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Toward a mechanistic understanding of the decadal trends in the Southern Ocean carbon sink

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[1] We investigate the multidecadal and decadal trends in the flux of CO_2 between the atmosphere and the Southern Ocean using output from hindcast simulations of an ocean circulation model with embedded biogeochemistry. The simulations are run with NCEP-1 forcing under both preindustrial and historical atmospheric CO_2 concentrations so that we can separately analyze trends in the natural and anthropogenic CO_2 fluxes. We find that the Southern Ocean (<35°S) CO_2 sink has weakened by 0.1 Pg C a^{-1} from 1979–2004, relative to the expected sink from rising atmospheric CO_2 and fixed physical climate. Although the magnitude of this trend is in agreement with prior studies (Le Quéré et al., 2007), its size may not be entirely robust because of uncertainties associated with the trend in the NCEP-1 atmospheric forcing. We attribute the weakening sink to an outgassing trend of natural CO_2, driven by enhanced upwelling and equatorward transport of carbon-rich water, which are caused by a trend toward stronger and southward shifted winds over the Southern Ocean (associated with the positive trend in the Southern Annular Mode (SAM)). In contrast, the trend in the anthropogenic CO_2 uptake is largely unaffected by the trend in the wind and ocean circulation. We regard this attribution of the trend as robust, and show that surface and interior ocean observations may help to solidify our findings. As coupled climate models consistently show a positive trend in the SAM in the coming century [e.g., Meehl et al., 2007], these mechanistic results are useful for projecting the future behavior of the Southern Ocean carbon sink.

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1. Introduction

[2] Many aspects of the Southern Hemisphere climate have exhibited trends over the past few decades. *Thompson et al.* [2000] observed a 30-year positive trend in the strength of the westerly winds at subpolar latitudes. A trend toward warming on the Antarctic Peninsula and cooling on the interior of the continent has also been observed over this time period [*Thompson and Solomon*, 2002]. Additionally, observations of sea ice cover point toward positive trends in the Ross Sea sector and negative trends in the Bellingshausen/Amundsen sector [see, e.g., *Parkinson*, 2004]. It has been suggested by *Thompson and Solomon* [2002] and others that a large fraction of these seemingly heterogeneous trends is closely linked to the positive trend in the Southern Annular Mode (SAM). There has been considerable debate about the robustness of the SAM trend, particularly in the period prior to 1979 [see, e.g., *Marshall*, 2003], but there is little doubt that the trend exists in observations and reanalyses since 1979 [*Thompson and Solomon*, 2002; *Archer and Caldeira*, 2008], even if its magnitude may differ among the reanalyses products (e.g., between NCEP-1 and ECMWF) because of imperfect models ingesting incomplete data.

[3] A positive trend in the SAM is characterized by a trend toward falling atmospheric pressure over the pole and rising pressure over the midlatitudes of the Southern Hemisphere [*Thompson et al.*, 2000]. This corresponds to a positive trend in the strength of the wind speed at ~55°S, and could therefore cause trends in the circulation and biogeochemistry of the Southern Ocean, ultimately impacting the air-sea flux of CO_2 in this region. This connection between the trend in SAM and a possible change in the trend in the Southern Ocean air-sea CO_2 flux was first described by *Wetzel et al.* [2005] on the basis of an ocean model simulation. *Le Quéré et al.* [2007] confirmed this finding with results from an inversion of atmospheric CO_2 observations, identifying a weakening of the Southern Ocean (<45°S) CO_2 sink of 0.008 Pg C a^{-2} from 1981 to

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2004, relative to the expected sink strength under a constant physical climate (i.e., the situation in which the Southern Ocean CO_2 sink becomes stronger with time owing to the rise in atmospheric CO_2 and the increased atmosphere-ocean gradient in pCO_2). A very similar reduction in the CO_2 flux trend was identified in our ocean model-based study [*Lovenduski et al.*, 2007], but only briefly discussed there. Here, we analyze, for the first time, the processes driving this change in the CO_2 flux trend by separately examining the trends in the natural and anthropogenic components of the total flux. This permits us to attribute the change in the total contemporary trend in the CO_2 flux and to establish an understanding of the mechanisms driving it. We will demonstrate that this change in trend is almost entirely driven by an enhanced outgassing of natural CO_2, which is the result of circulation changes within the Southern Ocean. These circulation changes bring additional carbon-rich waters to the surface, where CO_2 remains unconsumed by biology, permitting it to escape to the atmosphere. In contrast, the uptake trend of anthropogenic CO_2 is largely unaffected by the trends in the wind and ocean circulation, very nearly following that expected from the rise in atmospheric CO_2 alone. Although the exact magnitude of the Southern Ocean flux trend may not be robust because of uncertainty in the magnitude of the wind changes, the mechanistic results presented here will help to project the future behavior of this climatically important region.

2. Methods

[4] We achieve this attribution of the CO_2 flux trend by using two hindcast simulations from a coupled ocean biogeochemical-physical model (POP/CCSM), representing the years 1958 to 2004. In the first simulation, atmospheric CO_2 is kept constant, while atmospheric forcing is permitted to vary with time. In the second simulation, atmospheric CO_2 also varies with time, following the observed historical trajectory. The fluxes from the first simulation are that of natural CO_2, while the fluxes of the second are that of contemporary CO_2, with their difference constituting the anthropogenic CO_2 fluxes. The model simulations are forced at the surface with a combination of NCEP version 1 atmospheric reanalysis and satellite data products from 1958 to 2004 [*Doney et al.*, 2007]. The model captures the observed variability in sea surface temperature [see *Lovenduski et al.*, 2007, Figure 2] and sea surface height [see *Doney et al.*, 2007]. For further details regarding simulation configuration and analysis, please see *Lovenduski et al.* [2007].

