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. Law et al. (2) imply 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 consistencies 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 (2) 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.](http://science.sciencemag.org/content/319/5867/570c)

![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.](http://science.sciencemag.org/content/319/5867/570c)
This projects the reversal around an atmospheric CO₂ 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, CO₂ 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 CO₂ between the atmosphere and ocean will depend on the reequilibration 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 outgassed to the atmosphere and lead to a higher stabilization concentration of atmospheric CO₂.

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 CO₂ (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 CO₂ 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 CO₂ 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 CO₂ 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 unstrained by observations (19). The detection of trends from atmospheric CO₂ 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 CO₂ 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).

Fig. 4. Schematic view of the impact of increased winds on the Southern Ocean CO₂ sink. The three panels represent conditions in the present ocean (left), under very high atmospheric CO₂ (middle), and more than 100 years after the CO₂ emissions cease (right). C is the concentration of carbon in the surface and deep oceans in units of μmol kg⁻¹, whereas ΔC is the increase in carbon content of the ocean from human CO₂ emissions. The observed concentrations are from (25), south of 45°S.

20. Trends in the Southern Ocean CO₂ sink are updated annually, together with the global CO₂ budget by the Global Carbon Project (www.globalcarbonproject.org).


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