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Comment on “Saturation of the Southern Ocean CO₂ Sink Due to Recent Climate Change”

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We disagree with the conclusion of Le Quéré *et al.* (Reports, 22 June 2007, p. 1735) that poleward intensifying winds could continue to weaken the Southern Ocean sink in the future. We argue that altered winds, along with rising atmospheric carbon dioxide, will likely increase the efficiency of this sink in the 21st century.

Le Quéré *et al.* (1) recently concluded that the strengthening and poleward shifting of extratropical Southern Hemisphere winds observed over recent decades is likely to have weakened the Southern Ocean sink of CO₂. This finding is of great relevance in the context of climate change, as the Southern Ocean accounts for ~40% of the modern oceanic sink of anthropogenic CO₂ (2, 3). Moreover, the majority of state-of-the-art climate models project the poleward wind intensification to continue in the future, as CO₂ builds up in the atmosphere (4). However, the conclusion of Le Quéré *et al.* (1)—that a continuing trend in the winds will possibly lead to a positive feedback on atmospheric CO₂ in the future—disregards one important process regulating the exchange of CO₂ between the atmosphere and the Southern Ocean.

At present, the strong westerlies over the Southern Ocean drive a northward Ekman transport, which constitutes the surface branch of a meridional overturning circulation, the Deacon cell. Ekman-driven upwelling in the Antarctic Divergence (i.e., the region <55°S) exposes deep waters with elevated concentrations of dissolved inorganic carbon (DIC) to the surface, leading to outgassing of natural CO₂ to the atmosphere. At the same time, anthropogenic CO₂ is sequestered in the downwelling branch of the Deacon cell, in association with the formation of mode and intermediate waters (5).

Strengthening of the Southern Hemisphere westerlies enhances the rate of meridional overturning and hence influences the processes regulating the exchange of CO₂ between the atmosphere and the Southern Ocean. To illustrate

the effect of altered winds on the air-sea flux of CO₂ in the Southern Ocean, we draw on simulations with the University of Victoria Earth System Climate Model (UVic-ESCM) (6), aspects of which were reported in Zickfeld *et al.* (7, 8). The UVic-ESCM includes a state-of-the-art representation of the marine and terrestrial carbon cycle. Over the historical period (1800 to 2005), the model simulates an increase in atmospheric CO₂ of 212 Pg C, which is close to the observed value (9). The atmospheric CO₂ increase is 3.7 Pg C year⁻¹ for the 1990s and 4.1 Pg C year⁻¹ for 2000 to 2005, in good agreement with observation-based estimates (10). Global oceanic uptake of anthropogenic CO₂ is 1.8 Pg C year⁻¹ for the 1980s and 2.2 Pg C year⁻¹ for the 1990s, in excellent agreement with (10). The global oceanic sink of anthropogenic CO₂ for 1800 to 1994 is 105 Pg C, which is within the error bar of Sabine *et al.* (2). The fluxes of natural and anthropogenic CO₂ in the Southern Ocean agree with inverse model estimates (3, 11).

Figure 1 shows the modeled effect of poleward intensifying winds on the air-sea flux of natural and total (i.e., natural + anthropogenic) CO₂ for the period between 1900 and 2100. For the case of natural carbon (Fig. 1A), it is evident that more intense winds over the Southern Ocean lead to increased ventilation of natural CO₂ south

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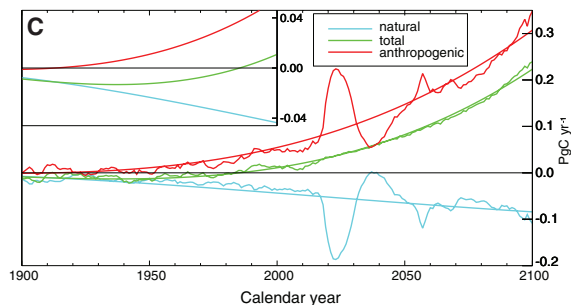
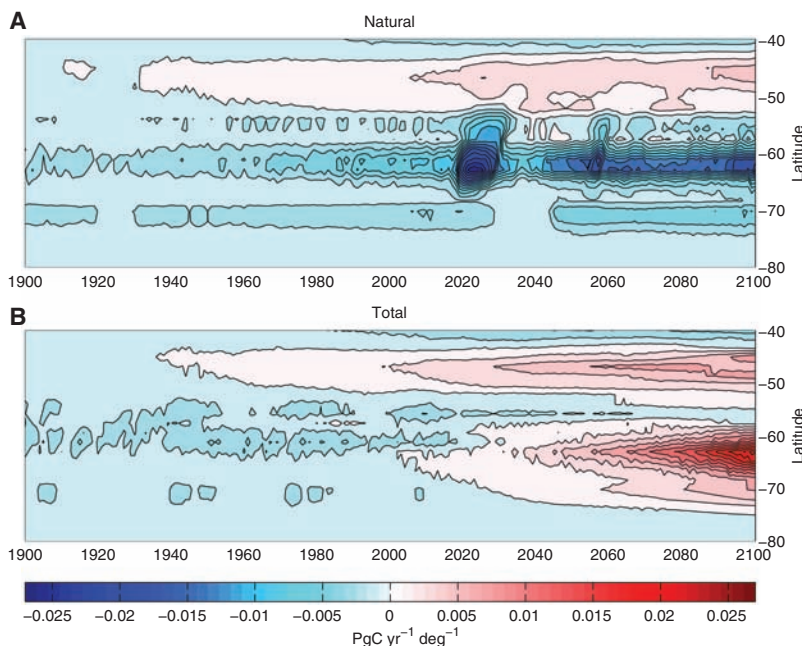


