[RADIOCARBON, VOL 31, NO. 3, 1989, P 503–509]

ATMOSPHERIC CO_2 EXCHANGE WITH THE BIOSPHERE AND THE OCEAN

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ABSTRACT. We model the exchange of carbon between the different reservoirs (atmosphere, ocean mixed layer, deep ocean and biosphere). The influence of the biosphere is investigated using two extreme assumptions: 1) no net biospheric effect and 2) biospheric uptake of CO_2 proportional to the atmospheric content of CO_2 and time-dependent deforestation. Observations of atmospheric CO_2 at Mauna Loa and the South Pole may be fit by both these assumptions.

INTRODUCTION

The atmospheric content of CO_2 has increased from a pre-industrial value of ~280 ppm to ~350 ppm today (Siegenthaler & Oeschger, 1987). The combustion of fossil fuel has long been regarded as the dominant source of excess CO_2. However, recent work indicates that the biosphere probably has played an important role with a net release of CO_2 back to the atmosphere (Woodwell, 1984; Siegenthaler & Oeschger, 1987). In contrast to fossil fuel input, well estimated by Rotty (1981), the historical input of CO_2 from the biosphere is rather difficult to calculate. Here we attempt to simulate the observations of Keeling at Mauna Loa and the South Pole under two extreme assumptions: 1) no net biospheric effect and 2) biospheric uptake of CO_2 proportional to the atmospheric content of CO_2 and time-dependent deforestation.

THE MODEL

In these calculations, we use a global double 4-box model, which contains atmosphere, ocean mixed layer, deep ocean and biosphere for both hemispheres (Fig 1). A double box model (Northern and Southern Hemispheres) is chosen because of the asymmetry in carbon reservoirs between the two hemispheres. We have assumed symmetry in the initial conditions, *ie,* the steady-state content of carbon in corresponding reservoirs is assumed to be equal in the two hemispheres. In addition to the usual exchange coefficients, we include a "deforestation factor", α, which regulates the flux of carbon from the biosphere to the atmosphere. As shown in Figure 1, CO_2 from combustion of fossil fuel enters the system through the northern atmosphere, since ca 96% of the fossil fuel is burned in the Northern Hemisphere.

Model equations and steady-state conditions for the exchange coefficients are shown in Appendix 1. The differential equations are solved with an explicit Runge-Kutta-method of order 8 (7).

Representing the biosphere by one box is an over-simplification because of its complex nature. A "mean exchange" is therefore modeled and the validity of the results is somewhat limited, especially on a long time

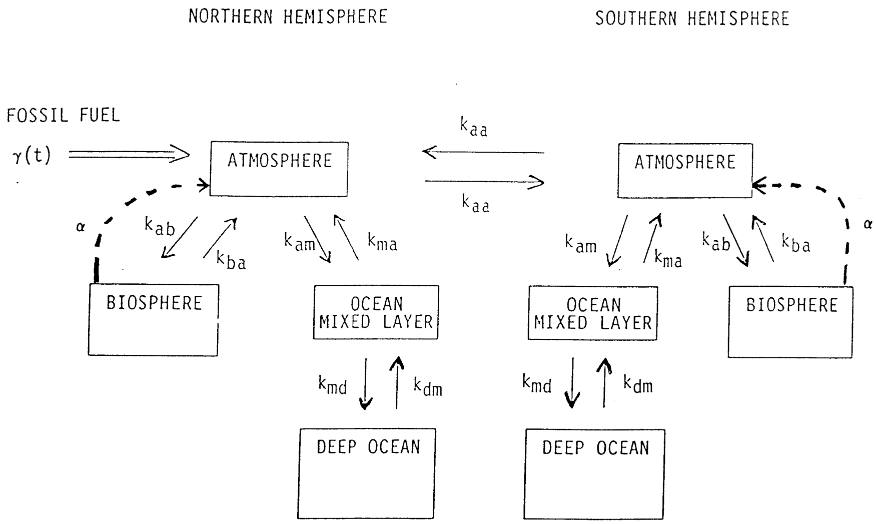

Fig 1. The global 8-box model, or "double" 4-box model

scale. The representation of the deep ocean by one well-mixed box has also been much disputed. More realistic models of carbon exchange in the ocean are available (Oeschger *et al,* 1975; Siegenthaler, 1983). However, a pure box model is useful for our study, as we are mainly interested in studying the biospheric influence on the atmospheric content of CO_2.

