The effects of buffer and temperature feedback on the oceanic uptake of CO_2

Chuixiang Yi,[1] Peng Gong, Ming Xu and Ye Qi

Department of ESPM, University of California, Berkeley, USA

Abstract. The feedback between climate and carbon cycle systems is critical to the prediction of future CO_2 concentration in the atmosphere and the capacity of the oceans to take up CO_2 from the atmosphere. We calculated the magnitudes of the potential feedback between the increase of atmospheric CO_2 concentration, the carbonate chemistry of the oceans (via a buffer factor), and the global temperature. We find that the magnitude of the buffer feedback depends strongly on the level of the dissolved inorganic carbon (DIC) in the oceans and increases rapidly with the increase of the atmospheric CO_2 concentration. The buffer feedback would result in an increase of 95 ppm in the atmospheric CO_2 concentration and a decrease of 236 GtC absorbed by the oceans from the atmosphere between year 2000 and 2100 under the Intergovernmental Panel on Climate Change (IPCC) scenario IS92e. By coupling our buffer feedback model with a global energy balance model, we find that global mean temperature increased 0.65 °C from 1860 to 1990, which agreed well with the recorded value of 0.61 °C. However, the ocean carbonate chemistry is quite insensitive to global temperature.

Introduction

The oceans are believed to be the largest long-term sink for atmospheric CO_2. A variety of models have been developed to estimate the amount of the oceanic uptake of CO_2 [e.g. *Oeschger et al.*, 1975; *Bacastow*, 1996]. The capacity of the oceans to take up CO_2 from the atmosphere is mainly controlled by a buffer mechanism described by a buffer factor, which is defined as

$$\xi = \frac{\partial \ln P_{CO_2}}{\partial \ln DIC} \qquad (1)$$

where P_{CO_2} is the CO_2 partial pressure in the oceanic mixed layer. Previous studies have shown that the value of the buffer factor empirically varies with DIC and temperature T, suggesting a nonlinearity in the oceanic carbon chemistry [e.g. *Sarmiento et al.*, 1992; *Joos et al.*, 1996]. However, few attempts have been made to quantify the feedback effects on oceanic CO_2 uptake and separate the buffer and temperature feedback from the total nonlinear feedback.

The buffer mechanism is actually the chemical equilibrium condition of the oceanic carbonate system as atmospheric CO_2 is added to the oceans. This condition can be attributed to the equilibrium relationship of P_{CO_2}, DIC and

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[1] Now at the Pennsylvania State University, University Park, USA.

T at a given level of borate and alkalinity. Few studies have been reported to model the relationship between the buffer factor and DIC and T due to the complexity of the ocean chemistry. *Sarmiento et al.* [1992] and *Joos et al.* [1996] obtained analytical relationships among P_{CO_2}, DIC and T, but the relationships were obtained using a narrow range of P_{CO_2} and T. *Sarmiento et al.* [1992] used $0 < \triangle P_{CO_2} < 200$ ppm in their model while *Joos et al.* [1996] only allowed T to vary between $17.7°C$ and $18.3°C$. In the present study we develop an analytical relationship between the buffer factor and DIC and T based on the GEOSECS data and incorporate it into the box-diffusion model [*Oeschger et al.*, 1975] to examine the effects of buffer feedback on global carbon dynamics between the atmosphere and the oceans. Even though further development of the box diffusion model was made such as the outcrop diffusion model and the HILDA model, the box diffusion model is still a basic model for evaluating oceanic CO_2 by *IPCC* [1992]. The HILDA model produces similar results as the box diffusion model and the outcrop diffusion model may overestimate the oceanic CO_2 uptake. The global average surface temperature, T, can be predicted by an energy balance model (EBM) [*Sellers*, 1969]. Greenhouse effects are also considered in the EBM [*Yi et al.*, 1994]. Therefore, the changes in atmospheric CO_2 concentration will affect the earth surface temperature which in turn will influence the oceanic carbonate chemistry through the buffer effect.

The objectives of this paper are to quantify the contributions of the nonlinear feedback to the oceanic uptake of CO_2 and the atmospheric CO_2 concentration and to separate the effects of buffer and temperature feedback from the total influences.

