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

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We estimated a weakening of the Southern Ocean carbon dioxide (CO₂) sink since 1981 relative to the trend expected from the large increase in atmospheric CO₂. We agree with Law *et al.* that network choice increases the uncertainty of trend estimates but argue that their network of five locations is too small to be reliable. A future reversal of Southern Ocean CO₂ saturation as suggested by Zickfeld *et al.* is possible, but only at high atmospheric CO₂ concentrations, and the effect would be temporary.

We showed that the Southern Ocean CO₂ sink has saturated between 1981 and 2004 despite the large increase in atmospheric CO₂ and attributed this saturation to increased windiness caused by human-induced climate change (1). Law *et al.* (2) suggest that our results critically depend on the data used. Whereas network choices do introduce additional uncertainty, further analysis indicates that the available body of data still supports a saturating CO₂ sink. Law *et al.*'s network of five locations appears too small to detect the regional signal, and their ocean model has been poorly validated with observations and contradicts all five other published estimates. Zickfeld *et al.* (3) suggest that the CO₂ saturation will reverse in the future. A reversal would be possible, but only if atmospheric CO₂ reaches very high concentration, and it would only be temporary. We expect that the Southern Ocean CO₂ sink will continue to weaken at least for another 25 years, and probably well into this century, and will have long-

term consequences for the stabilization of atmospheric CO₂ on a multicentury time scale.

Law *et al.* (2) reproduce the saturation of the Southern Ocean CO₂ sink with their atmospheric inverse method and our set of 11 atmospheric CO₂ observing stations (3). Conversely, we obtain an increasing sink as do Law *et al.* when using their set of only five locations (Fig. 1). This confirms that the inferred trends are not dependent on the method or model used but are present in the selected observations (4). We agree with Law *et al.* that inversions require a careful selection of observational stations. In our original report (1) we selected the largest station network that still reproduced results of shorter but better-constrained inversions. We also verified the consistency of our results with additional data records that were not originally selected (5). The results of Law *et al.* suggest that our sensitivity tests did not take into account influences of possible data inhomogeneities for signals seen only by individual sites. Over the long time period necessary for the detection of trends, the reality is that there is little redundancy in the available early data. In addition, sampling

and measurement technologies underwent important improvements during the earlier part of the records. The selection of stations requires a balance of the need for sufficient constraints with the risk of potential problems and is partly subjective. We agree with Law *et al.* that the additional uncertainty of network choice, not specifically quantified in (1), increases the uncertainty in trend estimates. As explained below, however, the saturating CO₂ sink found in (1) remains a more credible result than the increasing sink estimated with only five sites.

Law *et al.* invoke synthetic inversions to support that their five locations are sufficient to detect Southern Ocean trends. However, synthetic inversions are a necessary but not sufficient condition for concluding that a feature can be reproduced by an inversion. For example, if the fluxes chosen as “known truth” have an increasing sink both in the Southern Ocean and in the rest of the world [as seems to be the case in Law *et al.* (2)], the synthetic inversion will not fail even if the station set was not sufficient to distinguish the trends in these areas. Therefore, five locations may work in the synthetic inversions even if they do not work with real data (6). In fact, the five-station network of (2) does not include any data that could detect the northern limit of the Southern Ocean at 45°S and distinguish it from the tropics, and contains no stations in the Atlantic or Indian sectors (Fig. 1). Because there is no question that the global CO₂ sink outside the Southern Ocean increases in response to increasing CO₂ (7), it is conceivable that this behavior is then also aliased into the Southern Ocean. Amsterdam Island (AMS) and Ascension Island (ASC) provide additional constraints at 40°S in the Indian Ocean and 8°S in the Atlantic Ocean.