[5] The skill of this model in representing mean Southern Ocean CO_2 fluxes was found to be quite reasonable [see *Lovenduski et al.*, 2007, Table 1]. However, despite the 600-year spin-up period for these simulations, the model had not yet come into equilibrium with preindustrial atmospheric CO_2 when the variable forcing was introduced, resulting in a globally integrated ingassing of 0.15 Pg C a^{-1}. When correcting for this disequilibrium flux, we assume that it is spatially uniform. This correction only applies to the mean natural and contemporary CO_2 fluxes, and does not impact the trend analysis. The global disequilibrium flux is changing at a very slow rate (2×10^{-4} Pg C a^{-2}) during the 47 years of output that we analyze, equivalent to less than 5% of the trend that we report for the Southern Ocean.

[6] All trends described in this paper represent the slope of a straight line which exhibits the best fit to the deseasonalized data in a least squares sense. We report both long-term (multidecadal) and 10-year trends. In order to take possible errors in the wind forcing into consideration, we computed trends in our model results for the entire period (1958–2004) and also for the more data-rich recent period (1979–2004). Here we focus on the recent period, owing to the greater confidence in the atmospheric forcing, and refer to Table S1[1] and Figures S1–S7 for the results from the entire period. Long-term trends are determined by fitting a straight line to the time series from 1979 to 2004. Ten-year trends are calculated using a sliding window method, whereby the trend is determined for 120 months of data at a time.

[7] The trend in the SAM manifests itself as a trend in the surface wind. In order to investigate the ocean's response to this change in forcing more directly, we create a monthly wind speed index by averaging the deseasonalized, monthly wind speed forcing over the Southern Ocean south of 35°S. We use the technique outlined by *Thompson et al.* [2000] to estimate the congruence of the trends with this wind speed index. The trend in the deseasonalized data, D', is the slope of the best fit line to the deseasonalized data. The fraction of this trend that is linearly congruent with the wind speed, D'_{cong}, is estimated as

$$D'_{cong} = R \times WS', \tag{1}$$

where R is the regression coefficient of the deseasonalized data with the wind speed index, and WS' is the linear trend in the wind speed index. Significance of trends is calculated as by *Santer et al.* [2000], whereby the ratio of the estimated trend and its standard error is compared to a t value for the 95% significance level and a given effective sample size, while accounting for autocorrelation in the time series [*Bretherton et al.*, 1999]. Uncertainty estimates for the trends are reported as 95% confidence intervals.

3. Trends in Simulated Air-Sea CO_2 Fluxes

[8] The timeseries of the Southern Ocean (<35°S) integrated natural air-sea CO_2 fluxes in Figure 1 reveals a positive long-term trend, corresponding to more outgassing with time. From 1979 through 2004, the trend has a statistically significant value of 0.004 ± 0.005 Pg C a^{-2}, with a total increase in the outgassing flux of 0.1 Pg C a^{-1}. The mean 10-year sliding window trend for this period is also positive (0.009 Pg C a^{-2}; Figures S1–S2). The spatial pattern of the long-term natural CO_2 flux trend is shown in Figure 2a. The trend is positive throughout a large fraction of the Southern Ocean and largest in the region between 45°S and 60°S.

[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GB003139.

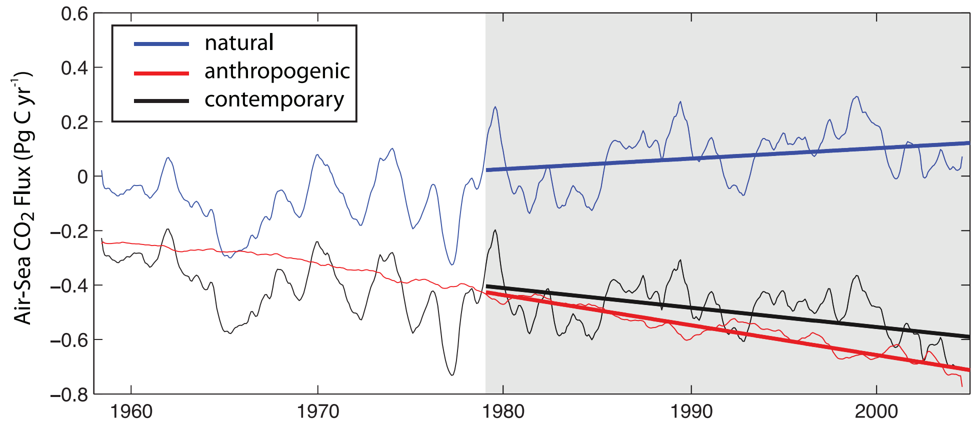

Figure 1. Trends in the spatially integrated Southern Ocean (<35°S) fluxes of natural, anthropogenic, and contemporary CO_2. Smoothed fluxes (12-month running mean) shown as thin lines for reference. Negative fluxes indicate ocean uptake. Natural and contemporary fluxes have been adjusted for a global -0.15 Pg C a^{-1} nonequilibrium flux. Trends have been calculated for the 1979–2004 (shaded) period. Trends fitted to the entire period of model output (1958–2004) can be found in Figure S3.

[9] The flux of anthropogenic CO_2 (Figure 1) exhibits a significant negative trend (more oceanic uptake with time) of -0.011 ± 0.001 Pg C a^{-2}, corresponding to a 0.3 Pg C a^{-1} increase in the uptake rate from 1979 to 2004. The trend is negative nearly everywhere in the Southern Ocean, with the southernmost regions and the western Atlantic at ~45°S exhibiting stronger trends (Figure 2c). The strong negative trend of anthropogenic CO_2 overwhelms the positive trend of natural CO_2, so that the Southern Ocean flux of contemporary CO_2 exhibits a long-term negative trend of -0.007 ± 0.007 Pg C a^{-2} (Figure 1).

