CLIMATE

An increasing carbon sink?

Southern Ocean carbon uptake may have strengthened between 2002 and 2012, slowing climate change

By **S. E. Mikaloff-Fletcher**

Since 1870, Earth's oceans have absorbed more than one-quarter of the carbon dioxide emitted to the atmosphere from fossil fuel burning and other human activities, thereby dramatically slowing climate change (*1*). The Southern Ocean is responsible for ~40% of this global ocean carbon sink (*2*). Recent studies have suggested that the rate of carbon uptake by the Southern Ocean may be slowing (*3*, *4*). Such a positive climate feedback effect would reduce the Southern Ocean's capacity to slow climate change. On page 1221 of this issue, Landschützer *et al.* show that although the rate of carbon uptake by the Southern Ocean slowed between the 1980s and early 2000s, it began to strengthen again in 2002 and continued to do so until at least 2012 (*5*).

Air-sea fluxes of CO_2 are proportional to the difference in partial pressure of CO_2 between the atmosphere and the surface ocean, ΔpCO_2 (*6*). Therefore, increases in atmospheric CO_2 concentrations are expected to drive increases in ocean CO_2 uptake. In 2007, Le Quéré *et al.* suggested that Southern Ocean carbon uptake began leveling off in the early 1980s while atmospheric CO_2 continued to rise (see the figure) (*3*). The authors based their conclusions on an analysis of ocean models and an atmospheric inverse model that estimates air-sea and air-land CO_2 fluxes from atmospheric CO_2 measurements and atmospheric model simulations. They and others attributed this trend to the strengthening and poleward shift of the westerly winds that overlay the Southern Ocean, bringing carbon-rich waters to the surface and thus reducing ΔpCO_2 (*3*, *4*). Because the changes in the westerly winds are linked to climate change and ozone depletion, the rate of carbon uptake by the Southern Ocean would then be expected to continue to slow in response to future climate change (*3*).

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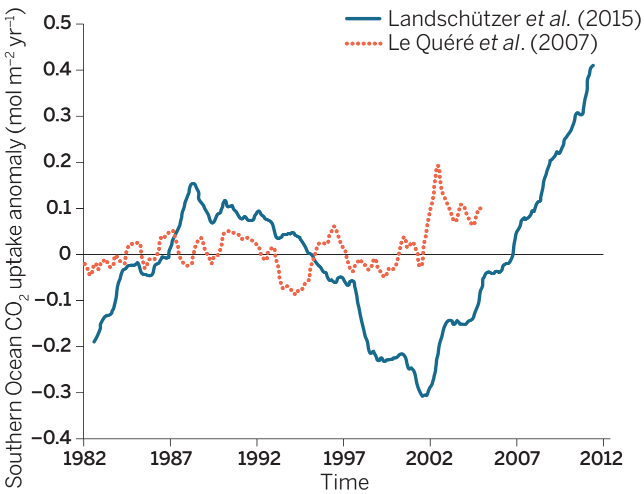
The hypothesized weakening of the Southern Ocean carbon sink has been the subject of vigorous debate, because many processes that play a critical role in the Southern Ocean are not well represented in coarse-resolution ocean models (*7*, *8*). Furthermore, estimates of trends in the Southern Ocean carbon sink from atmospheric inversion models are sensitive to data selection (*9*).



Beyond the slowdown. Southern Ocean CO_2 uptake anomalies from Le Quéré *et al.* (*3*) (red) and Landschützer *et al.* (*5*) (blue), averaged between 35°S and 90°S. Both studies found a flattening of the Southern Ocean carbon sink between the 1980s and early 2000s despite rising atmospheric CO_2 concentrations. On the basis of longer-term data, Landschützer *et al.* report a reinvigoration of this sink in the mid-2000s. Positive values reflect ocean uptake; anomalies are calculated relative to the 1980s average.

Landschützer *et al.* have now analyzed trends in a global data set of ΔpCO_2 measurements that includes 2.6 million observations in the Southern Ocean spanning 30 years (*10*). They used two novel statistical methods to interpolate ship data in space and time: a neural network approach that incorporates physical and biological observations, and a method that assimilates the ΔpCO_2 data into a mass budget of the mixed layer. As in the earlier study of Le Quéré *et al.* (*3*), they also compared their results with complementary estimates from atmospheric data. The analysis confirms that the rate of carbon uptake by the Southern Ocean slowed down between the early 1980s and the early 2000s. However, all three approaches reveal a striking reversal in this trend in 2002. From 2002 to 2012, Southern Ocean carbon uptake began to strengthen, a result that would not have been apparent during the time period studied by Le Quéré *et al.* (see the figure).

Further support for this finding comes from a coincident study by Munro *et al.* based on carbon measurements collected in the Drake Passage between 2002 and 2015 (*11*). Although focused on a single region, this study has a remarkable temporal coverage of more than 20 cruises per year. The results show a clear increase in ΔpCO_2 in the Drake Passage south of the Antarctic Polar Front from 2002 to 2015, implying a strengthening of the carbon sink in this region.

The reinvigoration of the ocean carbon sink demonstrated by the two studies (*5*, *11*) presents a puzzle. Between 2002 and 2012, there has been no reversal in the strengthening of westerly winds thought to have caused the slowdown between the early 1980s and the early 2000s (*5*). Landschützer *et al.* argue that the reinvigoration of the sink since 2002 may result from a combination of regional trends in sea surface temperature (which controls CO_2 solubility) and circulation-driven changes in the carbon balance at the sea surface.

Although these studies represent an intriguing new picture of the Southern Ocean sink in the recent past, it is not yet clear how this region will respond to future changes in climate. The Southern Ocean has long been undersampled, particularly during the austral winter, which may be a critical period for the reinvigoration of the carbon sink (*11*). An improved understanding of key processes controlling this important carbon sink will require more observations with higher spatial and temporal resolution of carbon and other physical and biogeochemical properties in the Southern Ocean and the overlying atmosphere. ■

REFERENCES AND NOTES

1. C. Le Quéré *et al.*, *Earth Syst. Sci. Data* **7**, 47 (2015).
2. T. L. Frölicher *et al.*, *J. Clim.* **28**, 862 (2015).
3. C. Le Quéré *et al.*, *Science* **316**, 1735 (2007).
4. N. S. Lovenduski, N. Gruber, S. C. Doney, *Global Biogeochem. Cycles* **22**, GB3016 (2008).
5. P. Landschützer *et al.*, *Science* **349**, 1221 (2015).
6. R. Wanninkhof, *J. Geophys. Res.* **97**, 7373 (1992).
7. T. Ito, M. Woloszyn, M. Mazloff, *Nature* **463**, 80 (2010).
8. K. B. Rodgers *et al.*, *Biogeosciences* **11**, 4077 (2014).
9. R. M. Law *et al.*, *Science* **319**, 570a (2008).
10. D. C. E. Bakker *et al.*, *Earth Syst. Sci. Data* **6**, 69 (2014).
11. D. R. Munro *et al.*, *Geophys. Res. Lett.* 10.1002/2015GL065194 (2015).

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