ to warm surface water perturbations, we perform a set of experiments with an idealized ocean-atmosphere carbon cycle model. The model is depicted schematically in Figure 2. We use the MIT ocean circulation model [*Marshall et al.*, 1997a, 1997b], configured in a sector extending from 20°S to 72°N, and sixty degrees wide at 3° × 3° horizontal resolution. There are 15 vertical levels from 50 m thick (uppermost) increasing to 690 m, and the ocean floor is at 5200 m. The model employs the *Gent and McWilliams* [1990] parameterization of eddy transport with thickness and isopycnal tracer mixing coefficients of 1000 $\mathrm{m}^2\ \mathrm{s}^{-1}$. A uniform, background vertical mixing rate of $5 \times 10^{-5}\ \mathrm{m}^2\ \mathrm{s}^{-1}$ is imposed. There is no explicit mixed-layer parameterization, though convective adjustment occurs when the water column is statically unstable.

[8] In this idealized model, we apply restoring boundary conditions for both temperature and salinity at the surface. The target temperatures and salinities, depicted in Figures 3a and 3b, are zonally uniform. The restoring timescales are 1 month for both temperature and salinity. In some experiments the model was also forced by an idealized zonal wind stress, τ_x (Figure 3c), with meridional variation based on the observed Northern Hemisphere pattern. While the details of the model results are sensitive to the specific parameter choices and forcing functions, sensitivity tests show that the main inferences drawn here are qualitatively robust.

[9] The model domain approximates the dimensions of the North Atlantic basin. This is convenient for idealized and computationally efficient experiments. One might envisage the ocean-atmosphere system as consisting of several such basins of differing geometry which reflect the same basic processes. In reality, of course, the ventilated thermocline and mode waters in each basin reflect different

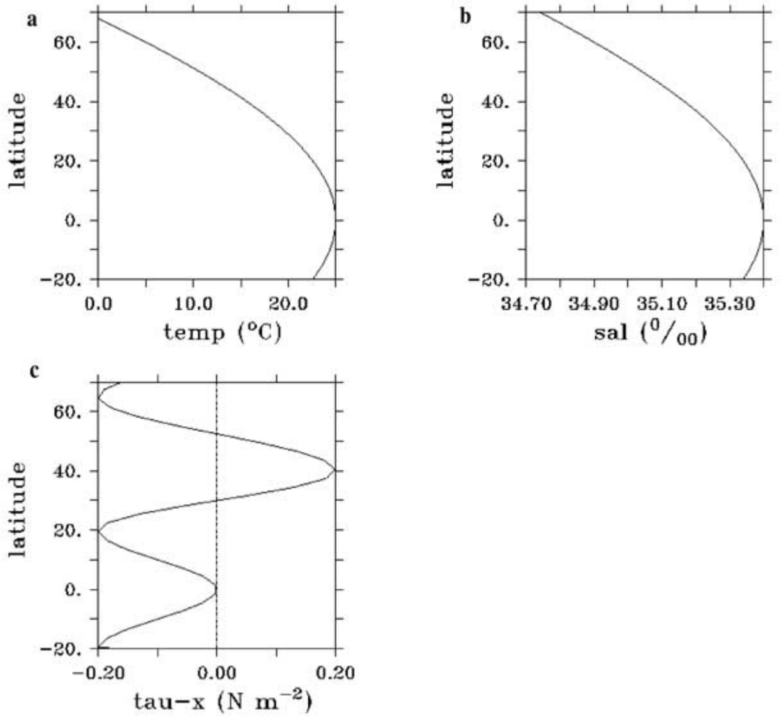

Figure 3. Surface boundary conditions for the sector GCM. (a) Target temperature (°C) and (b) salinity (psu). (c) Zonal wind stress ($\mathrm{N\ m}^{-2}$).

sites and rates of ventilation [see, e.g., *Hanawa and Talley*, 2001] and, in the Southern Hemisphere, interact significantly with processes and water masses associated with the Antarctic Circumpolar Current [*Rintoul et al.*, 2001].

