A first estimate of present and preindustrial air-sea CO_2 flux patterns based on ocean interior carbon measurements and models

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[1] The exchange of CO_2 across the air-sea interface is a main determinant of the distribution of atmospheric CO_2 from which major conclusions about the carbon cycle are drawn, yet our knowledge of atmosphere-ocean fluxes still has major gaps. A new analysis based on recent ocean dissolved inorganic carbon data and on models permits us to separately estimate the preindustrial and present air-sea CO_2 flux distributions without requiring knowledge of the gas exchange coefficient. We find a smaller carbon sink at mid to high latitudes of the southern hemisphere than previous data based estimates and a shift of ocean uptake to lower latitude regions compared to estimates and simulations. The total uptake of anthropogenic CO_2 for 1990 is 1.8 (±0.4) Pg C yr^{-1}. Our ocean based results support the interpretation of the latitudinal distribution of atmospheric CO_2 data as evidence for a large northern hemisphere land carbon sink. *INDEX TERMS:* 4806 Oceanography: Biological and Chemical: Carbon cycling; 4805 Biogeochemical cycles (1615); 1635 Global Change: Oceans (4203); 4842 Modeling. **Citation:** Gloor, M., N. Gruber, J. Sarmiento, C. L. Sabine, R. A. Feely, and C. Rödenbeck, A first estimate of present and preindustrial air-sea CO_2 flux patterns based on ocean interior carbon measurements and models, *Geophys. Res. Lett.*, *30*(1), 1010, doi:10.1029/2002GL015594, 2003.

1. Introduction

[2] Atmospheric modeling studies consistently confirm a large discrepancy between the observed latitudinal gradient of atmospheric CO_2 and that expected from fossil fuel emissions. Historically, two mechanisms have been proposed to explain why the observed gradient is lower, with important consequences for the spatial distribution of the sinks of anthropogenic carbon. The first is an interhemispheric carbon transport cell that operates since preindustrial times with ocean carbon uptake at northern hemisphere high latitudes and subsequent transport to southern hemisphere high latitudes where carbon is outgassing and is driving a return flow in the atmosphere [*Keeling et al.*, 1989]. The second mechanism is uptake of anthropogenic CO_2 by the northern hemisphere mid-latitude land biosphere [*Tans et al.*, 1990]. Results from follow up studies that used inversions of atmospheric CO_2 have not fully resolved the dispute as they vary substantially among each other [*Gurney et al.*, 2002].

[3] We provide here an independent constraint on the air-sea carbon fluxes that exploits the large body of observations of dissolved inorganic carbon (DIC) in the ocean interior. An advantage of these data is that they carry not only information on recent air-sea gas exchange, but also on the spatial distribution of fluxes during preindustrial times. This is because the ocean mixes on time-scales on the order of ten to hundreds of years. A major difficulty with this approach is that CO_2 in the ocean is not a conservative tracer, but subject to intense biologically mediated transformations. However, these processes also affect the nutrient and alkalinity (Alk) distributions. Thus by assuming constant stoichiometric ratios $r_{C:P}$ and $r_{N:P}$ of CO_2, phosphate (PO_4) and nitrate exchange during photosynthesis and respiration, the effect of these transformations can be removed and a tracer $C^* = DIC - r_{C:P}PO_4 - 1/2(Alk + r_{N:P}PO_4) = C_{gas\ ex} + \Delta C_{ant}$ may be defined that has effectively no sources and sinks in the ocean interior. The second term of the C* definition corrects for transformations due to photosynthesis, respiration and remineralization and the third for the transformations due to the formation and dissolution of $CaCO_3$ shells. As the C* tracer is conservative in the ocean interior it reflects just the net effect of preindustrial air-sea gas exchange $C_{gas\ ex}$ and the anthropogenic CO_2 invasion ΔC_{ant} on the interior ocean CO_2 distribution [*Gruber and Sarmiento*, 2002]. The concentration of anthropogenic CO_2, ΔC_{ant}, is estimated separately using the ΔC^* technique of *Gruber et al.* [1996], allowing us to solve for $C_{gas\ ex}$.

