A Two-Dimensional Zonally Averaged Ocean Carbon Cycle Model

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Received October 10, 1996; revised December 31, 1997

ABSTRACT

An ocean carbon cycle model driven by a constant flow field produced by a two-dimensional thermohaline circulation model is developed. Assuming that the biogenic carbon in the oceans is in a dynamic equilibrium, the inorganic carbon cycle is investigated. Before the oceanic uptake of CO_2 is carried out, the investigation of ^{14}C distributions in the oceans, including natural and bomb-produced ^{14}C, is conducted by using different values of the exchange coefficient of CO_2 for different flow fields (different vertical diffusivities) to test the performance of the model. The suitable values of the exchange coefficient and vertical diffusivities are chosen for the carbon cycle model. Under the forcing of given preindustrial atmospheric CO_2 concentration of 280 ppmv, the carbon cycle model is integrated for seven thousand years to reach a steady state. For the human perturbation, two methods including the prescribed atmospheric pCO_2 and prescribed industrial emissions are used in this work. The results from the prescribed atmospheric pCO_2 show that the oceans take up 36% of carbon dioxide released by human activities for the period of 1980-1989, while the results from the prescribed industrial emission rates show that the oceans take up 34% of carbon dioxide emitted by industrial sources for the same period. By using the simple method of subtracting industrial emission rate from the total atmosphere+ocean accumulating rate, it can be deduced that before industrial revolution a non-industrial source exists, while after 1940 an extra sink is needed, and that a total non-industrial source of 45 GtC is obtained for the period of 1790-1990.

Key words: Ocean carbon cycle model, Thermohaline circulation; Radiocarbon, Non-industrial sources

I. INTRODUCTION

Since industrialization the carbon dioxide content in the atmosphere has been increasing. If all carbon dioxide emitted by human activities remained in the atmosphere, including the emission of fossil fuel combustion, cement production and land-use change, the concentration of atmospheric carbon dioxide would be increased by 60%. It has been generally considered that the oceans have taken up about half of anthropogenic emissions of carbon dioxide. There are three main reservoirs for the calculation of transport of anthropogenic carbon, including the atmosphere, the oceans and terrestrial ecosystems. Although the ocean carbon cycle model has been studied for over 30 years, the development of global carbon cycle model has been constrained. In addition to the difficulty of evaluating the role of terrestrial biosphere, one of the reasons is that the present ocean carbon cycle model is not sufficiently satisfactory.

The ocean carbon cycle model can be mainly divided into the box models with the simple description of oceanic mixing and flow movement, and the circulation model based on the ocean dynamics. In the early one-dimensional upwelling-diffusion models, natural and bomb-produced ^{14}C were often used to calibrate the models so that some observed features can be reproduced. However, the mechanism of formation of the thermohaline circulation

cannot exactly be described in this kind of models. Toggweiler et al. (1989a, 1989b) used American GFDL three-dimensional ocean circulation model to study the distribution of ^{14}C and ventilation processes in the oceans. Maier-Reimer and Hasselmann (1987) used German Hamburg three-dimensional ocean circulation model to study the carbon cycle including ^{14}C and gave the results of oceanic uptake of CO_2. Sarmiento et al. (1992) used GFDL 3D model to study the anthropogenic carbon cycle in the oceans in terms of perturbation method, and compared their results with those from box model and Hamburg model. Because of different circulation models, the results from two 3D models have some differences, and also have some differences with the observed data. Stocker et al. (1994) used a zonally averaged global ocean circulation model to investigate the oceanic role to anthropogenic emissions of CO_2 in terms of industrial emission sources. Here we use a two-dimensional thermohaline circulation model to further study the problem in terms of two different forcing methods including the prescribed atmospheric pCO_2 and the prescribed industrial emission rates, which will provide the basis for the investigation of the role of the terrestrial ecosystem in the global carbon cycle. This work does not consider the sources and sinks related to the marine biology, marine sedimentation, and the river runoff. Maire-Reimer and Hasselmann (1987) gave three reasons of using this kind of basic inorganic carbon cycle model.