[10] Here we choose to examine an abiotic system since the two-dimensional, abiotic study of *Archer et al.* [2000] suggests that the sensitivity to low-latitude surface properties might be set by processes related to the solubility pump. For clarity, possible contributions from the biological pumps are not examined here. Dissolved inorganic carbon, DIC, is carried as a tracer in the model. Air-Sea exchange of CO_2 is parameterized with a uniform gas transfer coefficient of 5.5×10^{-5} m s^{-1}. Carbonate chemistry in the surface waters is treated as described by *Follows et al.* [1996] with surface alkalinity prescribed as a linear function of salinity.

[11] A well-mixed atmosphere with prognostic partial pressure of carbon dioxide, $p\mathrm{CO}_2^{at}$, overlies the ocean model. The total mass of the model atmosphere is appropriate for a surface pressure of 1000 mbar and an ocean:land surface area ratio of 7:3. The rate of change of $p\mathrm{CO}_2^{at}$ is determined from the net flux of CO_2 across the sea surface.

3.1. Experiment Design

[12] To examine the role of the low-latitude surface oceans in regulating atmospheric $p\mathrm{CO}_2$ and, in particular, the role of the solubility pump in the wind-driven gyres, we perform the following set of experiments, all with the same, fixed total ocean-atmosphere budget of carbon:

3.1.1. Thermohaline Forcing (TH)

[13] For thermohaline forcing, perform the following steps: (1) Spin up the ocean-atmosphere carbon cycle model to steady state with only thermohaline forcing. (2) Perturb the surface carbonate chemistry coefficients at latitudes between the southern boundary and 45°N by an increment equivalent to a temperature change of 5°C and integrate to new steady state.

3.1.2. Thermohaline and Wind Forcing (TH + W)

[14] For thermohaline and wind forcing, perform the following steps: (3) Repeat the first experiment (step 1) with both thermohaline and wind forcing. (4) Repeat perturbation experiment (step 2) with both thermohaline and wind forcing.

[15] By comparison of the TH and TH + W unperturbed, steady state atmospheric $p\mathrm{CO}_2$, we may gauge the impact of the wind-driven circulation on the mean state of the atmosphere. By comparing the change in $p\mathrm{CO}_2$ (between TH and TH + W) following the perturbation of low-latitude surface properties, we may gauge the effect of the wind driven circulation on the sensitivity to such changes. We measure the sensitivity as the change in atmospheric $p\mathrm{CO}_2$ relative to the change in the effective surface temperature (for the carbonate system), T_L', of the tropical and subtropical oceans: $\Delta p\mathrm{CO}_2/\Delta T_L'$.

4. Model Results

[16] We present model results from a small set of experiments with particular values of various model parameters; for example mixing coefficients and wind-stress amplitude. A wider set of sensitivity experiments has shown that the broad inferences drawn are robust over reasonable ranges of these parameters.

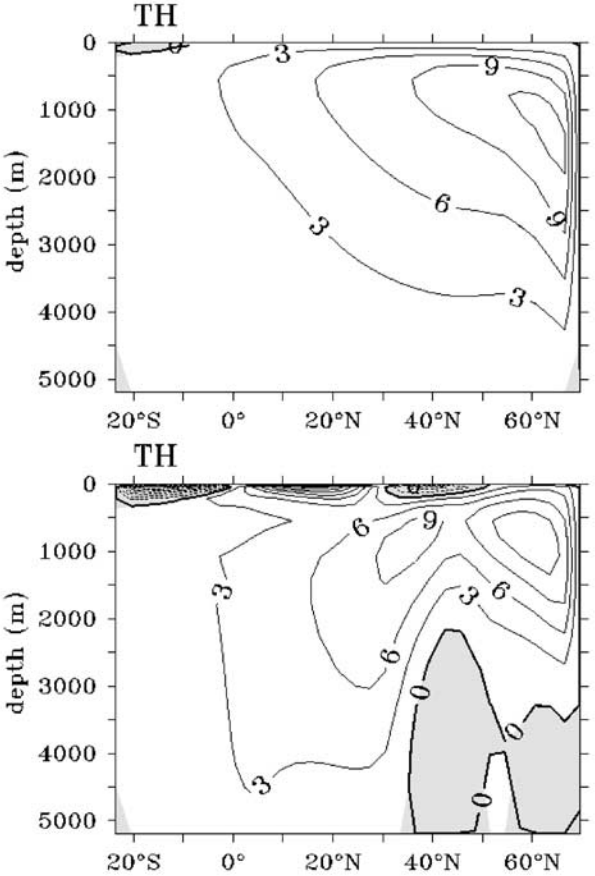

Figure 4. Meridional overturning circulation (Sv) of the thermohaline (TH) and thermohaline and wind (TH + W) forced models.

