OCEANIC SOURCES AND SINKS FOR ATMOSPHERIC CO_2

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ABSTRACT

Owing to the combination of greatly improved observational constraints and new data analysis and modeling techniques, our ability to constrain the role of the ocean in the global carbon cycle has made great advances in the past decade. By combining ocean interior carbon data with ocean general circulation models in an inverse manner, we can constrain the oceanic uptake of anthropogenic CO_2 to within an unprecedented narrow range of 2.20±0.25 Pg C yr^{-1} for a nominal year of 1995. The inversely estimated pre-industrial air-sea fluxes reveal the expected pattern with CO_2 outgassing in the tropics and CO_2 uptake at mid to high latitudes. The subpolar regions of the Southern Hemisphere defy this trend, exhibiting strong outgassing of natural CO_2. This outgassing nearly cancels the large uptake of anthropogenic CO_2 in this region, leading to a near zero net contemporary flux. The contemporary air-sea fluxes from the inversion agree reasonably well with flux estimates derived from ΔpCO_2 observations, with the exception of the above subpolar regions, where our flux estimates are three to five times smaller. When analyzed together with the observed atmospheric CO_2 gradients, our results support the existence of a substantial sink for atmospheric CO_2 in the northern hemisphere terrestrial biosphere, and a terrestrial carbon loss in the tropics.

INTRODUCTION

During the first half of the 20th century, the prevailing opinion was that the ocean constitutes a nearly infinite sink for the CO_2 that was being emitted as a result of anthropogenic activities, thereby largely mitigating the potential climate impact of these emissions. The discovery in the early 1960s by C.D. Keeling that atmospheric CO_2 increases at a rate that represents about half of the fossil fuel emissions firmly rejected this view and essentially jump-started carbon cycle research. Ever since, the determination of the sources and sinks for atmospheric CO_2 at Earth's surface has been at the forefront of carbon cycle research. The earliest insights on these fluxes arose in the mid to late 1960s, mainly in conjunction with the detailed analysis of atmospheric CO_2 gradients. At the same time, first large-scale surveys of the oceanic CO_2 fields began, and in 1968, Keeling and collaborators presented for the first time a global map of the climatological distribution of the surface ocean partial pressure of CO_2 (pCO_2), the primary factor determining the exchange of CO_2 across the air-sea interface. This map was drawn on the basis of a few transects only, using intuition and biogeochemical arguments to fill in the large swaths of ocean that were not sampled. In the meantime, our ability to observe, quantify, and understand the oceanic sources and sinks for atmospheric CO_2, and in particular the oceanic uptake for anthropogenic CO_2 has made great advances. The aim of this talk is to provide a synthesis of these advances and what we have learned from them.

MAJOR DEVELOPMENTS

The advances in our understanding and quantification of these fluxes are in large part due to four converging factors. First, we are able now, with some confidence, to compute directly the air-sea flux of CO_2 across the air-sea interface on a global basis thanks to the compilation of a large data base of observations of the air-sea difference in the partial pressure of CO_2 (*Takahashi et al.,* 2002). Second, the completion of the JGOFS/WOCE global carbon survey produced for the first time a high-quality global-scale data set of inorganic carbon (*Sabine et al.,* 2004). Third, a method has been devised, by which the small anthropogenic CO_2 signal can be separated from the large natural carbon background, allowing us to directly determine the oceanic inventory of anthropogenic CO_2 (*Gruber et al.,* 1996). The fourth and final factor is the development and application of inverse methods that take advantage of the first three developments in order to compute separately the air-sea flux of pre-industrial and anthropogenic CO_2 (*Gloor et al*., 2003; *Mikaloff-Fletcher et al.,* 2005) (see abstract by *Mikaloff-Fletcher et al.* in this volume for further details).

NEW INSIGHTS

Our inversion of the data-based oceanic inventory of anthropogenic CO_2 of *Sabine et al*. (2004) with 9 different ocean circulation models constrains the oceanic uptake of anthropogenic CO_2 to an unprecedented narrow range of 2.20±0.25 Pg C yr^{-1} for a nominal year of 1995. The uncertainty of this estimate includes errors that result from uncertainties in the data as well as ocean model transport (cf. *Mikaloff-Fletcher et al*.). This tight estimate of the oceanic uptake narrows the land uptake for the period of the 1990s to a similarly low range and reveals that for the period of the 1990s the ocean has been a sink for anthropogenic carbon that was three times larger than the land biosphere (cf *Jacobson et al.).*

The inversion of the pre-industrial oceanic carbon distribution shows that natural CO_2 is outgassing in the tropics, likely driven by the upwelling of respired CO_2 coupled with warming, while the high-latitudes act as sinks for natural CO_2, likely caused by cooling. This trend is defied by the subpolar regions of the Southern Hemisphere where upwelling leads to a strong outgassing of natural CO_2. The contemporary fluxes (Fig. 1) represent the superposition of the anthropogenic and the pre-industrial fluxes. In certain regions, such as the North Atlantic and North Pacific, the two fluxes reinforce each other, leading to strong contemporary sinks for atmospheric CO_2. In other regions, such as the subpolar Southern Ocean, the two fluxes nearly cancel each other, leading to a near-zero net flux. A comparison of our con-temporary air-sea fluxes with those derived from the ΔpCO_2 climatology of Takahashi et al. [2002]) reveals generally good agreement (Fig. 1), particularly for the Northern hemisphere. An important exception is the subpolar regions in the Southern hemisphere where our flux estimates are three to five times smaller. Second, there is a tendency for an equatorward shift of the main oceanic sink regions. A careful analysis of our inversion results reveals that these trends are robust and are driven by the oceanic observations. We therefore suspect that the discrepancy is primarily a result of the undersampling of these regions in the Takahashi et al. [2002] climatology, particularly in wintertime. A second comparison with the atmospheric inversion results obtained by the TransCOM experiment [*Gurney et al.,*2002] reveals similar agreements and differences, but given the fact that these atmospheric inversions used the Takahashi et al. [2002] estimates as priors, and given that atmospheric CO_2 inversions tend to be underconstrained [*Jacobson et al.,* 2005], this is not entirely surprising. In summary, the fusion of oceanic observations with models results in well constrained long-term mean estimates of the air-sea fluxes of both natural and anthropogenic CO_2, providing new insights into both the ocean and the land biosphere (cf.*Jacobson et al.*).

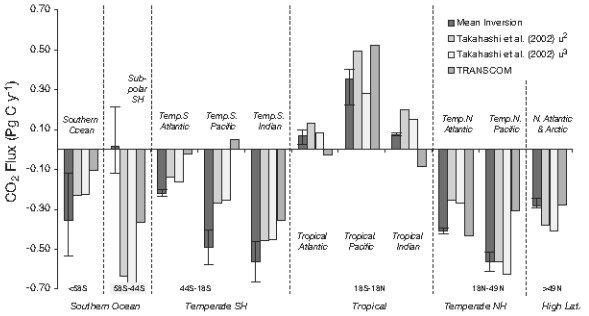

Fig. 1: Comparison of contemporary air-sea CO_2 flux estimates (1995) Shown are the ocean inverse estimates (average of 9 models with error bars indicating the 17% to 83% percentiles), two estimates based on the *Takahashi et al.* (2002) climatology (using either a u^2 or a u^3 dependence of the gas exchange coefficient on the wind speed), and the TransCOM estimates as reported by *Gurney et al.* (2002).

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