[4] In a first attempt to use $C_{gas\ ex}$ to estimate the interhemispheric transport *Broecker and Peng* [1992] estimated a southward transport of 0.6 Pg C yr^{-1} in the Atlantic. Their result supports to some extent the hypothesis of a strong interhemispheric ocean carbon transport loop of *Keeling et al.* [1989]. However, this estimate is based on only two water masses, and no interhemispheric transport in the Pacific Ocean is considered. In an update of the study, *Keeling and Peng* [1995] estimated the preindustrial cross-equatorial CO_2 transport in the Atlantic to be only 0.3 Pg C yr^{-1}.

[5] Here we expand the approach of estimating air-sea CO_2 fluxes and ocean transports from information contained in ocean interior observations by using ocean models in an inverse mode to establish the link to regional air-sea fluxes on a global scale. We then explore the implications of the resulting flux estimates on atmospheric CO_2.

[6] The first step in the flux estimation is to predict with an ocean general circulation model the ocean concentration patterns that are characteristic for release of a dye tracer from different regions of the ocean surface. As spatial flux

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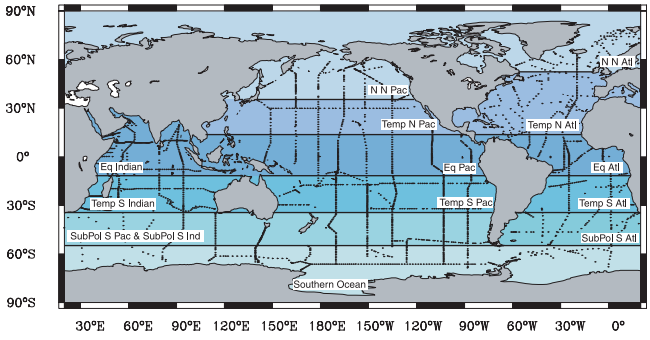

Figure 1. Locations of vertical profiles of dissolved inorganic carbon data used for estimation of air-sea CO_2 fluxes and partitioning of the ocean surface in the 13 flux regions used for the inverse calculations.

patterns within each region, we use for both the preindustrial and anthropogenic cases the absolute value of the heat fluxes estimated by *Esbensen and Kushnir* [1981]. To determine the sensitivity of our estimates to the spatial surface emission patterns, we also emitted tracer uniformly across each region. For each region the difference in the estimates was less than 20%.

[7] For the estimation of preindustrial carbon fluxes we inject dye tracers at a constant rate without seasonal variation separately from each of the 13 regions shown in Figure 1. We run the OGCM until the ocean concentrations increase at the same rate throughout the entire ocean [*Gloor et al.*, 2001]. We then determine with least squares the linear combination of the simulated concentration patterns that fits most closely the observed distributions of $C_{gas\ ex}$. Estimates of regional surface fluxes follow then from the product of the regionally applied dye tracer fluxes times the coefficients obtained by the linear regression. As data we use the approximately 60,000 inorganic carbon and nutrient observations of the recently completed Global Ocean CO_2 survey [*Sabine et al.*, 1997, 2002] augmented with data from selected prior studies. The estimation of the fluxes consists in the solution of 60,000 equations for 13 parameters.

[8] To estimate anthropogenic CO_2 fluxes, we use the finding from model simulation results that the ocean uptake history is linearly proportional to the atmospheric CO_2 perturbation. For anthropogenic carbon we therefore emit dye tracer into a dye-free ocean from each of the 13 regions starting in the year 1765 with a rate that increases like the atmospheric CO_2 perturbation as recorded in ice-cores and, since 1958, by atmospheric measurements. For ΔC_{ant} we use the approximately 60,000 estimates of *Gruber* [1998] and of *Sabine et al.* [1999, 2002]. As for pre-industrial carbon, the flux estimation then consists in the solution of 60,000 equations for 13 parameters.