[10] Thus, relative to the uptake trend of anthropogenic CO_2, results from our simulations suggest that the Southern Ocean (<35°S) sink of contemporary CO_2 has weakened at a rate of 0.004 Pg C a^{-2} between 1979 and 2004. We compare this trend with those reported in the ocean modeling study of *Wetzel et al.* [2005] and the atmospheric inversion study of *Le Quéré et al.* [2007] in Table 1, where we find a close agreement among the estimates of the long-term trends. Note that our estimated trend from 1979 to 2004 for the region south of 35°S is lower than that from 1981 to 2004 for the region south of 45°S. This reduction arises because of the negative trend in natural CO_2 flux between 1979 and 1981 (Figure 1), and because most of the trend is concentrated in the region south of 45°S (Figure 2a). Although the agreement between the different studies is encouraging, all ocean models were forced with the same atmospheric winds and fluxes of heat and freshwater, i.e., NCEP-1. A recent set of model experiments performed with the IPSL model (K. Rodgers, personal communication, 2008) suggests that the use of ECMWF forcing yields a smaller change in the Southern Ocean CO_2 sink, presum-

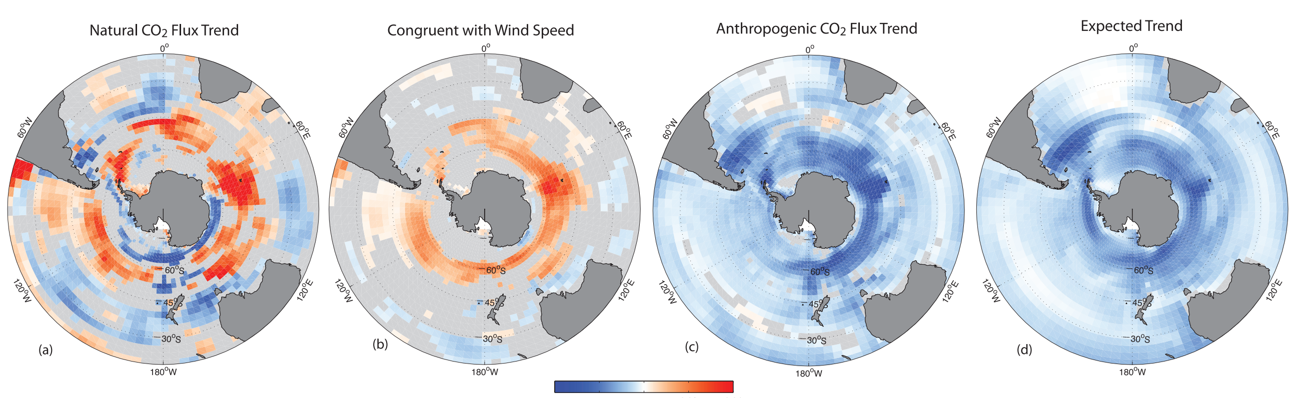

Figure 2. (a) Linear trends in the air-sea flux of natural CO_2 and (b) trends linearly congruent with the wind speed index. (c) Trend in the anthropogenic CO_2 flux and (d) trend expected from the atmospheric perturbation in anthropogenic CO_2 (mol m^{-2} a^{-2}). Trends are from 1979–2004, and only those trends with significance ≥95% are shown. Positive values indicate trends toward ocean outgassing. The corresponding figure for the entire period of model output (1958–2004) can be found in Figure S4.

Table 1. Estimated Weakening of the Southern Ocean Sink for Contemporary CO_2[a]

Source	Time Period	Area	Trend
Wetzel et al. [2005]	1948–2003	40°S–60°S	0.005
This study	1958–2003	40°S–60°S	0.006 ± 0.002
Le Quéré et al. [2007][b]	1981–2004	<45°S	0.008
This study	1981–2004	<45°S	0.007 ± 0.007
This study	1979–2004	<35°S	0.004 ± 0.005

[a]From this and two previous studies, expressed as a trend in the air-sea CO_2 flux (Pg C a^{-2}).
[b]Estimate is based on results from atmospheric inversions.

ably due to a smaller trend in the winds, but uncertainties still exist in both reanalyses products (the simulations have been analyzed for the equatorial Pacific by *Rodgers et al.* [2008]). Thus, the absolute value of our trend change needs to be viewed with some caution, although it does agree rather well with the trend change inferred from atmospheric CO_2 data [*Le Quéré et al.*, 2007], which are independent of ocean models.

[11] A weakening of the Southern Ocean carbon sink by 0.1 Pg C a^{-1} is a notable change given a global uptake of anthropogenic CO_2 of about 2.2 Pg C a^{-1} for the decade of the 1990s [e.g., *Mikaloff Fletcher et al.*, 2006], necessitating us to understand the causes for these trends.

4. Causes of the Trends

[12] As the natural and anthropogenic components of the total contemporary CO_2 flux have different driving factors in our model, we must investigate the mechanisms driving their trends separately.

4.1. Natural CO_2

[13] We investigate the mechanisms responsible for the trend in the flux of natural CO_2 by estimating the contributions to the total trend (F') from the trends in wind speed (WS), sea ice fraction (Ice), air pressure (p), surface dissolved inorganic carbon (DIC), alkalinity (Alk), temperature (T), and salinity (S). The trend in the CO_2 flux, F, can be deconvolved using a linear Taylor expansion:

$$F' = \frac{\partial F}{\partial WS}WS' + \frac{\partial F}{\partial Ice}Ice' + \frac{\partial F}{\partial p}p' + \frac{\partial F}{\partial DIC}DIC' + \frac{\partial F}{\partial Alk}Alk' + \frac{\partial F}{\partial T}T' + \frac{\partial F}{\partial S}S', \quad (2)$$

where the partial derivatives are determined from model equations and mean values in the Southern Ocean [see *Lovenduski et al.*, 2007], and the trends represent the slope of a linear regression to the data. As the Taylor expansion is only strictly correct for small perturbations, the sum of the terms of the right hand side is often not exactly equal to the left hand side. Cross correlations among the variables and the approximations used can cause differences as well [see *Lovenduski et al.*, 2007].