RESULTS AND DISCUSSION

The Combustion of Fossil Fuel

The input of fossil fuel from 1860 until today is estimated by Rotty (1981). In our calculations, we have fitted these data with an exponential, and the input function is given by $0.125\ e^{0.031t}$ (in units of 10^{15} grams of carbon), where the time t represents years after 1860.

1) No net biospheric effect. As an extreme case we assume that the net biospheric effect equals zero, *ie*, the flux of CO_2 between the atmosphere and the biosphere is constant at any time, no matter how much CO_2 there is in the atmosphere, and that biospheric regrowth equals deforestation. Fluxes between the atmosphere and the biosphere are then the same as the steady-state fluxes at any time. To model this, we simply let the exchange coefficients k_{ab} and k_{ba} be equal to zero (see Appendix 1). With an initial value of 290 ppm CO_2 in both the northern and the southern atmosphere, we achieve the model result shown in Figure 2, together with the observations of Keeling at Mauna Loa and the South Pole. The fit of the data are quite good, although the curves might be a bit steep. The parameter values are shown in Table 1.

TABLE 1

Parameter values for the calculations under the assumptions: 1) no net biospheric effect (Value 1) and 2) proportional uptake/linearly increasing deforestation factor α (Value 2). In α the time, t, is years after 1800, in $\gamma(t)$, t represents years after 1860.

Parameter	Symbol	Value 1	Value 2
Steady-state values of reservoir sizes (10^{15}g C):			
N atmosphere	N_{ao}	319	308
N biosphere	N_{bo}	1150	1150
N mixed layer	N_{mo}	335	335
N deep ocean	N_{do}	19,000	19,000
S atmosphere	S_{ao}	319	308
S biosphere	S_{bo}	1150	1150
S mixed layer	S_{mo}	335	335
S deep ocean	S_{do}	19,000	19,000
Exchange coefficients (yr^{-1}):	k_{am}	0.14	0.14
	k_{ma}	0.13	0.13
	k_{ab}	0	0.055
	k_{ba}	0	0.015
	k_{md}	0.14	0.14
	k_{dm}	0.0025	0.0025
	k_{aa}	1.00	1.00
Sea buffer factor:	ξ	10	10
Deforestation factor	α	0	0.003t/200
Input of fossil fuel (10^{15}gC):	$\gamma(t)$	$0.125e^{0.031t}$	$0.125e^{0.031t}$

2) Net biospheric effect not equal to zero. As another extreme case we assume that the CO_2 flux from the atmosphere to the biosphere is proportional to the atmospheric content of CO_2. This means that we include a "built-in" stimulated growth in our model. Which values to use for the exchange coefficients k_{ab} and k_{ba}, are not easily determined. As preliminary values, we choose $k_{ab} = 0.12$ and $k_{ba} = 0.033$, corresponding to mean residence times in the atmosphere and the biosphere of 8.3 and 30 years, respectively. Using the same parameters as before, we achieve that the model result for the atmospheric CO_2 content (the solid line in Figure 3) show a discrepancy of 10–15 ppm compared to the observations of Keeling. We now test the response of the model to changes in input parameters, *ie,* the fossil fuel input function and exchange coefficients.

