



A joint atmosphere-ocean inversion for surface fluxes of carbon dioxide:

2. Regional results

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[1] We report here the results from a coupled ocean-atmosphere inversion, in which atmospheric CO₂ gradients and transport simulations are combined with observations of ocean interior carbon concentrations and ocean transport simulations to provide a jointly constrained estimate of air-sea and air-land carbon fluxes. While atmospheric data have little impact on regional air-sea flux estimates, the inclusion of ocean data drives a substantial change in terrestrial flux estimates. Our results indicate that the tropical and southern land regions together are a large source of carbon, with a 77% probability that their aggregate source size exceeds 1 PgC yr⁻¹. This value is of similar magnitude to estimates of fluxes in the tropics due to land-use change alone, making the existence of a large tropical CO₂ fertilization sink unlikely. This terrestrial result is strongly driven by oceanic inversion results that differ from flux estimates based on ΔpCO₂ climatologies, including a relatively small Southern Ocean sink (south of 44°S) and a relatively large sink in the southern temperate latitudes (44°S–18°S). These conclusions are based on a formal error analysis of the results, which includes uncertainties due to observational error transport and other modeling errors, and biogeochemical assumptions. A suite of sensitivity tests shows that these results are generally robust, but they remain subject to potential sources of unquantified error stemming from the use of large inversion regions and transport biases common to the suite of available transport models.

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1. Introduction

[2] This manuscript is concerned with interpretation of flux estimates from a joint ocean-atmosphere inversion introduced in a companion paper [Jacobson *et al.*, 2007]. This joint inversion combines atmospheric and oceanic carbon observations with multiple transport simulations (16 in the atmosphere and 10 in the ocean) to produce estimates of surface fluxes. Results are produced independently for each unique combination of atmospheric and oceanic transport simulation, and the resulting ensemble of 160 permutations thus includes a sample of uncertainty due

to errors in transport modeling. Details of the construction of this joint inverse, discussion of its limitations, and results on global scales are presented by Jacobson *et al.* [2007].

[3] As described by Jacobson *et al.* [2007], the joint inversion does not use regularization techniques to decrease flux uncertainties. It thus admits larger uncertainties for underobserved land regions than inversions that use model-based priors to blend observationally derived fluxes with predictions from terrestrial carbon simulations. In the atmospheric inversion, a sparse observational data set combined with diffusive transport results in regions whose fluxes cannot be effectively distinguished from one another. The present unregularized atmospheric inversion preserves the raw correlations between such flux regions. It is via these correlations that information from the ocean interior is transmitted to terrestrial flux estimates in the joint inversion. Contemporary air-sea fluxes from the present oceanic inversion differ significantly from forward simulations and estimates based on ΔpCO₂ observations. These differences drive a reinterpretation of terrestrial fluxes in the tropics and Southern Hemisphere, suggesting that these regions may be

“Our results indicate that the tropical and southern land regions together are a large source of carbon.”

Jacobson et al., GBC 2007

NL: -2.9 ± 1.0 PgC/yr
T&SL: 1.8 ± 1.1 PgC/yr

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“... tropical ecosystems may currently be strong sinks for CO₂.”

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NL: -1.5 ± 0.7 PgC/yr
T&SL: -0.5 ± 0.8 PgC/yr

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Weak Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of Atmospheric CO₂

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Measurements of midday vertical atmospheric CO₂ distributions reveal annual-mean vertical CO₂ gradients that are inconsistent with atmospheric models that estimate a large transfer of terrestrial carbon from tropical to northern latitudes. The three models that most closely reproduce the observed annual-mean vertical CO₂ gradients estimate weaker northern uptake of -1.5 petagrams of carbon per year (Pg C year⁻¹) and weaker tropical emission of +0.1 Pg C year⁻¹ compared with previous consensus estimates of -2.4 and +1.8 Pg C year⁻¹, respectively. This suggests that northern terrestrial uptake of industrial CO₂ emissions plays a smaller role than previously thought and that, after subtracting land-use emissions, tropical ecosystems may currently be strong sinks for CO₂.

Our ability to diagnose the fate of anthropogenic carbon emissions depends critically on interpreting spatial and temporal gradients of atmospheric CO₂ concentrations (*1*). Studies using global atmospheric transport models to infer surface fluxes from boundary-layer CO₂ concentration observations have generally estimated the northern mid-latitudes to be a sink of approximately 2 to 3.5 Pg C year⁻¹ (*2–5*). Analyses of surface ocean partial pressure of CO₂ (*2*), atmospheric carbon isotope (*6*), and atmospheric oxygen (*7*) measurements have further indicated that most of this northern sink must reside on land. Tropical fluxes are not well constrained by the atmospheric observing network, but global mass-balance requirements have led to estimates of strong (1 to 2 Pg C year⁻¹) tropical carbon sources (*4, 5*). Attribution of the Northern Hemisphere terrestrial carbon sink (*8–13*) and

reconciliation of estimates of land-use carbon emissions and intact forest carbon uptake in the tropics (*14–19*) have motivated considerable research, but these fluxes remain quantitatively uncertain. The full range of results in a recent inverse model comparison study (*5*), and in independent studies (*3, 20, 21*), spans budgets with northern terrestrial uptake of 0.5 to 4 Pg C year⁻¹, and tropical terrestrial emissions of -1 to +4 Pg C year⁻¹. Here, we analyzed observations of the vertical distribution of CO₂ in the atmosphere that provide new constraints on the latitudinal distribution of carbon fluxes.

Previous inverse studies have used boundary-layer data almost exclusively. Flask samples from profiling aircraft have been collected and measured at a number of locations for up to several decades (*22–24*), but efforts to compile these observations from multiple institutions and to

compare them with predictions of global models have been limited. Figure 1 shows average vertical profiles of atmospheric CO₂ derived from flask samples collected from aircraft during midday at 12 global locations (fig. S1), with records extending over periods from 4 to 27 years (table S1 and fig. S2) (*25*). These seasonal and annual-mean profiles reflect the combined influences of surface fluxes and atmospheric mixing. During the summer in the Northern Hemisphere, midday atmospheric CO₂ concentrations are generally lower near the surface than in the free troposphere, reflecting the greater impact of terrestrial photosynthesis over industrial emissions at this time. Sampling locations over or immediately downwind of continents show larger gradients than those over or downwind of ocean basins in response to stronger land-based fluxes, and higher-latitude locations show greater CO₂ drawdown at high altitude. Conversely, during the winter, respiration and fossil-fuel sources lead to elevated low-altitude atmospheric CO₂ concentrations at northern locations. The gradients are comparable in magnitude in both seasons, but the positive

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Materials and Methods
Figs. S1 to S10
Tables S1 to S3
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