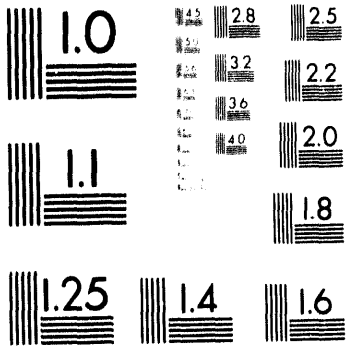
1.0
1.1
1.25
1.4
1.6
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2.0
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3.2
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4.0

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Simulation of the Carbon Cycle in the Oceans

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This project is being carried out in collaboration with J. L. Sarmiento, Princeton University.

Siegenthaler and Sarmiento (1993) prepared a review article on Atmospheric Carbon Dioxide and the Ocean. We conclude that the average oceanic uptake of anthropogenic CO_2, as determined from four different ocean models and normalized to the observed mean penetration depth of bomb-^{14}C (analogue to anthropogenic CO_2), is 2.0±0.5 GtC/yr (decade 1980-89). This oceanic uptake plus the year-to-year growth of the atmospheric CO_2 content together are less by 1.8±1.2 GtC/yr than the estimated anthropogenic CO_2 emissions from fossil fuels and land use. As there is no conceivable extra carbon sink in the ocean of the required magnitude, there seems to be a sink on land, for instance due to stimulation of vegetation growth by CO_2 and by anthropogenic nitrogen compounds. The oceanic uptake of 2.0±0.5 GtC/yr obtained from ocean carbon cycle models is significantly larger than the estimate by Tans et al. (1990) of <1 GtC/yr, obtained from an analysis of the atmospheric north-south CO_2 gradient and northern hemisphere oceanic pCO_2 measurements. The estimate of Tans et al. must be revised for several processes they neglected (river input of carbon as an extra pathway for transport from the atmosphere via continents to the ocean; a thermal skin effect at the very surface of the ocean, causing a systematic overestimate of the surface pCO_2 by the measurements using the temperature at several m depth; and a north-to-south atmospheric transport of carbon in the form of CO).

F. Joos, a post-doctoral scientist working on this project, and U. Siegenthaler have analyzed tracer simulations obtained from a 3-D ocean model in terms of the transport parameterizations used in simple models. The purpose is to better understand how well simple models, which are easy to run and are widely used, can represent oceanic fluxes as determined from a 3-D model. In box-type ocean models, like HILDA (High-latitude exchange/Diffusion-Advection model), designed for the simulation of large-scale tracer distributions, vertical transport is (partly)

represented as eddy diffusion. Typical values required for the vertical eddy diffusivity are of the order 1 $cm^2\ s^{-1}$ (several 1000 $m^2\ yr^{-1}$). On the other hand, eddy diffusivities estimated experimentally or theoretically for local mixing processes in the thermocline, such as breaking of internal waves or double-diffusion, are generally smaller by 1-3 orders of magnitude. This apparent discrepancy has puzzled many oceanographers. In order to get insight into this problem, Siegenthaler and Joos (1992) analyzed the results of simulations obtained using the Princeton 3-D Ocean General Circulation model. They calculated apparent eddy diffusivities from the velocity and steady-state ^{14}C fields obtained by Toggweiler et al. (1989). In this past year, we have extended the analysis to results concerning the invasion of anthropogenic CO_2 and of bomb-produced ^{14}C into the ocean's interior. In this analysis, the transport is considered as a combination of averaged advection velocity and (vertical) eddy diffusion, such that the ^{14}C distribution simulated by the 3-D ocean model can be reproduced with the derived transport parameters. Mathematically, the turbulent flux, given by the covariance of the fluctuations (= deviations from the space averages) of the vertical velocity component, v_z', and ^{14}C concentration, c', is set equal to a vertical diffusive flux:

$$\overline{v_z'\ c'} = -K_{app}\,\partial\,\overline{c}\,/\,\partial z$$

from which the apparent diffusivity K_{app} can be determined. The overbar denotes the horizontal averaging which, in order to correspond to the HILDA model regions (low and high latitudes) is carried out over large oceanic regions. In the top 1000 m, i.e. in the thermocline, the K_{app} values found in this way are in the range 2000-4000 $m^2\ yr^{-1}$, well comparable to the eddy diffusivities determined for HILDA and other ocean models (e.g. the box-diffusion model of Oeschger et al., 1975), but significantly larger than the values found for describing local mixing in the ocean. The reason for the difference is that the K_{app} values do not represent local turbulence, e.g. breaking internal waves, but rather large-scale mixing by the thermohaline and the wind-driven circulation. Thus, there is no real discrepancy between the different magnitudes of the vertical eddy diffusivities; they just describe processes on very different space scales.

The calculated K_{app} values are higher in the top few 100 m than in lower layers, reflecting more vigorous circulation near the surface than at greater depth. This supports qualitatively the depth-dependence of the eddy diffusivity obtained when calibrating the HILDA model using the distributions of bomb-produced as well as natural ^{14}C (Siegenthaler and Joos, 1992). It is, however, in contrast to the

finding that the eddy diffusivity, as derived locally from tracer fluxes, is related inversely to the stability of the water column (Sarmiento et al., 1976), from which one might expect the eddy diffusivity to be higher in the deep ocean than in the thermocline. The reason is again that the apparent K values were derived for very large oceanic regions and thus reflect the large-scale circulation rather than local stability.

The K_{app} values obtained for steady-state ^{14}C and for anthropogenic CO_2 agree generally well, and the latter do not markedly depend on the time chosen for the analysis. If these diffusivities are introduced into a (purely 1-D) box-diffusion model, then the oceanic CO_2 uptake calculated with this model is similar, but slightly higher than if calculated with the 3-D model from which the K_{app} values were derived. The reason for the slight difference has probably to do with different ocean surface areas of the two models, but also with the fact that in a 1-D model, the different behaviour of low- and high-latitude oceans with respect to vertical mixing is not accounted for. The apparent eddy diffusivities for bomb-^{14}C depend on the time for which the analysis is carried out. This indicates that for a tracer exhibiting rapid variations of the concentration, and therefore of the vertical oceanic gradient, oceanic mixing is not perfectly represented by eddy diffusion. We are presently studying the results and will present them at the 4th International CO_2 Conference at Carqueiranne, France, in September 1993.

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