A Two-Dimensional Zonally Averaged Ocean Carbon Cycle Model

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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 CO₂ is carried out, the investigation of ¹⁴C distributions in the oceans, including natural and bomb-produced ¹⁴C, is conducted by using different values of the exchange coefficient of CO₂ 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 CO₂ 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 pCO₂ and prescribed industrial emissions are used in this work. The results from the prescribed atmospheric pCO₂ 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 ¹⁴C 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

$$\frac{\partial A}{\partial t} + \frac{\partial}{\partial x} \left( \frac{c v A}{a} \right) + \frac{\partial}{\partial z} (w A) = \frac{\partial}{\partial x} \left( \frac{c^2 K_h \frac{\partial A}{\partial x}}{a^2} \right) + \frac{\partial}{\partial z} (K_z \frac{\partial A}{\partial z}),$$

(1)

$$\rho = \rho_0 - \alpha(T - T_0) + \beta(S - S_0),$$

(2)

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

(3)

$$-2x\Omega v = -\frac{1}{\rho_0} \frac{\Delta P}{ac \Delta \lambda} + \frac{\partial}{\partial z} (K_A \frac{\partial u}{\partial z}),$$

(4)

$$2x\Omega u = -\frac{c}{\rho_0} \frac{\Delta P}{a \Delta x} + \frac{\partial}{\partial z} (K_A \frac{\partial v}{\partial z}),$$

(5)

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

(6)

where all quantities are zonal averages; $A$ indicates temperature $T$ or salinity $S$; $\varphi$ 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; $\Omega$ and $a$ are the angular velocity and the radius of the Earth; $P$ and $\rho$ 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