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The Global Ocean Carbon Sink: Recent Trends and Variability

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With 1 Figure

The increasing load of anthropogenic CO_2 in the Earth System and the substantial amount of climate variability and change continues to challenge our understanding of the contemporaneous global ocean carbon sink, thereby providing us many lessons for our quest to explain the glacial-interglacial changes in atmospheric CO_2. Of particular interest are the changes in the Southern Ocean carbon sink, i.e., the region that remains at the forefront in any attempt to quantify how the ocean controlled the atmospheric CO_2 evolution over the last 20,000 years. The Southern Ocean is also pivotally important in current times, being responsible for more than 40 % of the global uptake of anthropogenic CO_2 (Mikaloff-Fletcher et al. 2006) despite covering only 30 % of the global ocean south of 30°S. Further, models suggest that it takes up three quarters of the total excess heat generated by the increasing levels of greenhouse gases in the atmosphere (Frölicher et al. in press), making it a key control valve not only for the past, but also for the present climate. While the annual rate of ocean uptake has increased considerably over the last few decades, as expected based on the substantial increase in atmospheric CO_2, there is considerable concern that this sink might saturate or even reverse in response to future climate change. In fact, several model-based studies have pointed out that this saturation might be occurring already in the Southern Ocean, as its sink strength began to slow down in the last two to three decades relative to expectations (Le Quéré et al. 2007, Lovenduski et al. 2008). These studies attributed this saturation to a southward movement and intensification of the westerly winds in the Southern Hemisphere, causing an increase in the upwelling of deeper waters that are naturally enriched in inorganic carbon, leading to an enhanced outgassing of this "natural" CO_2. This wind-driven mechanism has a direct analog to some of the proposed mechanisms for the glacial-interglacial CO_2 change (e.g. Anderson et al. 2009). However, while this proposed slow-down of the Southern Ocean carbon sink has been identified in several model studies including those that interpret atmospheric CO_2 gradients, it has not been corroborated with *in-situ* observations, nor is it clear whether this was a temporary "hiatus" from which the ocean recovered since then, or a progression toward a new low-uptake state.

Here, we use two novel sets of observations in order to assess the recent evolution of the oceanic sink for atmospheric CO_2 with an emphasis on the Southern Ocean. These two sets of very complimentary observations are: (*i*) surface ocean observations of the partial pressure of CO_2 (Bakker et al. 2014), from which monthly resolved global air-sea CO_2 fluxes can be estimated for the period from 1982 onward (Landschützer et al. 2014, Rödenbeck et al.

2014), and (*ii*) ocean interior observations of dissolved inorganic carbon and ancillary properties, from which the accumulation of anthropogenic CO_2 between the 1990s and the mid-2000s can be derived (Clement et al. in prep., Gruber et al. in prep.). The ocean interior results suggest a global increase in the anthropogenic CO_2 inventory of about 34±7 Pg C between 1994 and 2006, largely consistent with expectations based the increase in atmospheric CO_2 (Mikaloff-Fletcher et al. 2006). In contrast, the cumulative air-sea CO_2 flux over this period amounts to only about 19±4 Pg C. The large discrepancy can be resolved when considering that the CO_2 flux across the air-sea interface also contains a "natural" CO_2 flux component associated (*i*) with the steady-state outgassing of carbon stemming from the carbon input by rivers (about ~5 Pg C) and (*ii*) climatic perturbations (~5 Pg C). In fact, the surface ocean observations suggest that most of this lower than expected uptake between 1994 and 2006 stems from the Southern Ocean, whose sink strength was particularly weak in the 1990s, supporting the model based studies (Fig. 1). Interestingly, over the same period the thermocline of the temperate latitudes of the Southern Hemisphere accumulated a lot of anthropogenic CO_2, implying a strong uptake of anthropogenic CO_2 in the Southern Ocean. This apparent paradox can be resolved by considering that the enhanced upwelling and general vertical overturning in the Southern Ocean induced by the intensification of the westerly winds not only enhances the loss of natural CO_2 to the atmosphere, but also tends to enhance the uptake of anthropogenic CO_2 and its subsequent transport northward *via* mode and intermediate waters.

However, since ~2002, the situation in the Southern Ocean appears to have reversed (Fig. 1). We interpret this reinvigoration of the Southern Ocean carbon sink to be likely caused by a reorganization of the Southern Ocean westerly wind belt, which became more zonally asymmetric since 2002, with more cyclonically dominant conditions in the Pacific sector, and more anti-cyclonically dominant conditions in the Atlantic. As result, colder than normal air was advected from the Antarctic continent over the Pacific sector, and warmer than normal air advected from subtropical latitudes over the Atlantic and part of the Indian sector. The de-stratification effect of the cooling in the Pacific sector might have been partially compensated by a simultaneous freshening caused by the increased glacial melt water fluxes from Antarctica and increased northward transport of sea-ice and its subsequent melting. This likely kept the efficiency of the biological pump high, and avoided the build-up of high levels of dissolved inorganic carbon (DIC), which would have driven the surface ocean partial pressure of CO_2 (pCO_2) up. In the Atlantic and Indian sector, the atmospheric circulation changes likely caused also a southward deflection of the major fronts and a deepening of the thermocline, leading to the upwelling of warmer waters with lower than normal DIC. This reduction in DIC more than compensated the warming, keeping surface ocean pCO_2 well below that of the atmosphere. Thus, the cooling driven pCO_2 trend in the Pacific, and the dissolved inorganic carbon-driven trend in the Atlantic and Indian Ocean worked in tandem to prevent the partial pressure of CO_2 to increase across the entire Southern Ocean, thus enhancing the uptake of atmospheric CO_2 nearly everywhere.