Nevertheless, Law *et al.* argue that the trend in ASC must be incorrect because the difference between ASC and South Pole (SPO) measurements is not identical to the difference between Samoa (SMO) and SPO. However, because ASC and SMO are located more than 15,000 km apart

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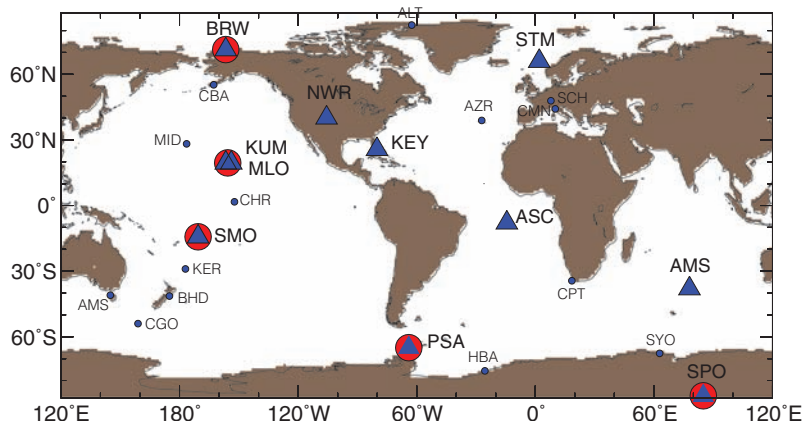


Fig. 1. World map showing the location of the 11 stations used in the standard inversion in (1) (blue triangles) and the five stations used in (2) (red circles). Other stations discussed in the text are shown in small blue dots.

in different ocean basins, they need not be identical. We reviewed the instrument changes at ASC (8). Documented parallel measurements using older and newer methods do not indicate biases of sufficient magnitude. Undocumented biases from the change in flask type in 1992 are conceivable, although similar instrument changes at other sites (e.g., SMO) did not cause problematic biases. Re-evaluation of site-specific effects on fluxes does not suggest a decisive offset, though further analysis is ongoing.

Law *et al.* further point out the larger number of bad flask pairs and the larger scatter in the earlier ASC record, which indeed call for caution. However, if ASC is considered unreliable on these grounds, this judgment would certainly also have to be applied to Palmer Station (PSA), which has similar scatter as well as substantial data gaps before 1988. Yet, PSA has been used by Law *et al.* Contrary to ASC, the effect of PSA is a more negative trend (increasing sink).

Law *et al.* argue that the observed seasonal cycle at AMS must be wrong after 1999 because it diverges from other Southern Ocean stations. All stations that Law *et al.* compared to AMS are located farther south than AMS. From 1999, the seasonality at AMS resembles the seasonality at Cape Point (CPT), which is located at the same latitude as AMS but farther west (Fig. 1). We reviewed the instrument changes at AMS (8) and found no signs of biases before 2001. However, a drift in calibration cylinders affecting data after 2001 was identified recently and these data are being revised (8). Trends in (1) calculated up to 2001 maintained the saturation of the CO₂ sink, although its statistical significance decreased to 92.5% (from 99.5%) and the inversion set-up had a larger influence on the results.

To investigate the influence of the choice of network, we performed additional sensitivity tests.

We tested the influence of individually adding AMS, ASC, CHR, PSA, and Baring Head (BHD) stations to a network of nine stations [similar to Law *et al.*'s but with additional Northern Hemisphere sites and excluding PSA (9)]. As in (2), each single station in this reduced network has a large influence and both AMS and ASC (individually) detect a saturation of the CO₂ sink (Fig. 2). We also tested the influence of ASC, BHD, Halley Bay (HBA), Cape Grim (CGO), Syowa (SYO), Kermadec (KER), and Azores (AZR) on a network now increased to 11 or 16 stations (Fig. 2). The influence of each individual station is reduced by approximately half. In all cases using this enhanced network, a saturation of the CO₂ sink was detected and was most influenced by ASC, AMS, and KER (individually). These sensitivity tests show that the selected network of stations has a smaller influence on the estimated trends as the number of stations increases.

Law *et al.* do not reproduce our results with their ocean model. However, they appear to contradict their own results published in (10) and results from all other process models published so far (11–13). In (10), their model estimates a reduction in the Southern Ocean CO₂ sink with a trend of +0.06 Pg C year⁻¹ decade⁻¹, very close to our estimate and in contradiction to their trend of -0.14 Pg C year⁻¹ decade⁻¹ presented in (2). In (2), wind changes in the Southern Ocean do produce a saturation of the Southern Ocean CO₂ sink as in (1) and (10–13), but this effect is entirely compensated by an enhanced CO₂ uptake in response to heat and water fluxes, which differ from (10). Neither the model results in (10) nor those presented in (2) have been evaluated with time-varying observations. We show in Fig. 3 that our model reproduces observed variations in sea surface temperature

(14, 15) (independent from our results), giving us confidence that the variability in heat and water fluxes in our model is reasonable. Thus, we conclude that results presented in (2) overestimate the influence of heat and water fluxes on the Southern Ocean CO₂ sink and that the model results of (1) and (10–13) are more realistic.