[17] First, we compare the physical characteristics of the unperturbed, thermohaline (TH) and thermohaline and wind (TH + W) forced models. Figure 4 shows the meridional overturning circulations: With thermohaline forcing only, downwelling is confined to the extreme north (east) with widespread upwelling throughout the rest of the basin. Equatorward flow at depth is balanced by poleward flow at the surface, with westward intensification leading to boundary currents. The circulation is consistent with that of previously published models of this type [e.g., *Marotzke and Scott*, 1999]. With wind forcing, the model's meridional circulation is altered. Deep water formation still occurs at high latitudes and the deep meridional overturning is of similar magnitude. However, shallow, wind-driven overturning cells modify the near-surface overturning circulation. There is upwelling near the surface in the subpolar gyre and throughout the column in the tropics. Ekman pumping leads to downwelling in the near surface subtropics. The broad patterns are consistent with previous, comparable models [e.g. *Vallis*, 2000, Figure 11a].

[18] The upper ocean temperature structure of the two cases is compared in Figure 5. The uniform low- and mid-

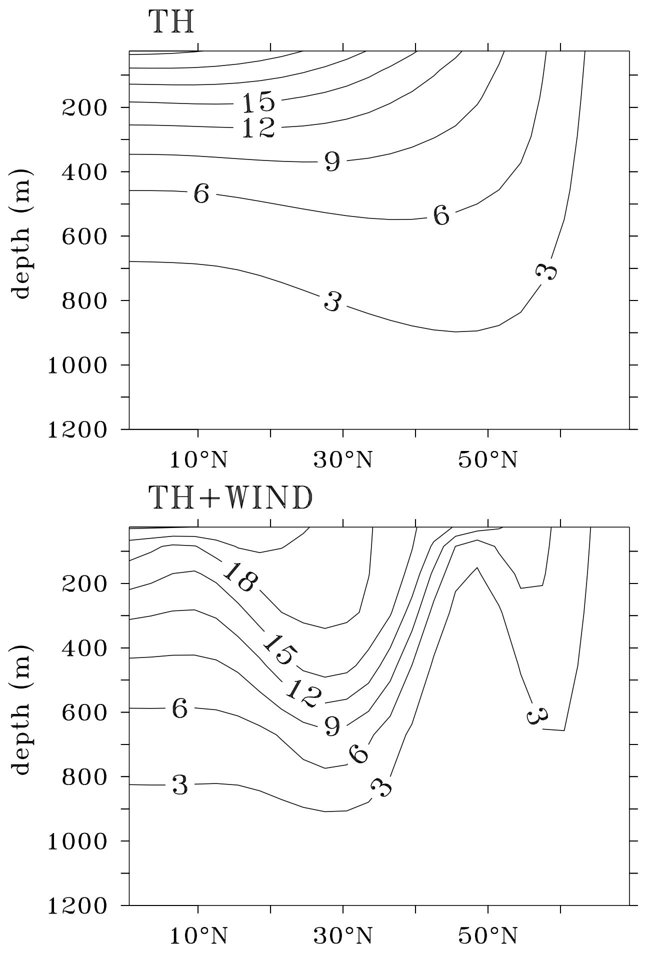

Figure 5. Upper ocean temperature structure (°C) at 40°W in the thermohaline (TH) and thermohaline and wind (TH + W) forced models.

latitude thermocline of the TH model reflects a balance between the broad-scale upwelling and vertical mixing. In the TH + W model, the subtropical thermocline is pumped downward, introducing a lens of relatively warm water to a depth of a few hundred meters, also ventilated by lateral transfer through the sloping mixed layer base. At midlatitudes the layer of weak stratification between 18° and 20°C indicates the subduction of mode waters (compare Figure 1). In the subpolar gyre, Ekman suction draws deep, cool waters toward the surface. Below 1200 m, the deep waters in both models are very similar in character since the location and rate of deep water formation are largely unchanged, partly due to the strong restoring boundary conditions for temperature and salinity. While warm waters are pumped into the subtropical thermocline in the wind-driven model, cooler waters are sucked toward the surface in the subpolar region. With this configuration, the mean ocean temperature undergoes a minor decrease (0.1°C) between TH and TH + W.