[14] The analysis of the contributions to the long-term trend in natural CO_2 flux from 1979 to 2004 (Table 2) demonstrates that the largest term is the trend toward elevated natural DIC. However, a large portion of the DIC term is canceled by the trend toward elevated alkalinity. The trend in surface temperature also contributes to reducing the total trend, while the impact of trends in wind speed, sea ice, air pressure, and salinity do not have a large impact on the CO_2 flux trend. Similar results are found from the estimated contributions to the 10-year CO_2 flux trends during this period (Figure S5). Prior to 1979, however, the driving factors for the 10-year and long-term trends in natural CO_2 flux are not as clear (Figure S1 and Table S1), but this is where we have much less confidence in the atmospheric forcing.

[15] The positive trends in surface DIC and Alk are primarily caused by trends in Southern Ocean circulation. We find a positive trend in the rate of Southern Ocean meridional overturning, upwelling around 60°S, and northward Ekman transport between 50°S and 60°S (Figure 3), as well as a significant trend in Antarctic Circumpolar Current strength (0.008 cm s^{-1} a^{-1}; Figure S6) from 1979 to 2004. These trends lead to enhanced upwelling of Circumpolar Deep Water (CDW) in the southernmost portions of the Southern Ocean. The DIC and Alk trends are also enhanced by a trend toward deeper mixed layers (Figure S7a). The strong response of surface DIC and Alk to these changes in ocean circulation is because the upwelled CDW is characterized by high DIC and Alk owing to its source waters, i.e., North Atlantic Deep Water and return flows from the deep Pacific and Indian. In our model, anomalously high DIC and Alk persist near the surface (see Figure 4a), as biological production remains largely unaltered in response to the enhanced upwelling (Figure S7b), perhaps because of light limitation (Figure S7a). Thus Southern Ocean biology in our model simulation is not compensating to the degree that the climate change simulation of *Sarmiento et al.* [1998] would have suggested.

[16] These trends in circulation and air-sea fluxes of natural CO_2 are consistent with those expected from previous

Table 2. Estimated Contributions to the Natural Air-Sea CO_2 Flux Trends, F'[a]

Quantity	Total Trend	Congruent With Wind Speed
	Individual Terms	
$\frac{\partial F}{\partial WS}WS'$	0.12	0.12
$\frac{\partial F}{\partial Ice}Ice'$	0	0
$\frac{\partial F}{\partial p}p'$	0.02	0.04
$\frac{\partial F}{\partial DIC}DIC'$	2.03	0.75
$\frac{\partial F}{\partial Alk}Alk'$	−1.57	−0.43
$\frac{\partial F}{\partial T}T'$	−0.48	−0.18
$\frac{\partial F}{\partial S}S'$	0.10	0.03
	Sum of Terms Versus Modeled	
Σ	0.22	0.33
F'_{mod}	0.35 ± 0.02	0.48 ± 0.08

[a]As in equation (2) (10^{-2} mol m^{-2} a^{-2}), averaged over the Southern Ocean (<35°S) from 1979 to 2004. Positive fluxes are to the atmosphere. Σ is the sum of all seven terms, and F'_{mod} is the modeled trend in F. The corresponding table for the entire period of model output (1958–2004) can be found in Table S1.

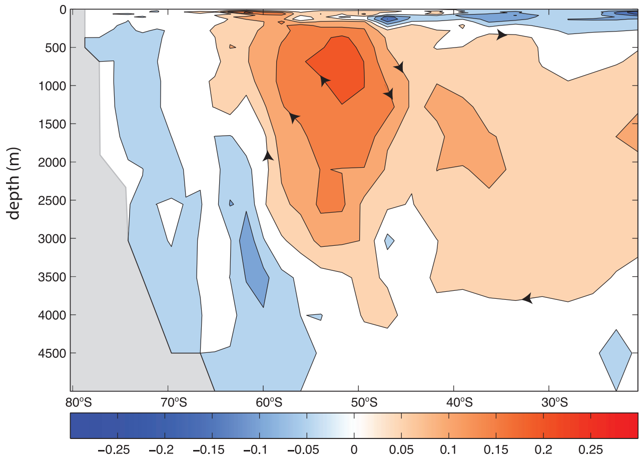

Figure 3. Linear trends in the meridional overturning streamfunction from 1979 to 2004, including the *Gent and McWilliams* [1990] bolus parameterization velocities (Sv a^{-1}).

studies of the response of Southern Ocean circulation and carbon cycle to interannual changes in Southern Ocean winds [*Lenton and Matear*, 2007; *Lovenduski et al.*, 2007; *Verdy et al.*, 2007]. We investigate this link between changes in Southern Ocean winds and air-sea fluxes of natural CO_2 by estimating how much of the natural CO_2 flux trend can be explained by projecting the response of the fluxes to interannual changes in the winds onto the trend in wind speed, i.e., we estimate the congruence of the natural CO_2 flux trend with the trend in wind speed. When spatially integrated over the Southern Ocean (<35°S), we find that 130% (0.006 Pg C a^{-2}) of the trend in the flux of natural CO_2 can be explained by the linear trend in the wind speed. The spatial congruence of the two is highest in the southernmost Southern Ocean (Figures 2a and 2b). This very large fraction implies that other processes, such as changes in buoyancy forcing may play a role in mitigating the trends caused by the winds.

[17] The mechanisms that control the fraction of the natural CO_2 flux trend related to the wind speed are largely the same as those that control the total trend (Table 2), particularly over the recent period (1979–2004; Table S1). The methods for this study are identical for those of the total trend, with the exception that contributions from each component were estimated using only the portion that is congruent with the linear trend in the wind speed. The congruent portion was then multiplied by its associated partial derivative to determine the contribution from each component.