Turning to the comment by Zickfeld *et al.* (3), the authors stipulate that the saturation of the Southern Ocean CO₂ sink will reverse in the 21st century. In (1), we projected that the saturation of the CO₂ sink would persist for at least 25 years, but we have not made projections beyond this time scale. For reasons explained below, we think a reversal of the saturation is possible, but not below an atmospheric CO₂ concentration of ~640 parts per million (ppm), and the effect would be only temporary.

First, let us explain why a reversal is possible. In (1), we showed that the observed weakening of the Southern Ocean CO₂ sink was caused by an intensification of the overturning circulation in the Southern Ocean in response to increased winds (Fig. 4). The deep ocean is rich in natural carbon. In the current ocean, the concentration of carbon in the deep ocean exceeds that of the surface ocean (Fig. 4, left panel). As the overturning circulation increases, the natural carbon of the deep ocean is transported up to the surface, and the carbon of the surface is transported down to the deep ocean. More carbon is currently transported upward than downward, which leads to a weakening of the Southern Ocean CO₂ sink.

CO₂ from human emissions penetrates the ocean from the surface and only slowly invades the deep ocean. If the surface carbon concentration exceeds the deep ocean concentration in the future, the impact of an increase in wind on the Southern Ocean CO₂ sink could reverse (Fig. 4, middle panel). The concentration difference between the surface and the deep ocean is currently ~140 μmol kg⁻¹, and the surface carbon concentration increases by ~0.5 μmol/kg for every ppm increase in atmospheric CO₂ (16, 17).

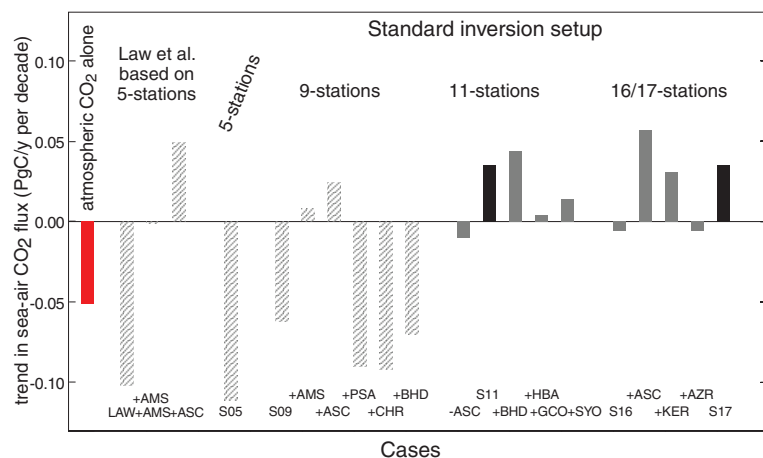


Fig. 2. Trends in sea-air CO₂ flux in the Southern Ocean from inversions with increasing number of stations (9). The trends used in (1) are shown in black. These include the most complete station network, excluding stations with large gaps in the data. Trends for inversions using 12 stations or fewer are computed over the 1981 to 2004 time period. Trends using 16 or 17 stations are computed over the 1986 to 2004 time period. As explained in the text, trends estimated with fewer than 11 stations (hatched bars) are strongly dependent on the station network and thus are not reliable estimates. Fluxes are integrated over 45°S to 90°S.

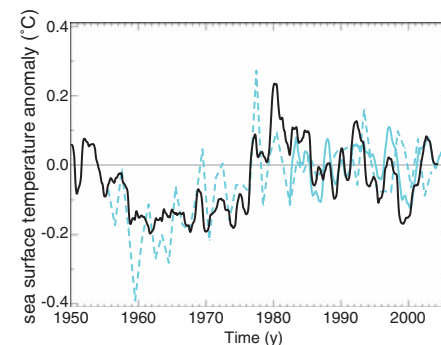


Fig. 3. Comparison between observed and modeled sea surface temperature anomaly in the Southern Ocean. The modeled estimate is from (1) (black line). The observed estimates are from (14) (dotted blue line) based on in-situ temperature observations and from (15) (full blue line) updated to 2006 based on satellite observations.