[19] Since this model is abiotic, the DIC distribution is determined by solubility effects and, to the extent that the surface waters equilibrate with the overlying atmosphere, it inversely follows the temperature structure. Hence the warm lens of the subtropical thermocline is depleted in carbon relative to its surroundings. Total ocean-atmosphere carbon is conserved throughout all the model runs, and comparing experiment (1), unperturbed TH, and experiment (2), unperturbed TH + W, we find an increase in $p\mathrm{CO}_2^{at}$ of 18 ppm. The influence of the wind in this simple, abiotic configuration is to drive CO_2 into the atmosphere but, as we have seen, the ocean has cooled very slightly, increasing the mean solubility. Why then, is CO_2 transferred into the atmosphere?

[20] This global outgassing occurs because the waters of the ventilated thermocline are more undersaturated than the waters at these depths in the model without wind forcing. In both models the western boundary current is rapidly losing heat, increasing the solubility of CO_2. In the wind-driven case it is also much swifter and penetrates into the interior of the basin. The air-sea equilibration timescale for carbon is relatively long (about a year for a 100-m mixed layer) and comparable to the timescale for the transit from the western boundary into the wind-driven gyre circulations. Recirculating, undersaturated waters in the subtropical gyre continue to absorb carbon from the atmosphere well downstream of the heat (and solubility) forcing associated with the western boundary current. Subduction of waters into the ventilated thermocline occurs at midlatitudes near the gyre boundary where they are still strongly undersaturated, as can be seen in Figure 6 for the wind-forced model (TH + W). In this case, near-surface upwelling and outgassing are confined to the tropics and the subtropical air-sea flux has changed sign relative to the experiment without wind forcing (TH). The subtropical uptake of CO_2 (TH + W) is consistent with more realistic models [*Follows et al.*, 1996] and the observed uptake of carbon by the subtropical gyres [*Takahashi et al.*, 1997], though the latter also reflects a contribution from biological processes.

[21] The region of net ocean outgassing near the intergyre boundary (TH + W) is due to the cyclonic circulation of the subpolar gyre, feeding subpolar, carbon rich waters to and is also consistent with the more realistic model [*Follows et al.*, 1996].

[22] In contrast, for the TH model, ocean uptake of CO_2 occurs at higher latitudes and in the western boundary region, associated with ocean heat loss and increased solubility. The region of ocean outgassing extends almost to midlatitudes in a broad meridional swath associated with the upwelling and warming of deep, carbon-rich waters. The surface currents without wind forcing are much slower and consequently the surface waters are generally closer to saturation than in the wind-driven case, even in the region of deep water formation.

[23] The action of the wind is to drive swift surface currents associated with the ocean gyres and to form the ventilated thermocline. The swiftness of the currents results in subduction of water into the thermocline before they have equilibrated with the overlying atmosphere. The wind-forced ocean (TH + W) is thus more undersaturated than the case without wind (TH), particularly in the subtropical thermocline.

