SEPARATING THE NATURAL AND AIR-SEA FLUX OF CO_2: THE INDIAN OCEAN

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ABSTRACT

We estimate the natural and anthropogenic components of the air-sea flux of CO_2 in the Indian Ocean. The increase in atmospheric CO_2 driven by human activity has caused the air-sea CO_2 flux, to increase significantly over the industrial era. We estimate the flux in the year 1780 to be approximately 0.2Gt/yr, increasing by 0.26Gt/yr to 0.5Gt/yr in 2000. The estimate of the natural (preindustrial) flux is highly sensitive to uncertainties in modern-day CO_2 disequilibrium measurements. By contrast, the estimate of the anthropogenic flux is only weakly sensitive to these measurements. Our anthropogenic estimate is smaller than other studies due to the removal in our methodology of the widely made weak-mixing and constant-disequilibrium assumptions, both of which cause positive bias.

INTRODUCTION

The ocean plays a major role in the perturbed carbon cycle, but considerable uncertainties remain in the uptake and ocean inventory of anthropogenic carbon. The air-sea CO_2 flux prior to the industrial era is poorly known. The flux of carbon into the ocean is driven by the difference between the atmospheric CO_2 partial pressure ($pCO_{2,atm}$) and the oceanic partial pressure ($pCO_{2,ocn}$) that would be in equilibrium with the dissolved inorganic carbon (DIC) concentration of surface waters. Prior to the industrial era the globally-averaged ocean was in approximate equilibrium with the atmosphere, but locally, the air-sea disequilibrium, and consequently the flux, was large in many places, due to spatial variation of transport and biochemistry. Superposed on this background natural disequilibrium is the oceanic signal of increasing $pCO_{2,atm}$ due to human activity.

We apply to the Indian Ocean recently developed techniques to estimate anthropogenic and preindustrial carbon uptake that avoid the assumptions of weak mixing and constant air-sea disequilibrium made in many other studies. This extended abstract is an abbreviated version of two recent studies [*Hall et al.*, 2004; *Hall and Primeau*, 2004].

METHOD

The flux of anthropogenic CO_2 across a region of the ocean surface into an interior domain can be expressed as the rate of change of the anthropogenic carbon inventory in the domain. The inventory, in turn, can be expressed as the history of DIC in the surface waters and a domain-averaged transit-time distribution (TTD) that summarizes the surface-to-interior transport. Thus

$$\delta F(t) = V \frac{d}{dt} \int_{1780}^{t} dt' \, \delta DIC(t') \, \mathcal{G}(t - t') \tag{1}$$

where δ indicates anthropogenic quantities, V is the domain volume, 1780 is the assumed start date of the industrial era, and $\mathcal{G}$(t) is the domain-averaged TTD. We estimate $\mathcal{G}$(t) by using a two-parameter inverse Gaussian functional form constrained by CFC observations.

Application of (1) also requires knowledge of δDIC(t) in surface waters. Many studies have assumed that δDIC(t) faithfully tracks the atmospheric CO_2 perturbation, $\delta pCO_{2,atm}$(t) ("constant disequilibrium"). In order to avoid this assumption we exploit a second expression for the flux, namely the air-sea disequilibrium times an exchange coefficient. Equating the two flux expressions gives

$$kA\left(\delta pCO_{2,atm}(t) - \delta pCO_{2,ocn}(t)\right) = V\frac{d}{dt}\int_{1780}^{t} dt'\,\delta DIC(t')\,\mathcal{G}(t-t') \qquad (2)$$

where k is the exchange coefficient, and A is the surface area over which the air-sea exchange occurs (the outcrop of V). $pCO_{2,ocn}$ and DIC are related by the equilibrium inorganic chemistry system. We write $\delta DIC(t) = f(pCO_{2,ocn}(t)) - f(pCO_{2,ocn}(1780))$, which, combined with (2), provides an integral equation for $pCO_{2,ocn}(t)$. To solve the equation we first make an initial guess for $pCO_{2,ocn}(1780)$ and solve (2) numerically for $pCO_{2,ocn}(t)$. We repeat the procedure, iterating on $pCO_{2,ocn}(1780)$ until $pCO_{2,ocn}(1995)$ agrees with the direct observational estimates of *Takahashi et al.* [2002] within some tolerance. Once $pCO_{2,ocn}(t)$ is determined we can compute $\delta F(t)$ by either side of (2), as well as $F(1780) = pCO_{2,atm}(1780)$-$pCO_{2,ocn}(1780)$.

RESULTS

Figure 1 shows the CO_2 flux, F(t), into the Indian Ocean. We estimate a preindustrial flux of 0.2 Gt/yr, increasing by 0.26 Gt/yr to 0.5 Gt/yr in 2000. Also shown in Figure 1 is the sensitivity to the uncertainty in the *Takahashi et al* [2002] estimate of $pCO_{2,ocn}(1995)$. The absolute value of F(t) is highly sensitive: F(1780) varies from about 0.0 to 0.4 Gt/yr. In contrast, the anthropogenic component, 0.26Gt/yr, is insensitive to this uncertainty, varying only by 3%.The anthropogenic flux component $\delta F(2000)$=0.26Gt/yr is about 30% smaller than the estimate of *McNeil et al.* [2003], who assumed weak mixing and constant air-sea disequilibrium., both of which cause positive bias.

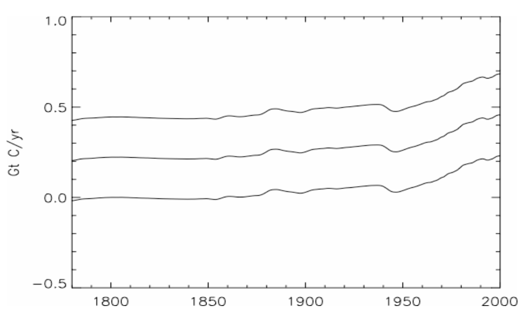

Fig.1. Total uptake of CO_4 by the Indian Ocean through the industrial era. The center curve is obtained using the $pCO_{2,ocn}(1995)$ of *Takahashi et al* [2002], while the upper (lower) curve is obtained by adding (subtracting) 5ppm uniformly to the Takahashi values.

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