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Science **319**, 570a (2008);
DOI: 10.1126/science.1149077

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Comment on "Saturation of the Southern Ocean CO_2 Sink Due to Recent Climate Change"

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Unlike Le Quéré *et al.* (Reports, 22 June 2007, p. 1735), we do not find a saturating Southern Ocean carbon sink due to recent climate change. In our ocean model, observed wind forcing causes reduced carbon uptake, but heat and freshwater flux forcing cause increased uptake. Our inversions of atmospheric carbon dioxide show that the Southern Ocean sink trend is dependent on network choice.

Le Quéré *et al.* (*1*) reported that the Southern Ocean sink of CO_2 has weakened since 1981 despite the increase in atmospheric CO_2 levels. To further test their assessment, we estimated the carbon flux from the Southern Ocean using a Bayesian synthesis inversion method (*2*, *3*). The inversion gives very similar results to (*1*) for the trend and interannual variability (IAV) in the Southern Ocean CO_2 sink provided that the same network of atmospheric CO_2 data is used. However, we also found that the estimated trend is dependent on the network choice.

Our control inversion used nine data records (*4*, *5*) from five locations (*6*) [a smaller network than (*1*)], and we compared this with inversions that added Amsterdam Island (AMS) and Ascension Island (ASC) data used in (*1*). Inversions of synthetic data (*7*) indicated that any of these cases should give estimates of Southern Ocean CO_2 flux IAV and trend that are consistent with the fluxes used to generate the synthetic data. Figure 1 shows the three estimates of the annual mean Southern Ocean carbon flux and the annual mean uncertainty for the control case. The interannual variations are similar between cases, but the trend in sink between 1981 and 2004 [the period used in (*1*)] is not. The control case gives an increasing CO_2 sink with a trend of –0.092 ± 0.084 petagrams of carbon (Pg C) year^{-1} decade^{-1} (*8*). Adding the AMS data to the inversion weakens the negative trend (–0.012 ± 0.081 Pg C year^{-1} decade^{-1}), whereas adding both AMS and ASC data gives a positive trend (0.049 ± 0.076 Pg C year^{-1} decade^{-1}) similar to (*1*).

The control inversion trend is consistent with that produced by an ocean carbon model (*9*) run with constant 1948 wind, heat flux, and freshwater flux forcing but with increasing atmospheric CO_2 (Fig. 1). This produces a trend for the period 1981 to 2002 of –0.088 ± 0.003 Pg C year^{-1} decade^{-1}. Hence, our control inversion does not produce a trend that is significantly different from that expected due to increasing atmospheric CO_2. Our inversion case closest to (*1*) (with AMS and ASC) is significantly different from the ocean model trend at the 95% level. The significance is less than in (*1*) because we included the flux uncertainty from the inversion in the calculation of the trend standard deviation. The inversion flux uncertainty (Fig. 1) is determined primarily from the data uncertainty used in the inversion [0.3 to 0.5 parts per million (ppm)] (*10*), which encompasses the ability to model CO_2 at the sites and measurement error (estimated to be 0.2 to 0.4 ppm based on differences between colocated CO_2 records at the South Pole and Samoa).

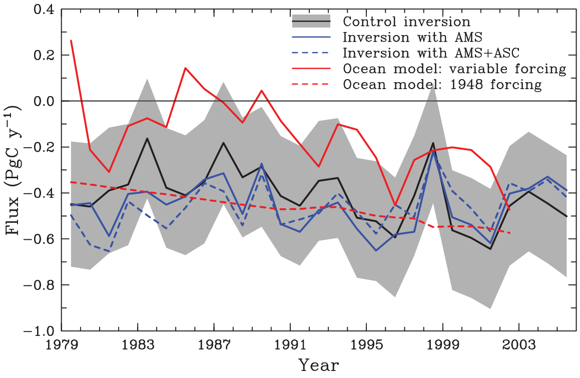

Fig. 1. Annual mean Southern Ocean CO_2 flux from inversions using the control network (black), adding AMS (solid blue), and adding AMS and ASC (dotted blue) and from an ocean model forced with observed winds and fluxes (solid red) and constant wind and fluxes (dotted red). The shaded region shows the ±1 SD uncertainty on the fluxes for the control inversion. The long-term mean flux cannot be reliably estimated from the inversions (7), so the mean offset between the ocean model with variable forcing and inversion fluxes is not considered significant.