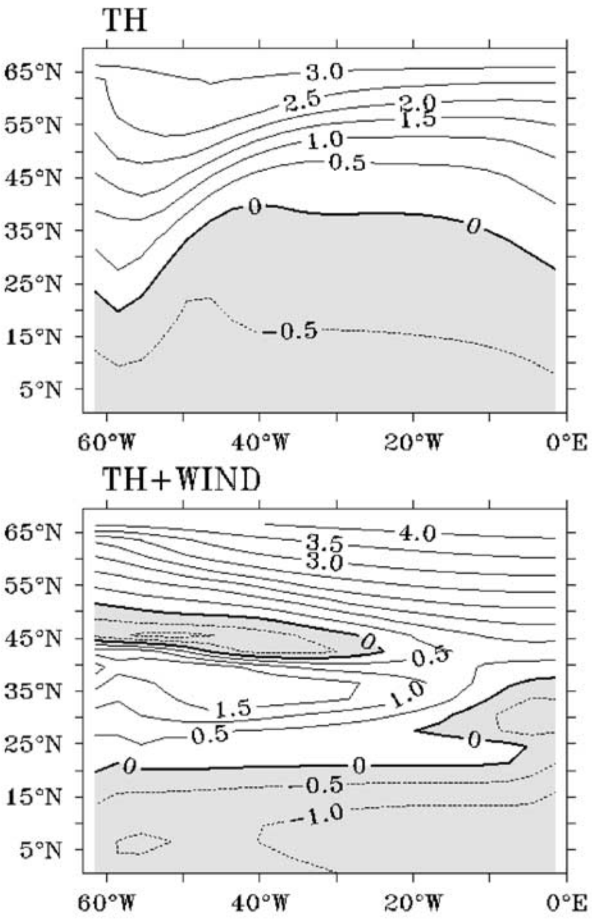

Figure 6. Air-sea CO_2 flux patterns of the steady state, unperturbed thermohaline (TH), and thermohaline-wind (TH + W) forced models (mol C m^{-2} $year^{-1}$).

[24] The effect of the wind on pCO_2^{at} depends on the strength of the wind-forcing which controls the depth of the ventilated thermocline [*Luyten et al.*, 1983] and its saturation state in this abiotic model. Sensitivity tests indicate a monotonic, positive relationship between the amplitude of the wind forcing and pCO_2^{at}. Though the relationship is not linear, there is a sensitivity of about 125 ppmv/(N m^{-2}) at realistic wind-stress levels.

[25] In this still very idealized model, water masses of both subtropical and subpolar origin return to the surface in the tropics. In the ocean today, there is also a pathway for the deep waters to return to the surface at high southern latitudes.

5. Sensitivity of Atmospheric pCO_2 to Subtropical Perturbations

[26] The comparison of experiments (1) and (3), the basic model state without and with wind forcing, has revealed the importance of the ventilated thermocline; a significant reservoir of undersaturated waters, with respect to atmospheric CO_2, formed at midlatitudes and screened from the atmosphere. What is the impact of this reservoir on the sensitivity of atmospheric pCO_2 in the model to perturbations of the tropical and subtropical surface water properties?

[27] To address this question we perform the sensitivity experiments, (2) and (4). In these experiments, following *Bacastow* [1996], the sea surface carbonate chemistry coefficients are perturbed as if there had been a 5°C increase in sea surface temperature everywhere south of 45°N. The model's sea surface temperature is not actually changed in order to preserve the steady state ocean circulation patterns. The models are then spun up to new steady states and the change in pCO_2^{at} evaluated relative to the low-latitude "temperature change," T'_L, $\Delta pCO_2^{at}/\Delta T'_L$ (ppmv/K). This perturbation experiment is done separately for both wind-forced (TH + W) and no-wind (TH) models.

[28] In the case with thermohaline forcing only, TH, the sensitivity to a low latitude perturbation, $\Delta pCO_2^{at}/\Delta T'_L$ = 1.8 ppmv/K, but this is almost doubled to 3.5 ppmv/K in the case with wind forcing, TH + W. Introducing the wind-driven circulation has enhanced the sensitivity to perturbations of the low-latitude surface waters by a factor of 2, sufficient to reconcile the warm surface ocean sensitivities of box models and GCMs discussed by *Broecker et al.* [1999] and *Archer et al.* [2000] (Table 1).