Two exponential functions to model the fossil fuel input are now introduced. We use one exponential input until 1930 and another, somewhat steeper, after 1930. During the period of observations, the difference in atmospheric CO_2 for the two input functions is small, only 1–2 ppm. On a longer time scale, however, the difference becomes more important. We find that the input of fossil fuel required to fit the data is almost twice the

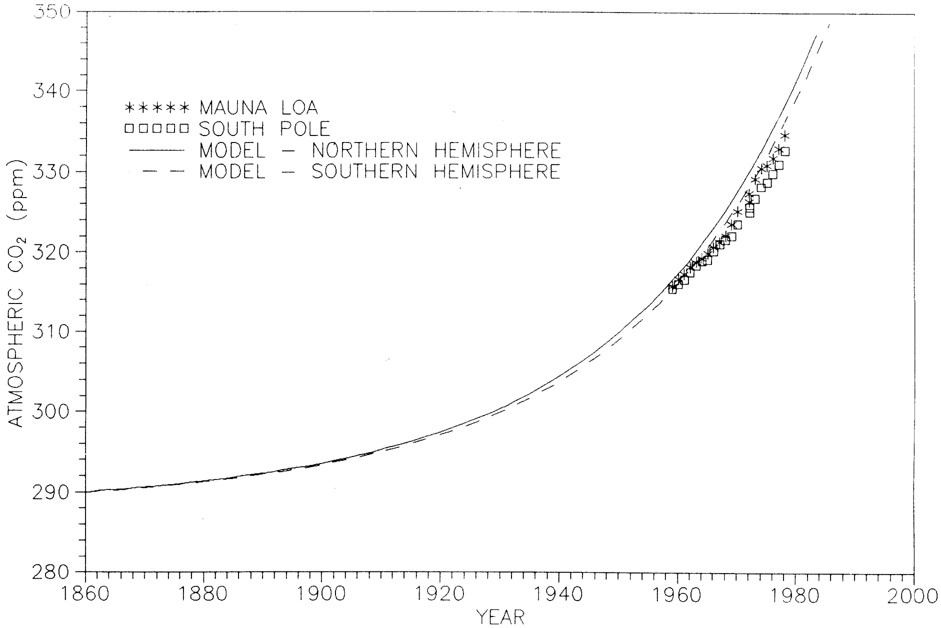

Fig 2. The model result of atmospheric CO_2 when the net biospheric effect is assumed to equal zero, compared with the observations at Mauna Loa and the South Pole

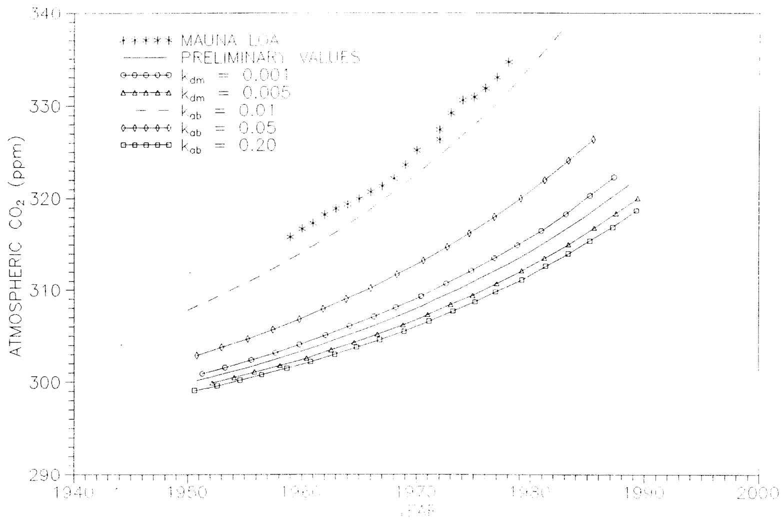

Fig 3. The model output for the atmospheric content of CO_2 on the Northern Hemisphere with some different values of the exchange coefficients. The preliminary values (solid line) are the parameter values listed in Table 1 (Value 1).

values given by Rotty. However, such an underestimation by Rotty of fossil fuel input is unlikely, so the reason for the discrepancy between the model results and the observations must be searched elsewhere.