II. MODEL DESCRIPTION

The zonally-averaged two-dimensional thermohaline circulation model used in this work was originally developed by Wright and Stocker (1991). With some modifications, Jin and Zhang (1994) used the model to study the global warming induced by the increase of greenhouse gases in the atmosphere. The circulation model and carbon cycle model are briefly described as follows.

1. *Circulation Model*

The zonally-averaged thermohaline circulation model equations are

$$\frac{\partial A}{\partial t}+\frac{\partial}{\partial x}\left(\frac{cvA}{a}\right)+\frac{\partial}{\partial z}(wA)=\frac{\partial}{\partial x}\left(\frac{c^2K_h}{a^2}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial A}{\partial z}\right), \tag{1}$$

$$\rho=\rho_*-\alpha(T-T_0)+\beta(S-S_0), \tag{2}$$

$$\frac{\partial P}{\partial z}=-\rho g, \tag{3}$$

$$-2x\Omega v=-\frac{1}{\rho_* ac}\frac{\Delta P}{\Delta\lambda}+\frac{\partial}{\partial z}\left(K_A\frac{\partial u}{\partial z}\right), \tag{4}$$

$$2x\Omega u=-\frac{c}{\rho_* a}\frac{\Delta P}{\Delta x}+\frac{\partial}{\partial z}\left(K_A\frac{\partial v}{\partial z}\right), \tag{5}$$

$$\frac{\partial}{\partial x}(cv)+\frac{\partial}{\partial z}(aw)=0, \tag{6}$$

where all quantities are zonal averages; A indicates temperature T or salinity S; φ is latitude, $x=\sin\varphi$, $c=\cos\varphi$, and z is the vertical coordinate, increasing from $-H$ at the bottom to 0 at the surface; Ω and a are the angular velocity and the radius of the Earth; P and ρ denote pressure and density, respectively; u,v and w indicate horizontal and vertical velocity components, respectively; K_A is the vertical eddy viscosity coefficient; K_h and K_z represent horizontal and

vertical diffusivities, respectively. In the linear equation of state, the values of parameters are taken as: $\rho_* = 1027.79$ kg m^{-3}, $T_0 = 4$°C, $S_0 = 35$ psu, $\alpha = 0.223$ kg m^{-3}K^{-1} and $\beta = 0.796$ kg m^{-3}psu^{-1}. The reader is referred to Jin and Zhang (1994) for the detailed description of other parameters and parameterization treatment.

Model ocean consists of the Atlantic, the Pacific, and the Southern Ocean that connects the Atlantic and the Pacific. The Atlantic has an east–west angular extent of 60 degrees and south–north extent from 55°S to 80°N, while the Pacific 120 degrees and from 55°S to 50°N. The extent of 55°S to 68°S is the Southern Ocean. The water depth H is taken to be 5000 m. Both the Atlantic and the Pacific have 14 water columns with the same area in the horizontal spatial discreteness, and the Southern Ocean is treated as a single water column. Ten unequally spatial vertical layers are adopted. The northern and bottom boundaries are solid, while the southern boundary is an exchange interface. Variables on the meridional plane are arranged based on the Arakawa–C grid.

The circulation model is forced by relaxing the simulated temperature and salinity to the prescribed values at the surface, and integrated over 4000 years from the ocean with a homogeneous and motionless state to reach the quasi-steady state. Results are used in the carbon cycle model.

2. *Carbon Cycle Model*

The transport, distribution and storage of inorganic carbon are considered in the model. The ocean is divided into the upper layer and the internal ocean. The upper layer is considered to exchange with the atmosphere. The atmosphere is treated as a well-mixed box approximately. The exchange of carbon dioxide between the atmosphere and the oceans is driven by their concentration (or partial pressure) difference. Therefore, the air–sea exchange flux of CO_2 can be written as follows:

$$F_{gc} = S_g \Delta pCO_2 = S_g (pCO_2(o) - pCO_2(a)), \tag{7}$$

where $pCO_2(a)$ and $pCO_2(\theta)$ indicate the partial pressure of carbon dioxide in the atmosphere and the oceans, respectively, in which $pCO_2(o)$ can be calculated from the known temperature, salinity, total alkalinity and total carbon dioxide (TC) (Xu, 1992) and $pCO_2(a)$ is calculated on the basis of prescribed mixing ratio (ppmv) of atmospheric CO_2 by assuming the water vapor saturated air at the temperature of the surface water; S_g is the exchange coefficient of CO_2 at the air–sea interface.