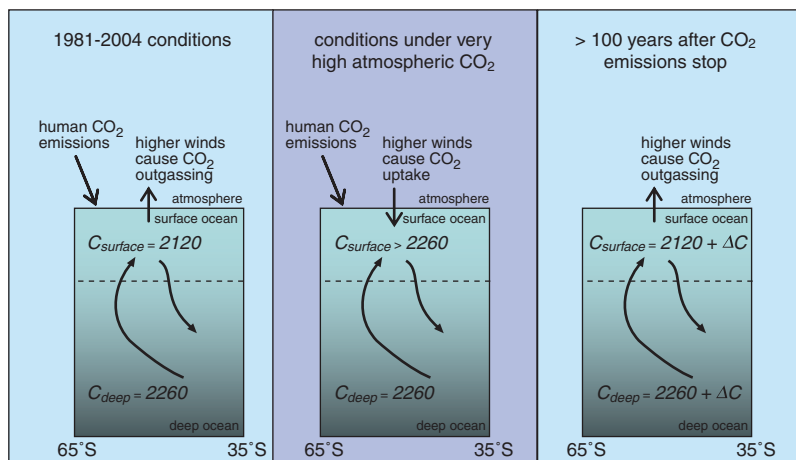


Fig. 4. Schematic view of the impact of increased winds on the Southern Ocean CO_2 sink. The three panels represent conditions in the present ocean (left), under very high atmospheric CO_2 (middle), and more than 100 years after the CO_2 emissions cease (right). C is the concentration of carbon in the surface and deep oceans in units of $\mu\text{mol kg}^{-1}$, whereas ΔC is the increase in carbon content of the ocean from human CO_2 emissions. The observed concentrations are from (15), south of 45°S .

This projects the reversal around an atmospheric CO_2 concentration of ~ 640 ppm (18), with large uncertainty caused by the patterns and depth of the overturning circulation, the response of eddy activity, and the reequilibration of carbon.

In the longer term, CO_2 from human emissions will be mixed throughout the entire ocean (Fig. 4, right panel). Surface carbon concentration will then again be lower than the deep carbon concentration, and the strengthened Southern Ocean sink suggested by Zickfeld *et al.* (3) will, if it occurs at all, revert back to a weaker Southern Ocean sink. The ultimate partitioning of CO_2 between the atmosphere and ocean will depend on the re-equilibration of the oceans to warmer waters, higher winds, and the readjustment of marine ecosystems. Based on the behavior of the ocean during the geological past, we expect that some of the ocean's natural carbon may be permanently out-gassed to the atmosphere and lead to a higher stabilization concentration of atmospheric CO_2 .

It is possible that the reversal hypothesized in (3) will not occur at all and that the weakening of the sink will instead intensify. This would be the case if there were a large warming of the Southern ocean surface, if the response of marine ecosystems to ocean acidification or other changes reduces their efficiency in exporting carbon to the deep ocean, or if the wind increases faster than the atmospheric CO_2 (for instance, if climate sensitivity is at the upper end of current estimates).

The model of Zickfeld *et al.* estimates a strengthening of the Southern Ocean CO_2 sink since 1950, whereas the observations and models we analyzed in (1) suggest a weakening sink. Zickfeld *et al.* show that a reversal is possible, but they provide no information regarding the time scale or the amplitude of change required. Based on the model we used in (1), which has been evaluated with existing observations over the past decades, we maintain that the Southern Ocean

CO_2 sink will continue to weaken compared with its expected trend at least for another 25 years and probably well into this century.

The detection of changes in the efficiency of CO_2 sinks is extremely challenging because trends are only beginning to emerge from the noise (7). Yet, this information is essential to test the response of climate-carbon models, which have up to now been unconstrained by observations (19). The detection of trends from atmospheric CO_2 observations appears robust to the inversion method used, at least in the Southern Ocean. Quality control of the observations is essential, but it must be based on rational criteria and applied to all stations equally. The exclusion of stations based on their unique signal risks removing real information. Early CO_2 observations are too sparse and precious to reject based on subjective grounds. Thus, the aim of inversion is to extract signals from the early data and to quantify their associated errors. Although our analysis contains uncertainties partly underestimated in (1), both our inversion and process model results suggest a persistence of the 1981 to 2004 trends when applied to data for 2005 and 2006 (20).