Nonlinear buffering

We used the program CO2SYS developed by *Lewis and Wallace* [1998] to calculate the equilibrium values of P_{CO_2}, DIC and T by assuming a salinity of 35 per mille and a constant alkalinity of 2.35 meq kg. A nonlinear relation of P_{CO_2} with DIC and T is obtained through the least squares method as the following (R^2=0.99)

$$P_{CO_2} = \exp(\theta_0 + \theta_1 T + \theta_2 T^2 + \theta_3 DIC + \theta_4 DIC^2$$
$$+ \theta_5 DIC^3 + \theta_6 TDIC), \qquad (2)$$

where $0 °C \leq T \leq 30 °C$ and 1.8 mol m^{-3} $\leq DIC \leq 2.3$ mol m^{-3}, and $\theta_0 = -40.5797$, θ_1=0.074487 °C, $\theta_2 = -0.000283$ (°C)^2, θ_3=63.69519 mol m^{-3}, $\theta_4 = -32.04292$ mol^2 m^{-6}, θ_5=5.761687 mol^3 m^{-9}, $\theta_6 = -0.010416$°C mol m^{-3}.

In the 3D space constructed by P_{CO_2}, DIC and T, (2) is an equilibrium surface by which the oceanic chemical buffering is determined. A constant buffer factor can be used only in a narrow range of DIC (Figure 1a). Meanwhile,
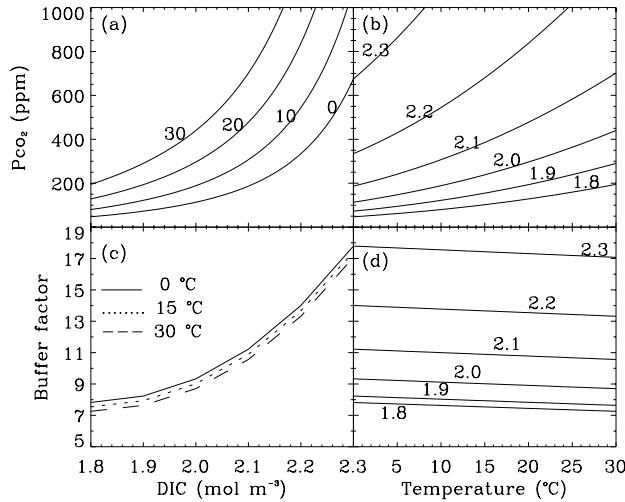
Figure 1. The equilibrium relation of CO$_2$ partial pressure P_{CO_2} versus (a) dissolved inorganic carbon DIC and (b) temperature T, and buffer factor versus (c) DIC and (d) T. The numbers in (a) represent T and in (b) and (d) DIC.

dP_{CO_2}/dT is not a constant, as has been used in many carbon cycle models. By combining (1) and (2), the buffer factor can be derived as follows.

$$\xi = \theta_3 DIC + 2\theta_4 DIC^2 + 3\theta_5 DIC^3 + \theta_6 T DIC. \quad (3)$$

Feedback model

With the equilibrium relation of P_{CO_2}, DIC and T given in (2), we established a dynamic model to explain the relation among them with the injection of anthropogenic CO$_2$ into the atmosphere. We chose global mean temperature T as a climate variable, and it is governed by the energy balance equation

$$C\frac{dT}{dt} = \frac{I_0}{4}(1-\alpha) - \varepsilon_s(1-\varepsilon_a)(a_1 + a_2 T), \quad (4)$$

where the planetary albedo α is a function of temperature T [*Sellers*, 1969] and the atmospheric effective emissivity

$$\varepsilon_a = \varepsilon_0 + \varepsilon_T T + \varepsilon_c \ln \rho_c \quad (5)$$

is related to temperature T and the atmospheric CO$_2$ concentration ϱ_c (ppm). The term $\varepsilon_c \ln \varrho_c$ in (5) is a greenhouse forcing, and $\varepsilon_c=0.0235$ derived by *Staley and Jurrica* [1972] from the theory of radiative transfer based on the observed data. The values of the other parameters in (4)-(5) can be found in Table 1.

The box diffusion model used considers the atmosphere, the mixed ocean surface layer and the terrestrial ecosystem each as a well mixed box coupled with a diffusive deep ocean. The governing equations can be written as follows

$$\frac{d\nu_a}{dt} = II + k_{am}(\xi\nu_m - \nu_a) - B\nu_a, \quad (6)$$

$$\frac{d\nu_m}{dt} = k_{ma}(\nu_a - \xi\nu_m) - D\nu_m, \quad (7)$$

where ν_a and ν_m denote the increases of the atmospheric CO$_2$ concentration and total DIC in surface water relative to their pre-industrial values, respectively. In (6) II is the

rate of anthropogenic CO$_2$ emissions relative to the preindustrial CO$_2$ in the atmosphere. It is the only input to our model. The feedback processes in the terrestrial ecosystem are neglected. The second term in (7) is responsible for CO$_2$ exchange between the mixed layer and the deep ocean. Following *Oeschger et al.* [1975] we use

$$D = \frac{\sqrt{\mu K}}{h_m} \tanh(h_d\sqrt{\mu/K}), \quad (8)$$

where $\mu=1/34.5$yr over the period from 1864 to 1999. For the emission scenario IS92e prescribed by *IPCC* [1992], μ can be estimated to be 0.0127 yr^{-1} and it is used over the period from 2000 to 2100. The results were insensitive to μ.