4.2. Anthropogenic CO_2

[18] The negative trend in anthropogenic CO_2 uptake is not surprising given the increasing trend in the atmospheric CO_2 concentration, which continuously increases the air-sea difference in the partial pressures of CO_2. However, it is of interest to know whether the changes in winds and ocean circulation have altered the uptake trend of anthropogenic CO_2 relative to a situation with constant physical forcing. We estimate the expected oceanic uptake of anthropogenic $CO_2(F^{anth}_{expt}(t))$ under constant physical forcing using the following scaling:

$$F^{anth}_{expt}(t) = F^{anth}_{o} \times \frac{\chi CO_2^{anth}(t)}{\chi CO^{anth}_{2,o}}, \quad (3)$$

where F^{anth}_{o} is the flux of anthropogenic CO_2 in 1958, and $\chi CO_2^{anth}(t)/\chi CO^{anth}_{2,o}$ is the ratio of the anthropogenic perturbation in atmospheric CO_2 at a given time with the atmospheric perturbation in 1958. This scaling was developed for the inverse modeling of the oceanic uptake of anthropogenic CO_2 [*Gloor et al.*, 2003; *Mikaloff Fletcher et al.*, 2006] and was successfully tested by using results from forward model simulations under constant physical forcing.

[19] The spatial pattern of the expected trend in anthropogenic CO_2 flux (Figure 2d) shows a close correspondence with that of the total anthropogenic trend (Figure 2c). We find that the linear trend in the spatially integrated (<35°S) values of $F^{anth}_{expt}(t)$ can explain a very large fraction (98%) of the linear trend in anthropogenic CO_2. The remaining trend is mostly one of ocean uptake, with the exception of the Amundsen/Bellingshausen sector and the western Atlantic at ~45°S, where the trend is toward ocean outgassing (not shown). Only a small amount (15%) of this remaining trend

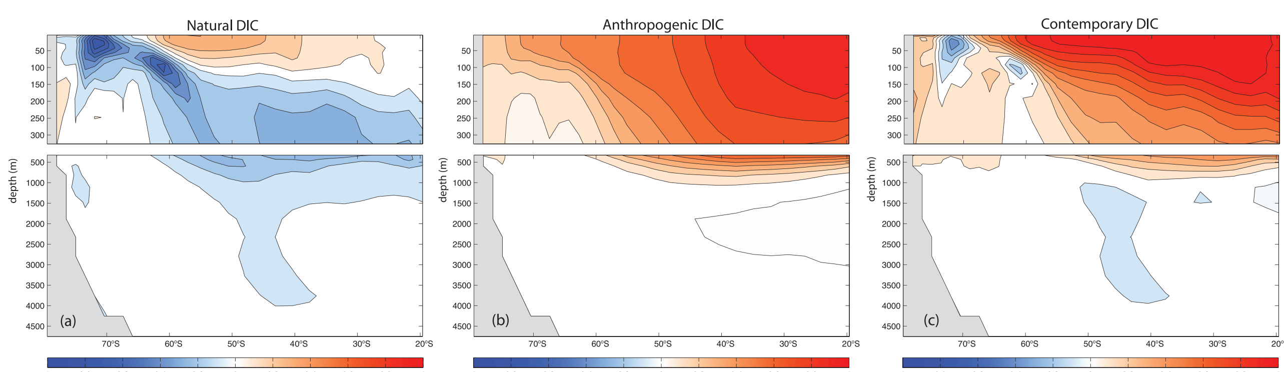

Figure 4. Linear trends in the zonally averaged (a) natural, (b) anthropogenic, and (c) contemporary DIC from 1979 to 2004 (mmol m^{-3} a^{-1}).

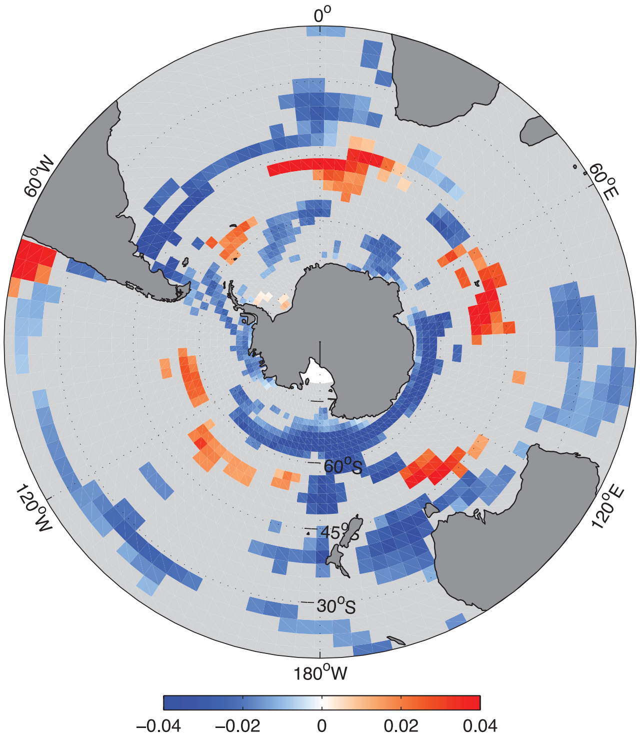

Figure 5. Trends in the air-sea flux of contemporary CO_2 from 1979 to 2004 (mol m^{-2} a^{-2}). Only those trends with significance ≥95% are shown. Negative values indicate trends toward ocean uptake.

in the region south of 35°S is congruent with the linear trend in the wind speed (not shown).

[20] Thus, in sharp contrast to natural CO_2, the flux of anthropogenic CO_2 appears to be only marginally affected by the changes in wind and ocean circulation. This is surprising given that the uptake of anthropogenic CO_2 by the ocean is primarily determined by how fast anthropogenic CO_2 is ultimately transported from the surface toward the interior of the ocean [*Sarmiento et al.*, 1992]. Thus, one would have expected an enhanced uptake of anthropogenic CO_2 in response to the enhanced meridional overturning. However, residence times of Southern Ocean surface waters with regard to the exchange of gases with the atmosphere [*Ito et al.*, 2004b] tend to be shorter than the ~9 months it takes to equilibrate the surface ocean with the overlying atmosphere [*Sarmiento and Gruber*, 2006], because of the presence of sea ice preventing air-sea exchange. As a result, surface waters in the Southern Ocean tend to fail to take up anthropogenic CO_2 up to their capacity [*Gruber*, 1998; *Ito et al.*, 2004a]. Hence, the reduction of the surface residence time due to the enhanced overturning circulation could have compensated for the enhanced wind speeds and enhanced surface to deep transports, so that the total uptake of anthropogenic CO_2 remained largely unaltered, relative to a situation with constant physical forcing.