[9] Sensitivity experiments with three different versions of an OGCM reveal that the regional air-sea carbon flux estimates varied by $\leq$20%. The formal uncertainties of regional estimates within a given model are <0.04 Pg C yr^{-1}, thus the model transport error is the largest factor in the overall uncertainty in the method. Unfortunately there is no formal method to determine this transport error. The realism of simulated transport has been tested through comparison with the observed flow, temperature, salinity, natural radiocarbon and transient tracers [*Gnanadesikan et al.*, 2002]. Secondly, the air-sea carbon flux varied by only a small amount between three model versions used for this study (differences in regional flux estimates $\leq$20% across three model versions). The model version used to obtain the results in this paper is the KVLOW-AILOW model [*Gnanadesikan et al.*, 2002].

2. Results and Discussion

[10] The estimated preindustrial CO_2 fluxes in Figure 2a show the expected pattern of equatorial carbon outgassing and uptake at temperate and high latitudes. Our estimates reveal an asymmetry between the two hemispheres: CO_2 is taken up throughout the entire mid and high latitude regions of the northern hemisphere, while in the southern hemisphere, CO_2 uptake is confined to the mid-latitudes. The outgassing of CO_2 in the high southern latitudes is probably a consequence of relatively weak cooling in combination with an incomplete biological utilization of the remineralized CO_2 that is upwelled in these regions. Globally, our estimates of preindustrial fluxes are almost in balance without applying a mass conservation constraint. We obtain an uptake of 0.09 Pg C yr^{-1}. Our method accounts on a global scale for most of the riverine input of carbon as well as its subsequent outgassing to the atmosphere. This is because most of the carbon that is added to the ocean by rivers acts to increase $C_{gas\ ex}$ (DIC is increased much more than $r_{C:P}PO_4$ or $1/2(Alk + r_{N:P}PO_4)$), mimicking an uptake of carbon from the atmosphere. Most of this carbon is eventually lost to the atmosphere by air-sea gas exchange with an associated decrease in $C_{gas\ ex}$. Our inverse estimates are roughly similar to forward model results obtained using two versions of the Princeton Ocean Biogeochemistry model (Figures 2a and 3a), except that carbon uptake in the Southern hemisphere is smaller compared to the model simulations and our estimates show a tendency for a shift of uptake regions from high towards mid latitudes.

[11] By assuming that the ocean carbon cycle was in steady-state in preindustrial times, we can compute ocean carbon transport by summing up the CO_2 flux estimates for each of the ocean regions proceeding from North to South (Figure 3b). We find a global southward carbon transport across the equator of 0.37 Pg C yr^{-1}, with 0 Pg C yr^{-1} across 3.5°S. The Atlantic transport is within the error bars of the estimates for cross-equatorial transport in the Atlantic obtained by *Keeling and Peng* [1995] but considerably smaller than the estimate of *Broecker and Peng* [1992] and much smaller than postulated by *Keeling et al.* [1989]. The total transport is comparable to the transport estimates of *Sarmiento et al.* [2000] obtained with OGCM's if riverine carbon is accounted for.

[12] To estimate the preindustrial atmospheric carbon distribution implied by our air-sea flux estimates, we apply the preindustrial air-sea CO_2 fluxes as boundary conditions in the atmospheric tracer transport models TM3 [*Heimann*, 1995] and GCTM [*Mahlman and Moxim 1978*]. In both models, the CO_2 concentrations in the northern hemisphere are lower than in the southern hemisphere (Figure 3c). While the sign of this interhemispheric difference is consistent with the idea of a large interhemispheric carbon transport loop, it is much smaller than the expected difference if a preindustrial transport of $\sim$1 Pg C yr^{-1} existed as suggested by *Keeling et al.* [1989].