Total carbon dioxide (TC) in the oceans satisfies an advection–diffusion equation:

$$\frac{\partial TC}{\partial t} + \frac{\partial}{\partial x}\left(\frac{cvTC}{a}\right) + \frac{\partial}{\partial z}(wTC) = \frac{\partial}{\partial x}\left(\frac{c^2 K_h}{a^2}\frac{\partial TC}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial TC}{\partial z}\right), \tag{8}$$

where TC is zonally averaged.

III. RESULTS AND DISCUSSION

1. *Natural and Bomb-Produced* ^{14}C

Before the oceanic uptake of anthropogenic CO_2 is studied, the distributions of natural and bomb-produced ^{14}C in the oceans have been respectively investigated by using the different values of S_g and K_z to see the performance of the circulation model. Since the dynamical equilibrium was reached between the atmosphere and the oceans before human

perturbation, the content of atmospheric ^{14}C can be used to force the oceans to obtain the steady state distribution of ^{14}C in the oceans. Under the forcing of atmospheric $\Delta^{14}C = 0‰$, the influence of different values of S_g on the distributions of ^{14}C in the oceans has been extensively discussed for different flow fields (different vertical diffusivities). Through the comparison of simulated results with the observations, it has been found that S_g from Broecker et al.'s equation (Broecker et al., 1985) and K_z from the following equation are reasonably good, that is,

$$S_g = 0.0127(W - 2.0), \tag{9}$$

where W is wind speed at the height of 10 m above sea surface in units of m / s, and annual mean wind speed data used here are taken from Broecker et al. (1985), and

$$K_z = 1.0 \times 10^{-4} + \frac{9.5 \times 10^{-5}}{\pi} \arctan(4.0 \times 10^{-3}(Z - 1000)), \tag{10}$$

where Z is the depth in units of meter, so K_z increases with depth from 0.6 cm^2 / s at the surface to 1.45 cm^2 / s at the bottom.

Using the interaction of observed atmospheric ^{14}C with the oceans and the steady state results obtained by above parameter values, the model was integrated with respect to time to study the penetration of bomb-produced ^{14}C into the oceans. Except for a large difference at the surface layer of the Atlantic, there is a good agreement between the simulated results and the GEOSECS observations. The difference at the surface layer is probably due to the model driven by thermohaline circulation. Wind stress likely has some influences on the surface layer. This further demonstrates that the present model is reasonable for the investigation of oceanic uptake of CO_2. The detailed results and discussion for ^{14}C distributions in the oceans can be found in Xu et al. (1997).

2. *Steady State Results*

For the simulation of steady state TC, there is an important variable, that is, pre-perturbation pCO_2 in the atmosphere. Ice core measurements show that during 1000 years before 1800, atmospheric CO_2 remained at the level of 280 ppmv with the variation of no more than 10 ppmv (Siegenthaler et al., 1988). Therefore, atmospheric pCO_2 of 280 ppmv is used to force the carbon cycle model. The model is integrated for 7000 years to obtain a steady state. Fig. 1 shows the difference of pCO_2 between the atmosphere and the oceans. Negative values indicate the transfer of CO_2 from the atmosphere to the oceans, opposite for the positive values. It is obvious that the North Atlantic is an important sink of atmospheric CO_2, and the Southern Ocean is also a sink while the tropics and most areas in the subtropics are the sources.

3. *Perturbation*

For the investigation of oceanic uptake of CO_2, there are two ways including the prescribed atmospheric pCO_2 as a force and the prescribed industrial sources with the combined model of the atmosphere and the oceans. Here the year of 1790 is defined as the steady state time, that is, initial time for the perturbation run. The steady state TC is used as an initial condition.