In our model there are two key factors for the feedback between atmospheric CO$_2$ and climate, the buffer factor ξ and the atmospheric effective emissivity ε_a. The anthropogenic CO$_2$ is first partitioned among the atmosphere, ocean and land using the box diffusion scheme in (6) and (7). The partition of CO$_2$ between the atmosphere and ocean is controlled by the buffer factor. It is not constant and depends instantaneously on $DIC = 2.053(1 + \nu_m)$. As seen from Figure 1c, the buffer factor increases with DIC, and this increase leads to a reduction of oceanic CO$_2$ uptake, i.e., the carbon cycle itself influences partition between the carbon reservoirs. We refer to this process as buffer feedback. In our model the change in atmospheric CO$_2$ concentration affects the temperature through the greenhouse forcing $\varepsilon_c \ln[292(1 + \nu_a)]$, and the change in temperature in turn affects the CO$_2$ partition between the atmosphere and the ocean. We refer to this process as the temperature feedback.

Results and Discussion

As seen from Figure 1c,d, the buffer factor ξ depends strongly on DIC and is insensitive to T. This conclusion differs from that of *Sundquist et al.* [1979], i.e. the variations of the buffer factor depend systematically on the sea surface temperature. The dependency of the buffer factor on the sea surface temperature was calculated by *Sundquist*

Table 1. Model parameters

Symbol	Meaning and value
C	Heat capacity, 10 W m^{-2} yr ($^\circ$C)$^{-1}$
I_0	Solar constant, 1360 W m^{-2}
a_1	Linear coefficient, 314.0 W m^{-2}
a_2	Linear coefficient, 4.6 W m^{-2} ($^\circ$C)$^{-1}$
α_0	Albedo coefficient, 0.34
ε_0	Emissivity coefficient, 0.1553
ε_s	Surface emissivity, 0.98
ε_T	Water vapor coefficient, 2.125×10^{-3} ($^\circ$C)$^{-3}$
ε_c	Greenhouse coefficient, 0.0235
N_a	Preindustrial CO$_2$ in atmosphere, 619.9 GtC
N_m	Preindustrial CO$_2$ in mixed layer, 668.8 GtC
k_{am}	Exchange coefficient, 1/7.8 yr
k_{ma}	Exchange coefficient, 1/8.4 yr
B	Biological coefficient, 6.5946×10^{-3} yr^{-1}
h_m	Mixed layer depth, 75 m
h_d	Deep ocean depth, 3725 m
μ	Emission exponential coefficient, 0.02899 yr^{-1}(1864-1996), 0.0127 yr^{-1}(IS92e)
K	Eddy diffusion coefficient, 4350 m^2 yr^{-1}

et al. [1979] holding P_{CO_2} as a constant. However, P_{CO_2}, *DIC* and T must meet the equilibrium relationship (2). As P_{CO_2} is kept unchanged *DIC* varies with T. Therefore, the variation of the buffer factor in Figure 1 of *Sundquist et al.* [1979] is caused largely by *DIC*, not by T.

The initial conditions of the feedback model were prescribed as 292 ppm of atmospheric CO$_2$ concentration, DIC_0=2.053 mol m^{-3}, $\nu_{m0} = \nu_{a0}$=0 and $T_0 = 15°$C. For the anthropogenic CO$_2$ production, the data compiled by *Marland et al.* [1999] from 1860 to 1996 were used. For the period of 1997 to 2100, the IS92e emission scenario [*IPCC*, 1992] was used as the model input. For the other emission scenarios, similar results were obtained but the result from IS92e is a bound of all possibilities as it is a scenario with the greatest changes. The simulations of atmospheric CO$_2$ concentration from 1860 to 1998 are shown in Figure 2a with a comparison to the observed values [*Keeling and Whoff*, 1999]. The observed atmospheric CO$_2$ concentration in 1998 is 366.7 ppm, 366.6 ppm is predicted by the feedback model and 364.4 ppm by the box diffusion model (ξ=9) with no feedback. The difference between the predictions with and without the feedback becomes more distinguishable as atmospheric CO$_2$ increases, and results from our feedback model are closer to the observed values. Even though the differences until 1998 are small, they indicate that the nonlinearity due to the feedback plays a more and more important role with the increased accumulation of anthropogenic CO$_2$ emissions. An increase of 0.65 °C in global mean temperature from 1860 to 1990 is predicted by the feedback model, which is in well agreement with the 0.61 °C reported by *IPCC* [1990]. The mean annual CO$_2$ flux into the ocean over the period from 1980 to 1989 is estimated as 1.73 GtC yr^{-1} (with feedback), quite a bit lower than 2.0 GtC yr^{-1} concluded by *IPCC* [1990]. If the buffer factor is kept constant ($\xi = 9$, without feedback), the model yields 1.91 GtC yr^{-1}.