4.3. Contemporary CO_2 and Summary

[21] The combination of the natural and anthropogenic flux trends creates a complex spatial pattern in the trends of the contemporary CO_2 flux (Figure 5) that is difficult to interpret. The mechanisms driving this contemporary trend pattern are a superposition of the mechanisms driving the natural and anthropogenic CO_2 flux trends, namely the trends in wind speed and atmospheric pCO_2. Since only the natural CO_2 flux component is congruent with wind speed, while the anthropogenic CO_2 flux component is not, the contemporary CO_2 flux trend has a low congruence with wind speed or the SAM, explaining the low congruence number (20%) reported by *Le Quéré et al.* [2007].

[22] In summary, our results indicate that there is a positive trend in the natural CO_2 outgassing over the course of our simulation, and that a large fraction of it is congruent with the linear trend in the wind speed, owing to the wind-change-induced trends in ocean circulation. Meanwhile, anthropogenic CO_2 has exhibited an ingassing trend over the same period, mostly due to the increasing anthropogenic perturbation in atmospheric CO_2, with changes in wind speed and ocean circulation playing only a minor role. Therefore, the wind speed trend has led to a reduction in the ability of the Southern Ocean to absorb CO_2, while the trend in the anthropogenic perturbation of atmospheric CO_2 has led to an increase in the strength of the Southern Ocean carbon sink.

5. Detection of Trends

[23] Our model results indicate that the Southern Ocean (<35°S) sink for CO_2 has weakened by 0.1 Pg C a^{-1} from 1979 to 2004, in quantitative agreement with previous ocean model and atmospheric inversion studies. Building additional confidence in these results will require observations of trends in the surface and interior properties of the Southern Ocean from cruise data.

[24] A promising route to detection of trends in the CO_2 sink is studying the evolution of measured surface ocean fCO_2 or pCO_2. One can compare these values to the growth rate of atmospheric pCO_2 over the same time period to infer the potential change of the ocean carbon sink. This method has been applied successfully by N. Metzl (Decadal increase of oceanic carbon dioxide in the Southern Indian Ocean surface waters 1991–2007, submitted to *Deep Sea Research II*, 2007) to show that oceanic fCO_2 has increased at a rate of 2.11 μatm a^{-1}, or 0.39 μatm a^{-1} faster than the atmospheric pCO_2 from 1991 to 2007 in the Southern Indian Ocean. We compare this value to our estimate of the long-term trend in surface ocean contemporary pCO_2 from 1991 to 2004, after subtracting an estimated atmospheric pCO_2 growth rate of 1.72 μatm a^{-1}. While our long-term trends have a large spatial variance in their study region, our average trend for the region bounded by 35°S–55°S and 50°E–75°E is approximately 0.1 μatm a^{-1}, in good agreement with their estimate (not shown; see also Figure 6).

[25] Detection of long-term trends in the Southern Ocean CO_2 sink using data from the ocean interior poses a greater challenge. Figure 4 shows our modeled trends in zonally averaged natural, anthropogenic, and contemporary DIC from 1979 to 2004. Natural DIC exhibits a negative trend in the Southern Ocean surface south of 60°S, and throughout most of the upper 1000 m north of this latitude, with the

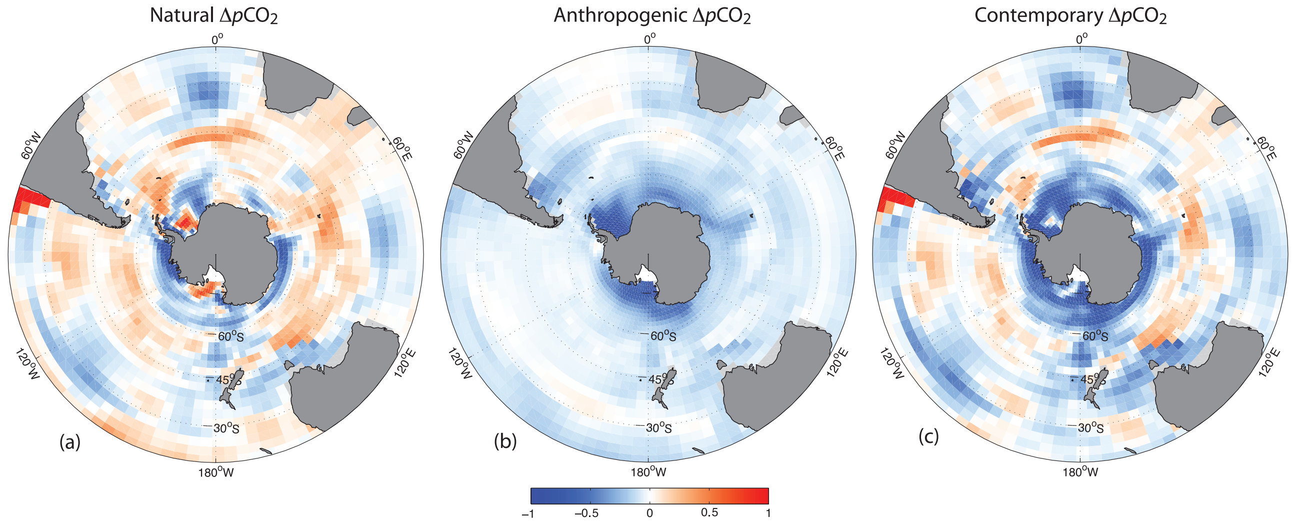

Figure 6. Linear trends in the surface ocean (a) natural, (b) anthropogenic, and (c) contemporary ΔpCO_2 from 1979 to 2004 (μatm a^{-1}), i.e., the trend in the difference between the oceanic and atmospheric pCO_2. The spatially uniform atmospheric trend of 1.63 μatm a^{-1} needs to be added to Figures 6b and 6c in order to obtain the oceanic pCO_2 trend.