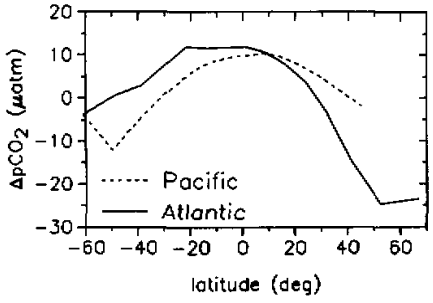

Fig. 1. Variations of ΔpCO_2 ($pCO_2(o) - pCO_2(a)$) with latitudes at steady state.

3.1 Prescribed atmospheric pCO_2

The atmospheric pCO_2 for 1790–1958 was from the Fig. 1 of Sarmiento et al. (1992). The curve was plotted according to the spline fit to Siple ice core data. After 1958, Mauna Loa annual mean data were directly used, in which atmospheric pCO_2 in 1990 was 353 ppmv. The absent data were supplemented in terms of linear interpolation and extrapolation. The prescribed atmospheric pCO_2 for 1800–1990 is shown in Fig. 2.

Fig. 3 shows the variations of $\delta\Delta pCO_2$ (relative to steady state, ΔpCO_2 (1990)–ΔpCO_2 (1790), where $\Delta pCO_2 = pCO_2(o) - pCO_2(a)$) with latitude. Negative values indicate that the oceans are a sink of atmospheric CO_2. Compared with Fig. 1, it can be known that the source in the tropics and subtropics is decreased while the sink in the mid- and high latitudes is increased. Fig. 4 shows the penetration of anthropogenic CO_2 into the oceans. It can be seen that CO_2 mainly enters the oceans from the high latitudes of the North Atlantic. Because of strong convection, CO_2 almost penetrates into the bottom of the oceans. In the Southern Ocean it reaches the depth of 2000 m, whereas in the other areas it reaches the depth of only about 1000 m.

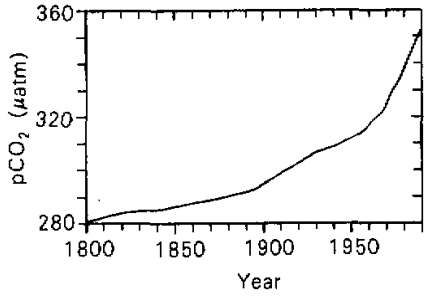

Fig. 2. Atmospheric pCO_2 for 1800–1990.

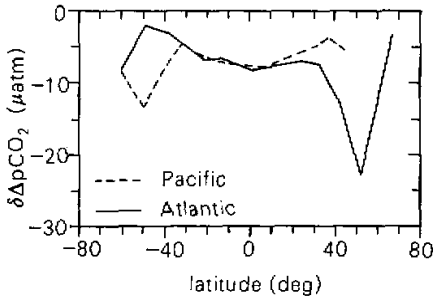

Fig. 3. Variations of $\delta\Delta pCO_2$ (ΔpCO_2(1990) − ΔpCO_2(1790)) with latitudes.

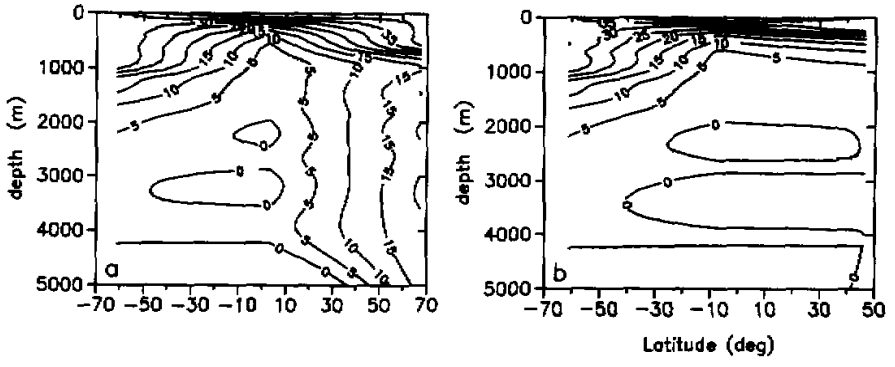

Fig. 4. Distributions of excess carbon (TC(1990)−TC(1790)) in the Atlantic (a) and the Pacific (b) in units of μmol / kg.