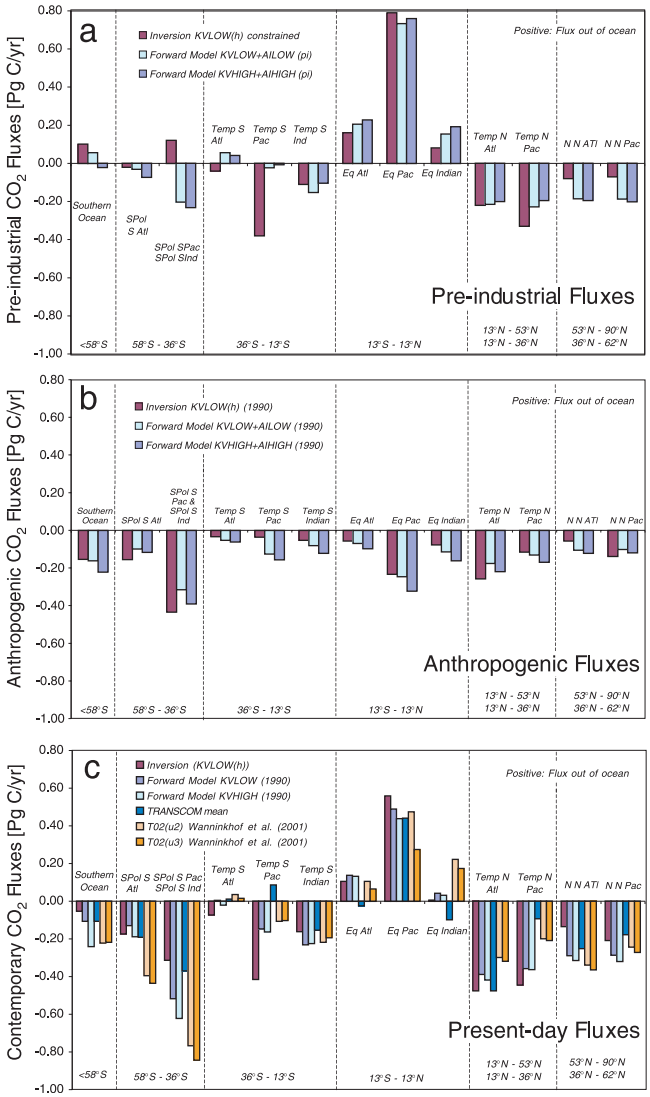

Figure 2. (a) Preindustrial air-sea flux estimates (Pg C yr^{-1}) for the ocean regions shown in Figure 1 as predicted by the inverse method (red) and forward simulations with two versions of the Princeton Ocean Biogeochemistry model (magenta and light blue). (b) same as in (a) except that anthropogenic CO_2 fluxes for the year 1990 are shown. (c) same as (a) except that the total contemporary fluxes (sum of preindustrial and anthropogenic perturbation) is compared with the air-sea CO_2 fluxes estimated using the pCO_2 climatology of *Takahashi et al.* [2002] (yellow: square dependence of gas exchange coefficient on wind speed, orange: cubic dependence [*Wanninkhof et al.*, 2001]) and the estimates from TransCom3 (blue).

[13] In order to assess our results further, we compare our contemporary flux estimates with the independent estimates of *Takahashi et al.* [2002] based on pCO_2 data, and the recent atmospheric CO_2 inversion intercomparison study TransCom3 [*Gurney et al.*, 2002]. The comparisons require that we add in our estimates of the air-sea fluxes for anthropogenic CO_2, which we summarize briefly. Our air-sea flux estimates of anthropogenic CO_2 are directed into the ocean everywhere (Figure 2b), totaling about 1.8 (±0.4) Pg C yr^{-1} for the year 1990, in very good agreement with a large range of other estimates [*Prentice et al.*, 2001]. Uptake is highest in the subpolar and equatorial latitudes and smallest in the subtropics. Present-day cross-equatorial transport is very small (−0.06 Pg C yr^{-1}) and directed to the north. The ocean south of 36°S account for more than 40% of the global uptake.

[14] While there is agreement in the main features between our present-day estimates and *Takahashi et al.* [2002] (Figure 2c) there is a striking difference in the southern hemisphere subpolar regions, where our inversions consistently find a much smaller sink, the same discrepancy as found by TransCom3 [*Gurney et al.*, 2002]. One reason for the difference may be biases in the pCO_2 climatology of *Takahashi et al.* [2002] caused by the sparse data coverage in this region.

