A CARBON CYCLE MODEL WITH LATITUDE DEPENDENCE

J. A. VIECELLI and H. W. ELLSAESSER
Lawrence Livermore Laboratory, University of California, Livermore, California 94550, U.S.A.
and
J. E. BURT
University of Illinois at Urbana Champaign, Urbana, Illinois 61801, U.S.A.

Abstract. A two-dimensional carbon cycle model is divided into three zones representing equatorial, middle and high latitude regions. The three zones are coupled together by a deep ocean meridional convective cell and atmospheric transport terms. The model is applied to the calculation of the dispersion of radiocarbon and tritium from nuclear weapons tests, to the calculation of the atmospheric record of bomb radiocarbon and to the calculation of the Mauna Loa record of atmospheric CO2. Calibrating on the basis of the Northern hemisphere bomb test data yields a model which has approximately twice the CO2 ocean uptake of the one-dimension box diffusion models calibrated on the basis of deep water equilibrium carbon 14.

1. Introduction

Several time-dependent carbon budget models have been developed for use as forecasting aids to predict future atmospheric carbon dioxide concentrations (Keeling, 1973; Oeschger et al., 1975, Hoffert et al., 1979). There are differences among the models, but basically they are box or one space dimensional models with varying degrees of resolution in the vertical and none in the horizontal. They compute only global average quantities and cannot predict effects which might result from latitudinal differences in exchange and eddy mixing rates.

Present estimates of carbon dioxide uptake by the oceans are based on the one-dimensional carbon budget model studies, especially the work of Oeschger et al. (1975). They subjected their model to a number of independent checks. Among the criteria used were the requirements that: the model when run to an equilibrium steady state should yield the pre-nuclear test global average concentration of 14C in the deep ocean waters; the model should reproduce the Suess effect; and the model should match the historical record of atmospheric CO2 concentration. The first test essentially specifies a deep water global average eddy diffusion coefficient because the one-dimensional model 14C depth profile is determined by a balance between radioactive decay loss and resupply of 14C by downward diffusion from the surface. The global average vertical eddy diffusion coefficient determined in this way is approximately 4000 m² yr⁻¹. Local eddy diffusion coefficient values can be expected to vary substantially from the model determined global average

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value. For example the Atlantic GEOSECS data (Ostlund et al., 1974, 1976), indicate that radiocarbon and tritium from nuclear weapons tests have rapidly penetrated to great depths in the regions of bottom water formation in the North Atlantic. Similarly, downward transport of $^{14}$C and tritium in equatorial waters is much slower than would be the case if the global average eddy diffusion applied.

The Oeschger et al. model is able to reproduce the historical record of atmospheric CO$_2$ concentration quite well, using the above global average eddy diffusion value, provided the only CO$_2$ source considered is the past combustion of fossil fuels. Recently however it has been suggested, on the basis of $^{13}$C/$^{12}$C analysis of tree ring samples, that the rapid expansion of cultivated lands during the 19th and early 20th centuries released as much CO$_2$ as did the burning of fossil fuel (Stuiver, 1978). The one dimensional global average diffusion models when run with this additional source of CO$_2$ predict substantially higher values of atmospheric CO$_2$ than are observed. Thus if agricultural development has been an equal or greater source of CO$_2$ than fossil fuel combustion then there is implied either some as yet unknown sink of CO$_2$ or else the ocean uptake is greater than estimated by the one-dimensional eddy diffusion models (Broecker, 1979).

There is a possibility that additional carbon dioxide uptake by the oceans could be resulting from latitude or depth variations in eddy mixing combined with the slow convective overturning of the deep waters and that the short run thermocline uptake rate is much greater than one would estimate on the basis of long term deep water $^{14}$C concentrations. In the following this possibility is examined by means of a crude latitude dependent model. It is essentially three vertical Oeschger et al. (1975) type models, representing respectively equatorial, middle, and high latitude zones, coupled together by horizontal transport terms. This model is calibrated by comparing with data from the GEOSECS program (Ostlund et al., 1974, 1976, 1979, 1980). It is then used to examine the effects of latitudinal variation in the thermocline eddy mixing rate and the effects of convective overturning on CO$_2$ uptake.

2. Description of the Model

The computational convection-diffusion model is fully two-dimensional and has the capability for approximating a zonally averaged meridional overturning flow in an ocean basin. It can have as many mesh zones in either the horizontal or vertical dimension as computer memory and time availability permit. In the present study we have limited the model calibration to the Northern hemisphere and three horizontal zones with uniform properties representing equatorial, middle and high latitudes. In terms of the GEOSECS data these zones cover respectively 0-20N, 20-40N, and greater than 40N latitude. The area of each of these zones is chosen so as to give the same fraction of total surface area as occupied by the oceans within that zone. Due to the latitude distribution of land the areas of the three zones within the Northern hemisphere are approximately in the ratio 5:3:2. These three regions represent physical groupings of GEOSECS derived properties. The actual computations are carried out with an ocean mesh of 22 vertical and 10 horizontal points which provide more numerical resolution. This mesh is also used to obtain