exception of the near surface, where the trend is positive. Although the trend is substantial (about 0.5 mmol m^{-3} a^{-1}) and therefore potentially detectable by decadal surveys, it will be difficult to identify this trend in observations given the presence of a larger trend in anthropogenic DIC (Figure 4b). The latter trend masks most of the natural DIC trend, so that the contemporary DIC trend, which is the observable trend, is dominated by the anthropogenic DIC trend (Figure 4c). Decadal surveys are also susceptible to aliasing, whereby interannual variability erroneously contributes to decadal estimates [*Levine et al.*, 2008]. However, it may be possible to use oxygen concentration observations, as these exhibit distinct trends at intermediate depths in our model (Figure 7). Interior ocean changes in natural DIC and O_2 are linked to the trend in the meridional overturning circulation in the Southern Ocean. A trend toward enhanced upwelling around 60°S brings waters low in O_2 up to the surface at a faster rate, while enhanced downward and lateral transport between 40°S and 60°S pushes waters low in natural DIC and high in O_2 from the surface to the interior thermocline at a faster rate, leading to the observed trend patters (Figures 4a and Figure 7).

6. Implications for the Future

[26] The future evolution of the Southern Ocean carbon sink will depend on how each of the two component fluxes, i.e., the fluxes of natural and anthropogenic CO_2 will evolve with time in response to changes in atmospheric CO_2 and physical climate.

[27] In a future characterized by increased atmospheric CO_2 concentrations, but with constant climate, one would expect the Southern Ocean sink strength to become stronger, because the flux of anthropogenic CO_2 tends to be proportional to the perturbation in atmospheric CO_2 (see (2)), while the flux of natural CO_2 would remain unaltered. However, many coupled models [see, e.g., *Fyfe and Saenko*, 2006] are now suggesting that the positive trend in the wind speed over the Southern Ocean will continue during this century, likely causing a continuation of the trend for enhanced outgassing of natural CO_2. The response of the anthropogenic CO_2 fluxes to this continuing wind trend is more difficult to predict, as it depends on the balance between transport across the air-sea interface and the downward transport. Although the changes in these factors appeared to have canceled each other in the last few decades, one cannot infer that this is equally the case in the future, where atmospheric CO_2 will continue to grow.

[28] The combination of the changes in the two flux components in a future characterized by increased atmospheric CO_2 concentrations and changing climate (i.e., wind stress trend) are thus not straightforward to predict. Some have suggested that the combined effect of increased wind speed and higher atmospheric CO_2 concentrations will eventually lead to a larger carbon sink in the Southern Ocean [*Russell et al.*, 2006; *Zickfeld et al.*, 2007], whereas [*Le Quéré et al.*, 2008] believe that the carbon sink will continue to weaken for the next 25 years. Our results tend to support the idea of a continued weakening sink, as our anthropogenic CO_2 flux remained unresponsive to trends in wind stress and circulation over the past few decades, however this may not be the case 50 or 100 years from now.

7. Conclusions

[29] Our results suggest that the Southern Ocean sink of contemporary CO_2 has weakened by 0.1 Pg C a^{-1} from 1979 to 2004, relative to what we would expect from the oceanic uptake of anthropogenic CO_2 in a constant climate, confirming the results of *Le Quéré et al.* [2007]. A caveat

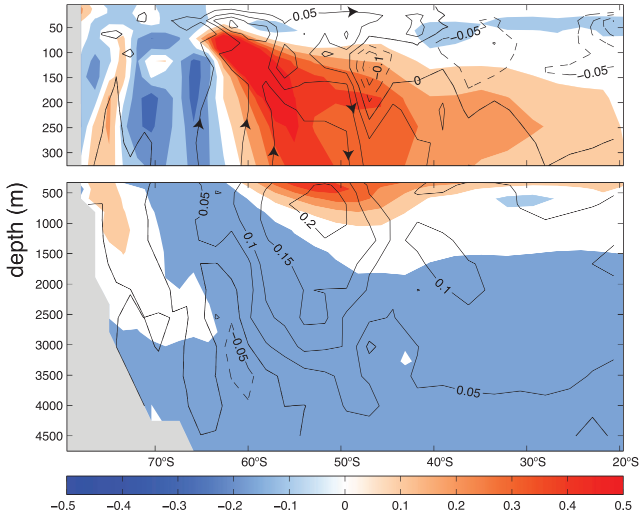

Figure 7. Linear trends in the zonally averaged oxygen concentration (shaded; mmol m^{-3} a^{-1}) and the meridional overturning streamfunction (contour lines; Sv a^{-1}) from 1979 to 2004.

remains regarding the exact magnitude of this trend as models forced with ECMWF winds tend to show a smaller response. We show here that the primary cause of the weakening is a trend toward more outgassing of natural CO_2 from the Southern Ocean. The outgassing is driven by a trend in the surface wind speed, which causes trends in the circulation of the Southern Ocean and enhances surface *DIC*. We regard this finding as robust and independent of the details of the atmospheric forcing, but discrepancies between the different wind products need to be understood and resolved before the evolution of the Southern Ocean over the last few decades can be more accurately reconstructed with models. Even if the current reanalysis trends are in question, however, future coupled climate models consistently find a trend toward stronger, poleward shifted winds over the Southern Ocean in the coming century [*Meehl et al.*, 2007]. The mechanistic results presented here are therefore useful for projecting the future behavior of the Southern Ocean carbon sink and argue strongly for a robust Southern Ocean monitoring system so that we can document how this important region for the global carbon cycle has changed over time.

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References

Archer, C. L., and K. Caldeira (2008), Historical trends in the jet streams, *Geophys. Res. Lett.*, *35*, L08803, doi:10.1029/2008GL033614.

Bretherton, C. S., M. Widmann, V. P. Dymnikov, J. M. Wallace, and I. Bladé (1999), The effective number of spatial degrees of freedom of a time-varying field, *J. Clim.*, *12*(7), 1990–2009.