The reasons underlying the development of a more asymmetric circulation pattern in the Southern Hemisphere are not fully understood yet, but could be associated with the more prevalent La Niña conditions in the equatorial Pacific since the early 2000. This is arguably speculative, but if it is indeed the case that changes in tropical climate can trigger changes in the Southern Ocean carbon sink, then entirely new scenarios for how the Earth System evolved out of the Last Glacial Maximum are conceivable, i.e., scenarios that involve teleconnection pattern between the tropics and the high latitudes with strong impacts on the Southern Ocean carbon window.

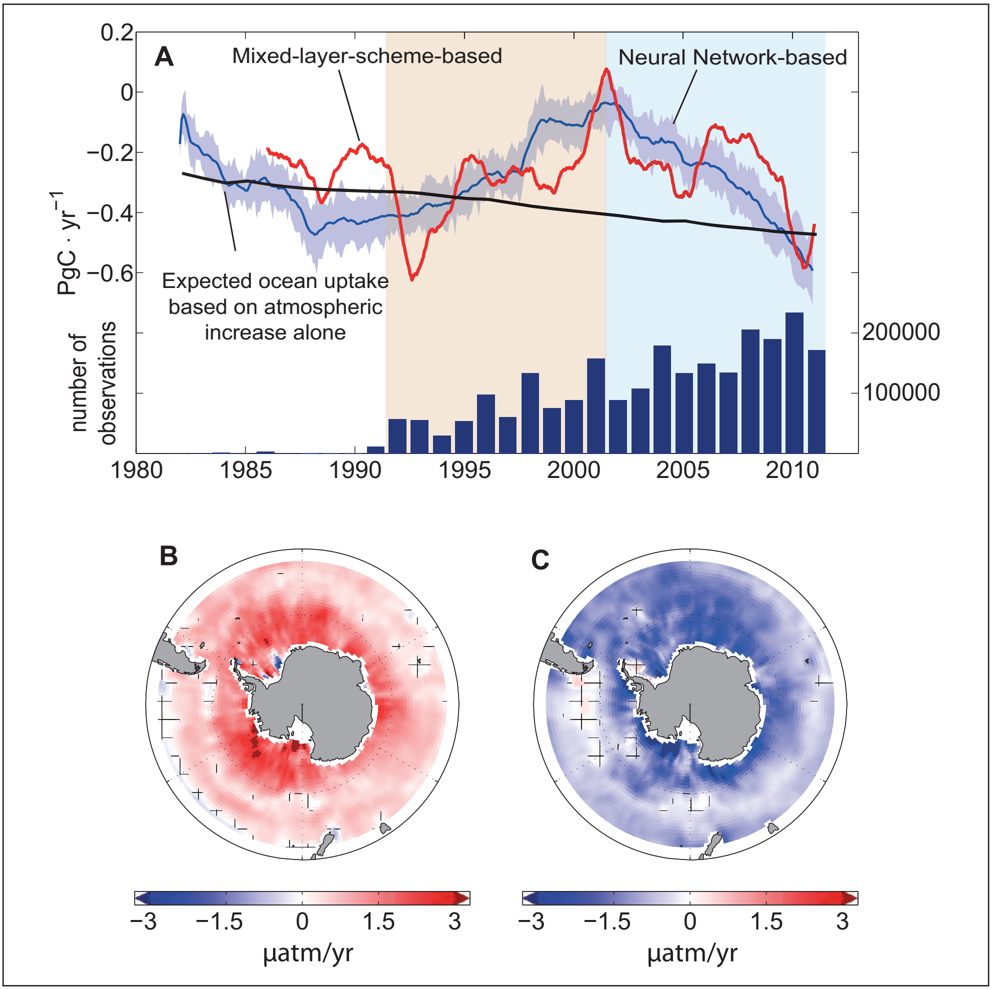

Fig. 1 Evolution of the Southern Ocean carbon sink over the last two decades. (*A*) Timeseries of the net air-sea CO_2 flux for the region south of 30°S. Shown are the neural network-based estimates of Landschützer et al. (2014) and the mixed-layer scheme-based estimates of Rödenbeck et al. (2014) together with a model-based estimate of the evolution of the sink in the absence of any climate variability. (*B*) Number oft observations in the SOCAT2 data base south of 44°S. (*C*) Spatial pattern of the linear trend in the air-sea pCO_2 difference for the 1990–2001 period based on the Landschützer et al. estimates. (*C*) as (*B*), except for the 2002–2011 period. The hatching masks trend estimates that are not statistically significant.

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