Because the model does not include the Indian Ocean, the model ocean is much smaller than the real world ocean. Here the weighted flux of CO_2 from the Atlantic and the Pacific is used to represent the one for the global ocean to calculate the oceanic uptake of CO_2. An area of $3.52 \times 10^{14} m^2$ for the global ocean is used. Table 1 lists the comparison of the modelled results with those from other models (Sarmiento et al., 1992). Here the airborne fraction is defined as the ratio of the amount ($\sum X_a$) of the accumulated CO_2 in the atmosphere to $\sum X_a$ plus the amount ($\sum X_o$) of oceanic uptake of CO_2 for the period of t_1 to t_2, that is:

$$AF(t_1 - t_2) = \frac{\sum_{t_1}^{t_2} X_a}{\sum_{t_1}^{t_2} (X_a + X_o)}, \tag{11}$$

where X_a and X_o indicate the accumulating rate of CO_2 in the atmosphere and the rate of

oceanic uptake of CO_2, respectively. It can be seen from Table 1 that our model takes up less CO_2 than the box model and 3D model. The differences with BD and 3D are about 16% and 4% for the period 1790–1980, respectively. Except that wind-driven circulation has likely an impact on the oceanic uptake of atmospheric CO_2, the extrapolation of flux for the calculation of global uptake probably causes some differences. The Southern Ocean may be underestimated because the model treats it as only one single column.

Table 1. Airborne Fraction (Prescribed Atmospheric pCO_2)

Model / Period	BD	3D(GFDL)	This work
1790–1980	0.510	0.582	0.607
1959–1983	0.581	0.642	0.656
1980–1989		0.63	0.644

3.2 Industrial sources

Industrial sources from 1860 to 1984 were based on the energy consumption (coal, oil and gas) and cement production (Rotty, 1981; Rotty, 1987), while from 1790 to 1860 the sources were obtained by extrapolation of emission data of 1800–1900 in terms of exponential function. The data from 1984 to 1990 were from the IPCC report (Houghton et al., 1992). The industrial sources (S_i) for 1800–1990 are shown in Fig. 5.

Using the industrial emission rate of CO_2 in Fig. 5 and a coupled model of the atmosphere and the oceans, the model is integrated from the steady state. Fig. 6 shows the evolution of simulated atmospheric pCO_2. It can be seen from the comparison of Fig. 6 with Fig. 3 that the values of simulated pCO_2 are smaller than the observations, indicating that the CO_2 in the atmosphere is not merely from industrial sources. The marginal airborne fraction AF_m is defined by the ratio of the amount of the accumulated CO_2 in the atmosphere to the amount of

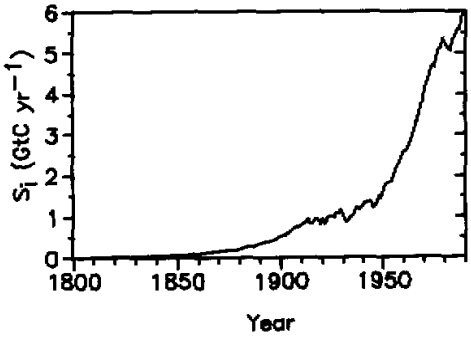

Fig. 5. Industrial sources for 1800–1990.

industrial emissions for the period of t_1 to t_2, that is:

$$AF_m(t_1 - t_2) = \frac{\sum_{t_1}^{t_2} X_a}{\sum_{t_1} S_i}. \tag{12}$$

AF_m in Fig. 6 (relative to 1790, that is, $t_1 = 1790$) decreases with time from the value of 0.84 in 1800. This is due to delay effect of oceanic uptake of atmospheric CO_2. About 50 years later, the variation of AF_m is relatively small, between 0.71 and 0.64. In 1990, AF_m is 0.66. Table 2 gives the results and those from other models (Sarmiento et al., 1992) for the different periods of time. The so-called observation in Table 2 is the ratio of the increase in observed atmospheric CO_2 from Fig. 2 to the industrial sources. The observation value larger than the simulated one demonstrates that the CO_2 in the atmosphere is not only from the industrial sources, which means that a non-industrial source exists. On the contrary, an extra sink is needed. The results in Table 2 are quite similar to those in Table 1. The airborne fraction from our model is larger than that from the box model or 3D model (GFDL), indicating that our model has the smaller capability of taking up CO_2 than other models. In fact, the differences with 3D model (GFDL) and box model are about 4% and 8% (1790–1980), respectively, which are not large. This further confirms the important role of thermohaline circulation in the ocean.