Doney, S. C., S. Yeager, G. Danabasoglu, W. G. Large, and J. C. McWilliams (2007), Mechanisms governing interannual variability of upper-ocean temperature in a global ocean hindcast simulation, *J. Phys. Oceanogr.*, *37*, 1918–1938.

Fyfe, J. C., and O. A. Saenko (2006), Simulated changes in the extratropical Southern Hemisphere winds and currents, *Geophys. Res. Lett.*, *33*, L06701, doi:10.1029/2005GL025332.

Gent, P. R., and J. C. McWilliams (1990), Isopycnal mixing in ocean circulation models, *J. Phys. Oceanogr.*, *20*(1), 150–155.

Gloor, M., N. Gruber, J. Sarmiento, C. L. Sabine, R. A. Feely, and C. Rödenbeck (2003), A first estimate of present and preindustrial air-sea CO_2 flux patterns based on ocean interior carbon measurements and models, *Geophys. Res. Lett.*, *30*(1), 1010, doi:10.1029/2002GL015594.

Gruber, N. (1998), Anthropogenic CO_2 in the Atlantic Ocean, *Global Biogeochem. Cycles*, *12*, 165–191.

Ito, T., M. J. Follows, and E. A. Boyle (2004a), Is AOU a good measure of respiration in the oceans?, *Geophys. Res. Lett.*, *31*, L17305, doi:10.1029/2004GL020900.

Ito, T., J. Marshall, and M. Follows (2004b), What controls the uptake of transient tracers in the Southern Ocean?, *Global Biogeochem. Cycles*, *18*, GB2021, doi:10.1029/2003GB002103.

Lenton, A., and R. J. Matear (2007), Role of the Southern Annular Mode (SAM) in Southern Ocean CO_2 uptake, *Global Biogeochem. Cycles*, *21*, GB2016, doi:10.1029/2006GB002714.

Le Quéré, C., et al. (2007), Saturation of the Southern Ocean CO_2 sink due to recent climate change, *Science*, *316*, 1735–1738, doi:10.1126/science.1136188.

Le Quéré, C., et al. (2008), Response to comments on "Saturation of the Southern Ocean CO_2 sink due to recent climate change", *Science*, *319*, 570c, doi:10.1126/science.1147315.

Levine, N. M., S. C. Doney, R. Wanninkhof, K. Lindsay, and I. Y. Fung (2008), Impact of ocean carbon system variability on the detection of temporal increases in anthropogenic CO_2, *J. Geophys. Res.*, *113*, C03019, doi:10.1029/2007JC004153.

Lovenduski, N. S., N. Gruber, S. C. Doney, and I. D. Lima (2007), Enhanced CO_2 outgassing in the Southern Ocean from a positive phase of the Southern Annular Mode, *Global Biogeochem. Cycles*, *21*, GB2026, doi:10.1029/2006GB002900.

Marshall, G. J. (2003), Trends in the Southern Annular Mode from observations and reanalysis, *J. Clim.*, *16*, 4134–4143.

Meehl, G. A., et al. (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 747–845, Cambridge Univ. Press, Cambridge, UK.

Mikaloff Fletcher, S. E., et al. (2006), Inverse estimates of anthropogenic CO_2 uptake, transport, and storage by the ocean, *Global Biogeochem. Cycles*, *20*, GB2002, doi:10.1029/2005GB002530.

Parkinson, C. L. (2004), Southern Ocean sea ice and its wider linkages: Insights revealed from models and observations, *Antarct. Sci.*, *16*(4), 387–400.

Rodgers, K. B., O. Aumont, C. Menkes, and T. Gorgues (2008), Decadal variations in equatorial Pacific ecosystems and ferrocline/pycnocline decoupling, *Global Biogeochem. Cycles*, *22*, GB2019, doi:10.1029/2006GB002919.

Russell, J. L., K. W. Dixon, A. Gnanadesikan, R. J. Stouffer, and J. R. Toggweiler (2006), The Southern Hemisphere westerlies in a warming world: Propping open the door to the deep ocean, *J. Clim.*, *19*(24), 6382–6390.

Santer, B. D., T. M. L. Wigley, J. S. Boyle, D. J. Gaffen, J. J. Hnilo, D. Nychka, D. E. Parker, and K. E. Taylor (2000), Statistical significance of trends and trend differences in layer-average atmospheric temperature time series, *J. Geophys. Res.*, *105*(D6), 7337–7356.

Sarmiento, J. L., and N. Gruber (2006), *Ocean Biogeochemical Dynamics*, 526 pp., Princeton Univ. Press, Princeton, N. J.

Sarmiento, J. L., J. C. Orr, and U. Siegenthaler (1992), A perturbation simulation of CO_2 uptake in an ocean general circulation model, *J. Geophys. Res.*, *97*(C3), 3621–3645.

Sarmiento, J. L., T. M. C. Hughes, R. J. Stouffer, and S. Manabe (1998), Simulated response of the ocean carbon cycle to anthropogenic climate warming, *Nature*, *393*, 245–249.

Thompson, D. W. J., and S. Solomon (2002), Interpretation of recent Southern Hemisphere climate change, *Science*, *296*(5569), 895–899.

Thompson, D. W. J., J. M. Wallace, and G. C. Hegerl (2000), Annular modes in the extratropical circulation. Part II: Trends, *J. Clim.*, *13*(5), 1018–1036.

Verdy, A., S. Dutkiewicz, M. J. Follows, J. Marshall, and A. Czaja (2007), Carbon dioxide and oxygen fluxes in the Southern Ocean: Mechanisms of interannual variability, *Global Biogeochem. Cycles*, *21*, GB2020, doi:10.1029/2006GB002916.

Wetzel, P., A. Winguth, and E. Maier-Reimer (2005), Sea-to-air CO_2 flux from 1948 to 2003: A model study, *Global Biogeochem. Cycles*, *19*, GB2005, doi:10.1029/2004GB002339.

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.

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