[29] In the wind-driven case (TH + W, experiment (4)) the modification of warm surface properties is reflected in a change in the carbon reservoir of the subtropical thermocline. This reservoir is big enough for the change to impact significantly on atmospheric pCO_2. Typically, however, ocean biogeochemical box models have only represented the major thermohaline circulation pathways in the ocean and are analogous to the no-wind model (TH). (There are some exceptions; the six-and seven-box models of *Toggweiler* [1999] include a representation of a thermocline and intermediate water reservoir and *Boyle* [1986] discussed sensitivities of the oceans biological pumps using a box model with a representation of the wind-driven circulation.) Here we have demonstrated a significant consequence of the wind-driven gyres using a sector ocean model. It is straightforward to modify the classical three-box ocean model to explicitly represent the subtropical thermocline (shown schematically in Figure 7) We add to the box model a subtropical thermocline a few hundred meters thick which is ventilated by subduction in the subtropics. The subducted waters return to the surface in the tropical upwelling.

[30] This modification brings into consistency the sensitivities of the box model, sector model, and a global GCM.

Table 1. Comparison of Sector Model Experiments With and Without Wind Forcing[a]

	pCO_2, ppmv	$\frac{\Delta pCO_2}{\Delta T'_L}$, ppmv K^{-1}
No wind	268	1.8
Wind	286	3.5

[a] The middle column shows steady state atmospheric pCO_2, and the right-hand column indicates the sensitivity of atmospheric pCO_2 to tropical and subtropical surface perturbations (see text for details).

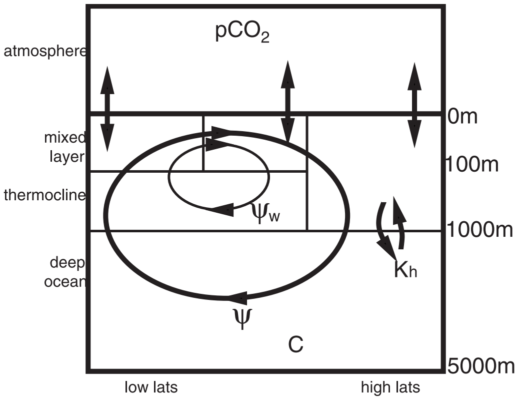

Figure 7. Schematic depiction of a box ocean-atmosphere carbon cycle with explicit representation of the ventilated subtropical thermocline.

The sensitivity experiments described above using a sector model can be mimicked in the box model by the choice of ψ_w, the overturning associated with thermocline ventilation. We switch on or off the wind-driven circulation by setting ψ_w = 0 or 5 Sv, roughly corresponding to the integrated Ekman pumping rate over the North Atlantic gyre. In addition, we have performed a similar perturbation experiment in a coarse resolution, abiotic global carbon cycle model (a four-degree resolution configuration of the MIT circulation and biogeochemistry model).

[31] The results of the sensitivity experiments from the sector model, enhanced box model, and GCM are summarized in Figure 8. Here, model results are grouped not by model type, but by the absence or presence of the wind-driven subtropical circulation and ventilated thermocline. Clearly, all the wind-forced models show similar sensitivity to the global coarse resolution general circulation model, whereas those models with no wind forcing show similar sensitivities to a three-box model similar to the original "Harvardton Bear" models. While we have not discussed these models in terms of the "Harvardton Bear Equilibration Index" (HBEI, [*Broecker et al.*, 1999]), it is readily evaluated for the three- and five-box ocean models, showing the same qualitative increase in sensitivity to low-latitude processes with wind forcing as measured by the parameter $\Delta p\mathrm{CO}_2^{at}/\Delta T_L'$.

6. Discussion

[32] These idealized experiments suggest a reconciliation of the contrasting inferences concerning the sensitivity of atmospheric $p\mathrm{CO}_2$ to warm surface water properties from box and general circulation models [*Broecker et al.*, 1999; *Archer et al.*, 2000]. The wind-driven subtropical gyres are at least crudely resolved in global general circulation models and as such the higher sensitivity of GCMs to low-latitude processes is perhaps more plausible than that of the highly idealized box models.

[33] Why are the wind-forced models so much more sensitive? The subtropical ventilated thermocline represents a significant body of water, some hundreds of meters thick and of great areal extent, the properties of which reflect those of the midlatitude surface waters from which they are formed. This reservoir of carbon is shielded from the atmosphere by the overlying mixed layer and weak diapycnal mixing rates [*Ledwell et al.*, 1993] relative to rates of ventilation along isopycnal surfaces by the mean flow and eddy stirring. Hence, the ventilated thermocline acts as a smaller and warmer analog of the deep ocean reservoir of the classical three-box models.