Fig. 1. Modeled effect of poleward intensifying winds on zonally integrated air-sea CO₂ flux in the Southern Ocean over the time period 1900 to 2100. (A) Flux of natural CO₂, (B) flux of total CO₂, and (C) CO₂ fluxes integrated over the Southern Ocean (90°S to 40°S). The smoothed curves are polynomial fits to the modeled fluxes. The nested plot in (C) displays the polynomial fits for 1900 to 2000. Negative fluxes indicate ocean outgassing. The flux of natural CO₂ (A) is obtained as the difference between a control simulation with all forcings held at 1800 levels and a simulation with atmospheric CO₂ fixed at 1800 levels and Southern Hemisphere winds evolving according to the Inter-

governmental Panel on Climate Change AR4 model-ensemble mean, which projects a 25% strengthening and a 3.5° poleward shift of the maximum annual mean zonal wind stress by 2100 (4). The flux of total carbon is calculated as the difference between a simulation with CO₂ emissions following historical estimates for the period 1800 to 1990 and the Special Report on Emissions Scenarios A2 scenario thereafter (with wind forcing held constant at 1800 levels) and a simulation with both anthropogenic CO₂ emissions and poleward intensifying winds. The flux of anthropogenic CO₂ shown in (C) is derived as the difference between the fluxes of total and natural CO₂. The model simulations are described in detail in Zickfeld *et al.* (7).

of 55°S and increased uptake in the mode water formation region (55°S to 40°S) throughout the 20th and 21st centuries. Both effects are associated with the higher rate of meridional overturning, leading to stronger upwelling of deep, DIC-rich waters south of 55°S and stronger subsuction north of 55°S (7). As the anomalous outgassing of natural carbon dominates, the total wind effect is a weakening of the Southern Ocean sink (Fig. 1C).

In the case of total CO₂ flux, the time evolution is more complex. Initially, altered winds lead to anomalous outgassing of CO₂ and, from the end of the 20th century on, to anomalous uptake of CO₂ in the upwelling region (Fig. 1B). The initial trend toward enhanced outgassing is in agreement with the results of Le Quéré *et al.* (1), although the timing is different. We find a significant negative trend (more outgassing with time) between 1850 and 1950 (-0.0011 ± 0.0001 Pg C year⁻¹ decade⁻¹) and a significant positive trend (less outgassing with time) from 1950 to 2000 (0.0053 ± 0.0005 PgC year⁻¹ decade⁻¹) (Fig. 1C), which is in contrast to the findings by Le Quéré *et al.* (1) of a negative trend between 1980 and 2004. This difference is not surprising because we use modeled instead of observed winds over the historical period. However, the focus of our comment is not so much on the timing of the trend reversal, which is certainly model-dependent, as on the fact that this reversal occurs at all.

The reversing effect of the poleward intensifying winds, acting initially to weaken and then to strengthen the uptake of CO₂ in the Southern Ocean, can be explained as follows: As anthropogenic CO₂ builds up in the atmosphere, the deep, older waters are exposed to higher atmospheric CO₂ levels, so that stronger upwelling is associated with simultaneous natural CO₂ outgassing and anthropogenic CO₂ uptake anomalies (5, 7). Until about 1980, the anomalous outgassing of natural carbon is the dominant mechanism, so that despite the uptake anomaly between 55°S and 40°S, stronger winds act to weaken the Southern Ocean CO₂ sink, as described by Le Quéré *et al.* (1). However, as CO₂ concentrations continue to rise, the effect on uptake of anthropogenic CO₂ dominates, resulting in a more efficient Southern Ocean sink (7).

We thus suggest that the current trend toward a weakening of the Southern Ocean sink reported by Le Quéré *et al.* (1) may not be indicative for the future. We rather suggest that a continuing poleward intensification of the Southern Hemisphere winds, along with rising atmospheric CO₂ levels, will likely increase the efficiency of Southern Ocean carbon uptake, providing for a small negative feedback on atmospheric CO₂.

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