Figure 1 also shows the Southern Ocean carbon uptake simulated by the ocean carbon model forced with observed winds (*11*) and heat and freshwater fluxes from 1948 to 2002. The increase in sink over the last two decades is slightly larger (–0.139 ± 0.043 Pg C year^{-1} decade^{-1}), but not significantly different from that seen in the constant forcing ocean run and in the control inversion. In the variable forcing case, we find compensating trends from the wind forcing and from the flux forcing; variable wind forcing gives the saturating Southern Ocean sink found by (*1*) in their ocean model simulation. In contrast to the findings of Le Quéré *et al.* (*1*), variable flux forcing increases CO_2 uptake in the Southern Ocean. Our fluxes (*12*) differ from (*1*), but it is difficult at present to determine which flux fields are more reliable. Clearly, the ocean model simulations are highly sensitive to the choice of flux fields and how they are used in the model.

The ocean model results suggest that the control inversion trend may be more realistic than the trend from the inversions including AMS and ASC. This is supported by inspection of the CO_2 records for ASC (*13*) and AMS (*14*). High proportions of positive outliers in ASC samples before 1991 result in poor definition of the seasonal cycle and increased uncertainty in annual averages. Also, differences from South Pole (ASC-SPO) compare well with Samoa-South Pole differences (SMO-SPO) after 1989, but from 1982 to 1986 the ASC data appear 0.7 ± 0.4 ppm higher than expected if SMO and ASC are responding to the same long-term trends. At AMS, after 1999, springtime values tend to be lower than those from other Southern Hemisphere sites by up to 0.5 ppm, with the August-September 2004 data appearing low by an additional 0.7 ppm.

To assess the impact of these apparent anomalies, we performed an inversion with ASC data reduced by 0.5 ppm from 1981 to 1986, and AMS data increased by 0.2 ppm from 1999 to 2005. The Southern Ocean source increased by about 0.12 Pg C year^{-1} from 1981 to 1986 and decreased by about 0.08 Pg C year^{-1} from 1999 to 2005. These differences are smaller than the source uncertainty from the inversion (0.23 Pg C year^{-1}) but change the 1981 to 2004 sink trend from positive to negative (–0.037 Pg C year^{-1} decade^{-1}). Unless we can be confident that the changes in CO_2 at AMS and ASC relative to SPO are driven by changes in surface fluxes rather than measurement or sampling errors, we cannot estimate a robust trend in the Southern Ocean sink.

Both our inversion of atmospheric CO_2 and our ocean model indicate that the Southern Ocean trend found by (*1*) is not robust and that there is insufficient evidence to conclude that the Southern Ocean sink of CO_2 has saturated as a result of recent climate change. The inversion of atmospheric CO_2 remains a vital method for monitoring the response of the natural sources and sinks

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of CO_2 to anthropogenic emissions and climate change, but the ability to detect long-term trends requires careful use of the atmospheric measurements and greater resources to provide a denser network in space and time. Our ocean model simulations show that changes in heat fluxes, freshwater fluxes, and winds all substantially affect the trend in Southern Ocean CO_2 uptake, and how these fields are used in the ocean model is important. Obtaining consistent interannual variations in ocean fluxes from the ocean model and atmospheric inversions would increase confidence that model processes are well represented.