[34] There are two ways in which the subtropical thermocline waters may influence atmospheric $p\mathrm{CO}_2$; through physical modulation of the extent, formation sites, and ventilation rates of these water masses, or through physically and biogeochemically induced changes in the water properties at the sites of subduction.

[35] In the ocean, mode waters and the ventilated thermocline exist in all basins, but vary in character and extent. The rich structure of mode waters and the ventilated thermocline leads to a variety of carbon pools which can influence atmospheric $p\mathrm{CO}_2$. These reservoirs, typically ventilated on decadal timescales, can impact the atmosphere on those and longer timescales. They also represent important oceanic sinks for anthropogenic gases; for example, *Gruber* [1998] shows the subduction of CO_2-enriched waters into the North Atlantic subtropical thermocline.

[36] In the Southern Hemisphere, there is also a potentially important interaction between the waters of the ventilated thermocline and processes associated Antarctic Circumpolar Current and meridional transport circulation of the Southern Oceans. *Rintoul et al.* [2001] suggest an exchange rate of about 80 Sv between the Southern Hemisphere subtropical thermocline, Sub-Antarctic Mode Waters and Antarctic Intermediate Waters. These intermediate water masses associated with the Circumpolar Current provide another reservoir of carbon and probably modify the role of the southern gyres relative to the idealized basin study presented above.

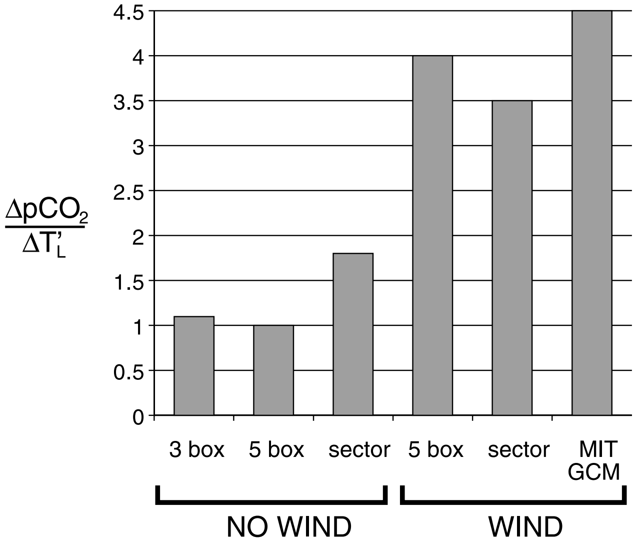

Figure 8. Sensitivities of atmospheric $p\mathrm{CO}_2$ in several abiotic carbon cycle models to perturbations of low-latitude carbon chemistry parameters, expressed as an equivalent temperature change (ppmv K^{-1}).

Southern Ocean processes have been implicated as potentially important agents of glacial-interglacial change [e.g., *Toggweiler*, 1999; *Keeling and Stephens*, 2001; *Sigman and Boyle*, 2000], and these intermediate water masses could play a more significant role in the associated changes of atmospheric $p\mathrm{CO}_2$.

[37] The sector model, of intermediate complexity, provides a useful and idealized instrument to examine specific mechanisms related to the nature and role of the wind-driven gyre circulations and thermocline ventilation. The results of this particular study suggest that the global general circulation models are resolving significant oceanic carbon reservoirs which are not explicitly represented in many of the highly idealized box models. This does not detract from the essential advantage of box models, which is their transparency and simplicity, enabling a clear illustration of basic processes and interactions in the system. On the other hand, it is an illustration that such simplified representations of the global ocean may exclude important processes. While global biogeochemical models based on GCMs explicitly represent more detailed dynamics, including the gyre circulations, they still do not resolve important smaller scale processes including mesoscale eddy transfers, localized deep convection, and overflows important in deep water formation. Consequently, such models have a wide range of chlorofluorocarbon uptake rates, particularly at higher latitudes [*Dutay et al.*, 2001].