[15] We next compare the atmospheric signals predicted using our estimate of the present air-sea CO_2 fluxes with those obtained with the air-sea flux estimates of *Keeling et al.* [1989], *Tans et al.* [1990], *Takahashi et al.* [2002] and TransCom3 [*Gurney et al.*, 2002] (Figure 3d). We carry out the atmospheric simulations in TM3 and GCTM. The difference between the atmospheric signal obtained from our air-sea flux is very large when compared with the distribution based on the air-sea flux estimates of *Keeling et al.* [1989] and also substantial compared to *Takahashi et al.* [2002], while there is quite good agreement when using the estimates of *Tans et al.* [1990] and TransCom3. The large difference of up to 3 ppm (GCTM) and 4 ppm (TM3) between the northern hemisphere atmospheric predictions based on our air-sea CO_2 flux estimates and those of *Keeling et al.* [1989] is not so surprising in light of the large cross-equatorial transport postulated by *Keeling et al.* [1989].

[16] Putting all the pieces together, our analysis suggests the following on the nature of the northern hemisphere sink. The small preindustrial gradient (−0.3 ppm CO_2 difference between Mauna Loa and South Pole) does not support the conclusions of *Keeling et al.* [1989], but rather the analysis

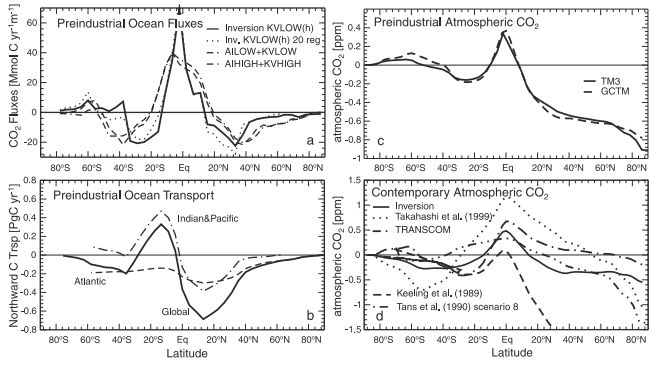

Figure 3. (a) Preindustrial air-sea CO_2 flux estimates from an inversion based on 13 regions (solid) and 20 regions (dotted) and as simulated with two versions of the Princeton Ocean biogeochemistry model [*Gnanadesikan et al.*, 2002]. (b) Preindustrial ocean transports implied by the ocean inversion estimates. (c) Zonal mean atmospheric preindustrial carbon distribution implied by the air-sea CO_2 flux ocean inversion estimates as simulated by the atmospheric tracer transport models TM3 and GCTM. (d) Present-day atmospheric CO_2 distributions caused by air-sea carbon fluxes as estimated by different studies simulated with TM3.

of *Fan et al.* [1999], who ascribed a portion of the atmospheric Mauna Loa South Pole CO_2 difference extrapolated to preindustrial times of −0.8 ppm to a misattribution of a contemporary tropical land source and Northern hemisphere land sink. As we find only a small pre-industrial cross-equatorial carbon transport and a contemporary atmospheric signal caused by air-sea fluxes close to *Tans et al.* [1990], our results support the interpretation of contemporary atmospheric data as indicating a large northern hemisphere net sink for anthropogenic carbon. The implications of our present-day ocean air-sea fluxes for the partitioning of the northern hemisphere carbon sink between land and ocean depends ultimately on the total magnitude of the northern hemisphere sink. If we use alternatively the estimates of *Keeling et al.* [1989] (2.9 Pg C yr^{-1} for 1984), *Tans et al.*'s [1990] scenario 5 to 8 (2.0 to 3.4 Pg C yr^{-1} for 1981–1987), or TransCom3 (3.3 Pg C yr^{-1} for 1992–1996), we find a northern hemisphere land sink of approximately 1.7 Pg C yr^{-1} which lies in between the estimates from the first two studies and is smaller than the TransCom3 estimate by an amount similar to estimates of riverine carbon transport to the oceans.

[17] We have explored the implications of ocean interior data on atmospheric CO_2 using inverse methods. In contrast to the application of this approach to atmospheric CO_2 it does not suffer from insufficient data coverage and thus no regularizations of the inverse calculations are needed. It has the great virtue of avoiding the use of a parameterization of gas exchange that remains highly uncertain. Further enhancements of the method will come from improved models and possibly the joint use of atmospheric and oceanic data.

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