In order to estimate the effects of feedback on the predictions of atmospheric CO$_2$ concentration we fixed ξ=9 in (6)-(7) and T= 15 °C in (4). Thus the box diffusion model becomes a linear model that does not consider feedback of either CO$_2$ or temperature. The results show that the total feedback causes an increase of approximately 98.1 ppm in atmospheric CO$_2$ concentration by 2100 and a cumulative reduction of 242.5 GtC in oceanic uptake of CO$_2$ between 1860 and 2100 (Figure 2b). Out of the total feedback, the buffer feedback causes an increase of 98.7 ppm in atmospheric CO$_2$ concentration and a cumulative reduction of 244.1 GtC in the oceans. The temperature feedback causes a decrease of 0.6 ppm in the atmosphere and an increase of 1.6 GtC in the oceans. This implies that the temperature feedback is negligible compared with the buffer feedback. The result also indicates that ocean carbonate chemistry is insensitive to global temperature.

Warming caused by the increase of atmospheric CO$_2$ has no substantial impact on the oceanic carbon cycle but may significantly influence terrestrial carbon sources and sinks locally and seasonally. Warming may enhance net primary production in the north as indicated by satellite remote sensing [*Myneni et al.*, 1997] but this increase may offset the decrease in the tropics. Increases in soil respiration by warming in winter and spring may offset increases of net ecosystem production in summer. On the global scale, the annual imbalance of terrestrial sources and sinks caused by
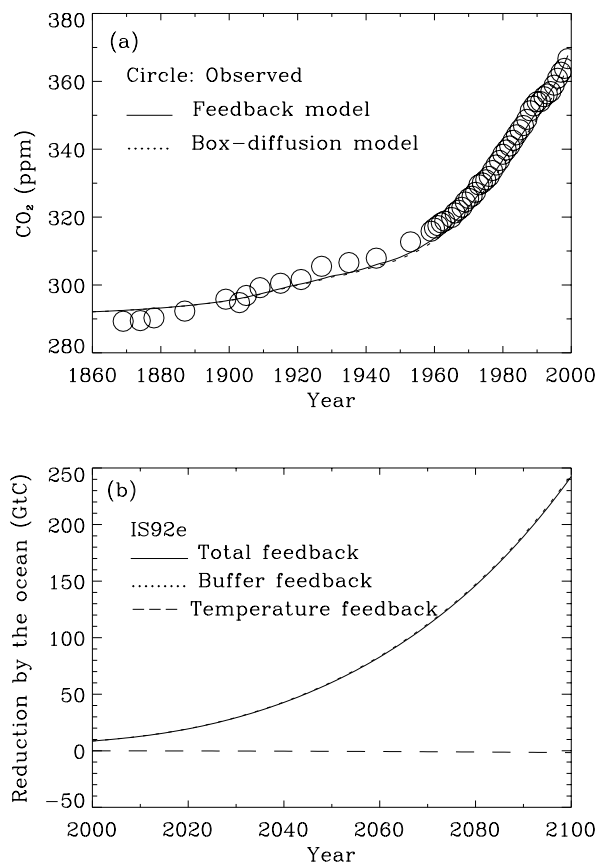
Figure 2. (a) Predictions of atmospheric CO$_2$ concentration by the models (with and without feedback) and comparison with the observation; (b) The cumulative reductions of oceanic uptake of CO$_2$ caused by the buffer, temperature and the total feedback.

climate change is quite small [*Cao and Woodward*, 1998]. Therefore, the ignored feedback between terrestrial carbon cycle and climate change may not significantly affect our conclusions.

Conclusions

(1) The capacity of the oceanic uptake of anthropogenic CO$_2$ emission will be greatly reduced due to nonlinear buffer feedback between 2000 and 2100 under IPCC scenario IS92e.

(2) Ocean carbonate chemistry is insensitive to global temperature.

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C. Yi, Department of Meteorology, the Pennsylvania State University, 416 Walker Building, University Park, PA 16802, USA.

P. Gong, M. Xu, and Y. Qi, Department of Environmental Science, Policy and Management, University of California, Berkeley, CA 94720, USA. (e-mail: cxyi@essc.psu.edu)