[38] Our experiments suggest a reconciliation of current models, but what do they indicate in regard to the broader question of climate and biogeochemical change? What is the role of changes in the wind-driven gyres on glacial-interglacial timescales? First, while changes to subtropical surface waters have an increased impact in the models which represent the wind-driven ventilation, consistent with the global GCMs, the sensitivity to perturbations is still much lower than that at high latitudes. From the models illustrated here, compare 4 ppmv K^{-1} for the tropical and subtropical region and about 10 ppmv K^{-1} for the subpolar region. The high-latitude sensitivity, by this measure, is more than double that of low latitudes and is much more significant on an area weighted basis. It changes very little between TH and TH + W, probably due to the strong restoring boundary conditions. While subtropical changes to the solubility pump may have a more significant modulating effect than previously considered, high-latitude processes, through their influence on the large deep ocean reservoir, and still have more leverage to effect significant changes in atmospheric $p\mathrm{CO}_2$.

[39] What might be the response of the ocean gyres, and their influence on the solubility pump and atmospheric $p\mathrm{CO}_2$, to global climate change such as glacial-interglacial variations? Ventilating cooler waters into the thermocline would promote an uptake of CO_2 from the atmosphere. *Slowey and Curry* [1992] published paleo-evidence from North Atlantic sediments which indicates that the subducted waters of the subtropical thermocline may have been as much as 4°C cooler at the Last Glacial Maximum. If the thermocline were cooled by that amount globally and if there were no change in the volume of the thermocline, the sensitivity of the wind-forced models ($\sim$4 ppmv K^{-1}) would lead to an associated reduction of atmospheric $p\mathrm{CO}_2$ on the order of 16 ppmv.

[40] On the other hand, we might also expect a strengthening of the westerly Wind stress, during a glacial period which would enhance the gyre circulation and the thicken the ventilated thermocline [*Luyten et al.*, 1983] which would oppose the oceanic uptake of CO_2 by promoting a greater volume of more undersaturated waters. *Slowey and Curry* [1992], however, find that the depth of the thermocline was not enhanced during the Last Glacial Maximum. This might also reflect a lateral shift in the gyre structure.

[41] Clearly this back-of-the-envelope estimate is very speculative, but suggests an upper limit to the enhancement subtropical solubility pump equivalent to a decrease in atmospheric $p\mathrm{CO}_2$ on the order of 16 ppmv. It suggests that while this mechanism could have a significant impact on atmospheric $p\mathrm{CO}_2$, it is unlikely to be the major player in the recorded glacial-interglacial change. If the thermocline does thicken, the impact could be much less.

[42] Here we have focused only on the solubility pump of carbon, but the wind-driven circulation can also affect the oceans biological pumps of carbon. *Boyle* [1986], using a box model, illustrated a mechanism for enhancement of the biological pump by changes to the wind-driven circulation resulting in a reduction of atmospheric CO_2 of similar magnitude. In addition, marine ecosystem response to climate change, or independent variability, could have a profound effect on the surface biogeochemistry and the composition of subducted waters.

[43] Here we have examined the sensitivity of $p\mathrm{CO}_2$ to the warm surface waters of the oceans, and the contrasting inferences from box models and GCMs. We have not addressed the related question raised by *Archer et al.* [2000] concerning the contrasting sensitivity to high-latitude nutrient drawdown. Both issues are also discussed by *Toggweiler et al.* [2002a, 2002b], who examine the importance of the very localized nature of deep water formation sites which may affect the saturation state of the deep waters and may be difficult to represent appropriately in ocean models.

[44] In summary, this study may reconcile some of the apparent differences of box and general circulation model representations of the ocean-atmosphere carbon cycle. The wind-driven circulation and ventilated thermocline can have a significant, but not dominant, role in modulating the solubility pump of carbon and atmospheric $p\mathrm{CO}_2$. Box models which do not represent this mechanism underestimate the sensitivity of atmospheric $p\mathrm{CO}_2$ to tropical and subtropical surface water properties. This study also motivates the use of models of intermediate complexity to bridge the gap between highly idealized box models and global GCMs. The interaction of Antarctic Intermediate and Mode Waters with the Southern Hemisphere gyres presents an interesting and important extension of the mechanisms highlighted here which could be studied using models of similar complexity.

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