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3. K. Zickfeld, J. C. Fyfe, M. Eby, A. J. Weaver, *Science* **319**, 570 (2008); www.sciencemag.org/cgi/content/full/319/5863/570b.
4. We further tested the robustness of our inversion by imposing an increasing CO_2 sink as prior constraint. The inversion still produced a saturating sink when used with our set of 11 atmospheric observing stations.
5. Stations were excluded primarily when they showed large gaps in the data records.
6. This could be investigated by testing a suitable set of "known truths" with different trends, although the choice of land trends and the unavoidable absence of finer features in the model-based "known truth" will make the interpretation difficult.

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8. Improvements in air sampling methods throughout the National Oceanic and Atmospheric Administration (NOAA) network (including ASC and SMO) were introduced between 1988 and 1994. The largest improvement was to change the flasks used for the collection of air. Through 1988, samples at ASC were collected in 0.5 L flasks with greased, ground-glass stopcocks. Between 1989 and January 1991, both teflon O-ring stopcocks and greased flasks were used for comparison. There is a slight offset between the two types of flasks, with an average monthly difference of 0.16 ppm ($\sigma = 0.31$ ppm). The offset is smaller than the 0.2 ppm considered tolerable for estimates of variability in Rödenbeck *et al.* (21) and one-third of the assumed offset of 0.5 ppm used in (2). In January 1992, an improved sampling apparatus was introduced along with 2.5-L teflon O-ring flasks, which decreased the scatter of the data and led to fewer rejected samples, thus accounting for the reduction in flagged data. At AMS, atmospheric CO_2 measurements have been taken from 1981 to 2005 using two nondispersive infrared (NDIR) analyzers: URAS 2T from 1981 to 1990 and Siemens Ultramat5F from 1990 to 2005. The calibration of atmospheric CO_2 is based on a suite of six high-pressure cylinders (station primaries), which are used every 2 months to determine the concentrations of four working gases, which are themselves used every 2 hours to calibrate the NDIR instrument. For logistical reasons, the link between the AMS observatory and the central lab was made using a suite of traveling gases. In January 2001, the calibration gases at AMS were reevaluated based on five traveling cylinders calibrated at NOAA/Climate Monitoring and Diagnostics Laboratory in 1999. The installation of a new suite of seven station primaries at AMS in 2006 indicates that the concentrations of the traveling tanks used between 2001 and 2005 were too low by 0.22 to 0.36 ppm depending on the CO_2 concentration. In addition, a leakage of one station primary has corrupted the CO_2 concentration by 0.73 ppm for a 2-month period from 13 August to 10 October 2004. The AMS data set and associated flags are being corrected to take these offsets into account.
9. Summary of station networks discussed in this comment and presented in Fig. 1. The positions of the various stations are given in (22). LAW (Law *et al.*): Northern Hemisphere: BRW, MLO; Southern Hemisphere: SMO, PSA, SPO. S09 (nine stations, similar to Law *et al.* in the Southern Hemisphere but without PSA): Northern Hemisphere: ALT, BRW, SCH, NWR, KEY, KUM, MLO; Southern Hemisphere: SMO, SPO. Tested individual addition of CHR, BHD, ASC, AMS, PSA. S11 [11 stations as in (1)]: Northern Hemisphere: BRW, STM, NWR, KEY, KUM, MLO; Southern Hemisphere: SMO, ASC, AMS, PSA, SPO. Tested individual addition of BHD, HBA, CGO+SYO, and removal of ASC. S16 (16 stations): Northern Hemisphere: ALT, BRW, STM, CBA, NWR, SCH, CMN, KEY, KUM, MLO, CHR; Southern Hemisphere: SMO, BHD, AMS, PSA, SPO. Tested individual addition of ASC, KER, AZR. S17 [17 stations as in (1)]: Northern Hemisphere: ALT, BRW, SHM, STM, NWR, MID, KEY, KUM, MLO; Southern Hemisphere: SMO, BHD, ASC, AMS, CGO, PSA, SYO, SPO.
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