Table 2. Marginal Airborne Fraction (Prescribed Industrial Sources)

Model / Period	BD	3D(GFDL)	3D(Humburg)	This work	Observation
1790–1980	0.612	0.638		0.662	0.775
1955–1975	0.66	0.672	0.68	0.679	0.566
1959–1983	0.625	0.666		0.677	0.578
1980–1989				0.658	0.558

In general, the airborne fraction is always lower in simulations forced by a prescribed atmospheric CO_2 than that in simulations forced by a fossil fuel CO_2. The main explanation is due to the early biospheric input (Sarmiento et al., 1992). Effect is much larger in BD models

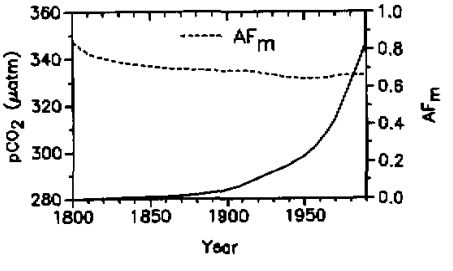

Fig. 6. Variations of simulated atmospheric pCO_2 and marginal airborne fraction with time.

than in 3D models and our models. For the period 1959–1983, the difference between using the prescribed atmospheric CO_2 and using the industrial sources in our models is 0.055, compared with 0.102 for BD models and 0.056 for 3D models. It has been explained that the difference in behavior between BD and 3D models results from the simplification of BD models (Sarmiento et al., 1992). The difference between our models and 3D models is very small, which implies that the 2D thermohaline circulation models can basically maintain the most important features of 3D models.

4. *Estimate of Non–Industrial Sources*

It can be known from the above discussion that an additional sink or source is needed besides the industrial source and oceanic sink in order to balance carbon budget. To identify the evolution of this sink or source, here a simple calculation is made, that is, the atmospheric CO_2 increase+oceanic uptake (from the results of prescribed atmospheric pCO_2)–industrial emission. The results are shown in Fig. 7. It can be seen from Fig. 7 that pre–1860 a small non–industrial source (S_b) exists, and that at about the end of nineteenth century and early in the twentieth century the emission reaches a maximum, whereas after 1940 the curve fluctuates strongly and displays negative and positive values, a main reason of which is referred to the data used in the model. Atmospheric CO_2 increases quickly and interannual variation is large but the data used are annual mean values. In general, after 1940, the increase of CO_2 in the atmosphere plus oceanic uptake is smaller than industrial emissions. This demonstrates that after 1940 there is an unknown sink for the present carbon cycle model. For the period of 1790–1990, on the average, besides the industrial sources, it needs a net non–industrial source with a total carbon amount of 45 GtC (10^{15} g of carbon). It is generally considered that this non–industrial source is the terrestrial ecosystem, which is mainly due to the land–use change. These conclusions are basically in agreement with those from the box model by Siegenthaler and Oeschger (1987) and from 3D–OGCM by Sarmiento et al. (1992).

From 1958 to 1990, there was a good record of atmospheric CO_2. For this period, atmospheric increase plus oceanic uptake is smaller than the industrial emission. In order to explain this industrial source, the oceans would take up more carbon dioxide or there would be another sink with an equivalent order. Furthermore, the emissions from the land–use change must be explained. Therefore, the atmospheric increase plus oceanic uptake cannot explain the carbon amount from the industrial source and land–use change. In order to balance the

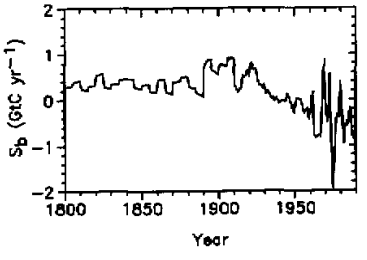

Fig. 7. Variation of non–industrial sources with time.

global carbon budget, besides the oceanic sink, an additional sink is needed, which is so called "missing sink". At present, it is generally thought that the "missing sink" is in the terrestrial ecosystem. The likely explanation includes the carbon dioxide fertilization, nitrogen fertilization and climatic feedback, which still needs to be further studied.