References and Notes

1. C. Le Quéré *et al.*, *Science* **316**, 1735 (2007).
2. D. F. Baker *et al.*, *Global Biogeochem. Cycles* **20**, GB1002 (2006).
3. We solve for 116 regions globally, 6 of which make up the Southern Ocean region, using monthly mean CO_2 mixing ratio measurements.
4. GLOBALVIEW-CO_2, Cooperative Atmospheric Data Integration Project–Carbon Dioxide, CD-ROM, NOAA GMD, Boulder, CO (2006). [Also available on Internet via anonymous FTP to ftp.cmdl.noaa.gov, Path: ccg/co2/GLOBALVIEW.]
5. C. D. Keeling, T. P. Whorf, *Trends: A Compendium of Data on Global Change* (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, 2005).
6. Control inversion sites with data type and uncertainty used in the inversion: Barrow (71°N, 157°W), NOAA (National Oceanic and Atmospheric Administration) in situ, 0.7 ppm; Mauna Loa (20°N, 156°W), NOAA in situ, 0.5 ppm; Samoa (14°S, 171°W), NOAA flask and in situ, SIO (Scripps Institution of Oceanography) flask, 0.5 ppm; Palmer Station (65°S, 64°W), NOAA flask, 0.3 ppm; South Pole (90°S, 25°W), NOAA flask and in situ, SIO flask, 0.3 ppm. Additional sites for sensitivity tests: Amsterdam Island (38°S, 78°E), LSCE (Laboratoire des Sciences du Climat et de l'Environnement) in situ, 0.3 ppm; Ascension Island (8°S, 14°W), NOAA flask, 0.5 ppm. The NOAA and LSCE records were from GLOBALVIEW-CO_2, and four pseudo-weekly values were averaged to give monthly means. Gap-filled values were used, but the data uncertainty was increased by up to a factor of five when this occurred.
7. The inversion set-up was tested using a synthetic data test for 1971 to 1999 in which interannually varying CO_2 fluxes were input into an atmospheric model to create CO_2 concentration time series. The fluxes were retrieved using an inversion performed with a different atmospheric model. The forward simulation included interannually varying meteorology, whereas the inversion did not. We found that the control inversion was unable to retrieve the long-term mean flux but was successful in retrieving the interannual variations (with a slight underestimate in variability) and sink trend (–0.063 Pg C year^{-1} decade^{-1} for 1976 to 1999 compared with –0.068 Pg C year^{-1} decade^{-1} for the input fluxes). Inversions including Amsterdam Island without or with Ascension Island gave comparable results with slightly smaller trends (–0.049 and –0.050 Pg C year^{-1} decade^{-1}, respectively).
8. The standard deviation of the trend incorporates two components that we consider to be independent: interannual variability in the estimated annual mean sources and the uncertainty estimated by the inversion for each of those annual means. The variance of the trend is the sum of the variance of the annual mean sources around the trend line and the variance from the inversion estimate divided by the sum of the squared deviations of the years from the mean year (1993). The calculation assumes that the annual mean sources are normally distributed around the trend line. For the ocean model simulations, only the interannual variability component is used.
9. A. Lenton, R. J. Matear, *Global Biogeochem. Cycles* **21**, GB2016 (2007).
10. The number of sites constraining the Southern Ocean region also determines the flux uncertainty. For example, a network with five extra sites in the Southern Ocean and Antarctic region (such as currently available) would reduce the uncertainty by about 25%.
11. E. Kalnay *et al.*, *Bull. Am. Meteorol. Soc.* **77**, 437 (1996).
12. Our simulation uses heat and freshwater fluxes from the National Centers for Environmental Prediction reanalysis, with additional fluxes due to restoring the simulated sea surface temperature and salinity fields to observations on a 30-day time scale.
13. P. P. Tans, T. J. Conway, *World Data Centre for Greenhouse Gases* (Japan Meteorological Agency, Tokyo, 2007); http://gaw.kishou.go.jp/wdcgg.html.
14. M. Ramonet, M. Schmidt, P. Ciais, V. Kazan, S. G. Jennings, *World Data Centre for Greenhouse Gases* (Japan Meteorological Agency, Tokyo, 2007); http://gaw.kishou.go.jp/wdcgg.html.

10 August 2007; accepted 28 December 2007
10.1126/science.1149077