IV. CONCLUSION

Using a zonally averaged thermohaline circulation model, it is found that the depth-dependent vertical diffusivity and the exchange coefficient from Broecker et al.'s equation can make the simulated results of natural and bomb-produced ^{14}C reflect the observations well by several numerical experiments. The chosen values of parameters are used for the simulation of the oceanic uptake of carbon dioxide emitted by human activities. The steady state of *TC* is obtained by a forcing of atmospheric pCO_2 of 280 ppmv in 1790. The results from the prescribed atmospheric pCO_2 show that the oceans take up 36% of anthropogenic emission of carbon dioxide for the period of 1980-1989 while the results from the prescribed industrial emission rate show a marginal airborne fraction of 0.66 in 1990. Some results from the comparison of these two methods are helpful for the further investigation of the role of terrestrial ecosystems in the global carbon cycle.

REFERENCES

Broecker, W. S., T. -H. Peng, G. Ostlund and M. Stuiver (1985), The distribution of bomb radiocarbon in the ocean, *J. Geophys. Res.*, **90:** 6953-6970.

Houghton, J. T., B. A. Callander and S. K. Varney (1992), *Climate Change*, The Supplement Report to the IPCC Scientific Assessment, Cambridge Univ. Press, New York, 200pp.

Jin Xiangze and Zhang Xuehong (1994), Simulation of thermohaline circulation and global warming, (I) Simulation of zonal mean thermohaline circulation, *Scientia Atmospherica Sinica*, **18:** Sup, 769-779.

Maier-Reimer, E. and K. Hasselmann (1987), Transport and storage of CO_2 in the ocean—(an inorganic ocean-circulation carbon cycle model, *Cli. Dyn.*, **2:** 63-90.

Rotty, R. M. (1981), Data for global CO_2 production from fossil fuels and cement, *In: Carbon Cycle Modelling*, SCOPE 16 (ed. B. Bolin). Chichester. Wiley, 121-125.

Rotty, R. M. (1987), A look at the 1983 CO_2 emissions from fossil fuels (with preliminary data from 1984), *Tellus*, **39B:** 203-208.

Sarmiento, J. L., J. C. Orr, and U. Siegenthaler (1992), A perturbation simulation of CO_2 uptake in an ocean general circulation model. *J. Geophys. Res.*, **97:** 3621-3645.

Siegenthaler, U., H. Friedli, H. Loetscher et al. (1988), Stable-isotope ratios and concentration of CO_2 in air from polar ice cores, *Ann. Glacial.*, **10:** 1-6.

Siegenthaler, U. and H. Oeschger (1987), Biospheric CO_2 emissions during the past 200 years reconstructed by deconvolution of ice core data, *Tellus*, **39B:** 140-154.

Stocker, T. S., W. S. Broecker, and D. G. Wright (1994), Carbon uptake experiments with a zonally-averaged global ocean circulation model, *Tellus*, **46B:** 103-122.

Toggweiler, J. R., K. Dixon and K. Bryan (1989a), Simulations of radiocarbon in a coarse-resolution world ocean model, I, Steady state, pre-bomb distributions, *J. Geophys. Res*, **94:** 8217-8242.

Toggweiler, J. R., K. Dixon and K. Bryan (1989b), Simulations of radiocarbon in a coarse-resolution world ocean model, 2, Distribution of bomb-produced ^{14}C, *J. Geophys. Res.*, **94:** 8243-8264.

Wright, D. G. and T. F. Stocker (1991), A zonally averaged ocean model for the thermohaline circulation, *J. Phys. Oceanogr.*, **12:** 1713-1739.

Xu Yongfu (1992), The buffer capability of the ocean to increasing CO_2, *Adv. Atmos. Sci.*, **9:** 501-510.

Xu Yongfu, Wang Mingxing and Jin Xiangze (1997), A study of the distribution of ^{14}C in the ocean using a two-dimensional thermohaline circulation model, *Chinese J. Atmos. Sci.*, **21:** 31-40.