Now we test model sensitivity to variations of the exchange coefficients. Variation of coefficient k_{ij} (i, j = a, b, m, d) implies a corresponding variation of k_{ji}, because k_{ij} and k_{ji} are connected through the steady-state conditions (see Appendix 1). First, varying the value of k_{am} (between the atmosphere and the ocean mixed layer) from 0.10 to 0.20 has very little effect (~1–2 ppm during the observation period). Figure 3 shows how the values of other coefficients affect the model result (Northern Hemisphere only). We see that varying k_{dm} (between deep ocean and mixed layer) from 0.001 to 0.005 has a similar small effect. Finally, by varying k_{ab} (between the atmosphere and the biosphere) from 0.20 to 0.05, we see that the effect is considerable, and when k_{ab} is reduced to 0.01 (=100 yr), the model result almost fits the data. Although this indicates that the biospheric exchange relates to the discrepancy, it is unlikely that the mean residence time of CO_2 in the atmosphere before biosphere uptake is 100 years.

Time-Dependent Deforestation

We now introduce factor α, which increases the back flux from the biosphere. A steady-state value of atmospheric CO_2 of 280 ppm is assumed according to ice-core data (Siegenthaler & Oeschger, 1987), and we let α increase linearly from zero in year 1800 to an arbitrary value of 0.003 in year 2000 (as several workers have suggested a net release of biospheric carbon already in the 19th century). Figure 4 shows a very good fit of the model to

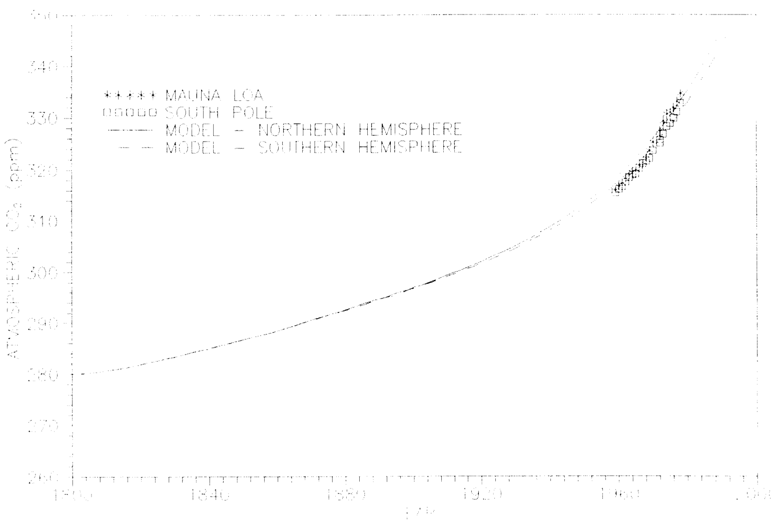

Fig 4. The model fit of the observations when biosphere uptake is assumed to be proportional to the atmospheric content of CO_2 and the deforestation factor α increases linearly from zero in year 1800

observations; the model results are also in good agreement with ice-core data. The parameter values are listed in Table 1.

The proportional uptake of CO_2 by the biosphere and the increasing "deforestation factor" α are concurrent effects. According to the model calculation, deforestation is dominant from 1800 to 1950, followed by a period of balance during the 1950s. This agrees well with a result obtained with a box-diffusion model by Siegenthaler and Oeschger (1987). After 1960 regrowth dominates, with unreasonable high increase after 1980, which is a consequence of the model design with the proportional uptake and the increasing "deforestation factor" α. The cumulative biospheric effect of the 200-yr model run seems to be small, *ie,* early deforestation is compensated by recent increasing regrowth. Further investigations must be done to check whether this dominating regrowth is real or only a model effect. The distribution of ^{14}C from previous nuclear tests in the atmosphere may give additional information about this problem.

SUMMARY AND CONCLUSION

We have demonstrated that our double 4-box model fits the observed increase of atmospheric CO_2 either by assuming no net biospheric effect or by combining biospheric growth proportional to the atmospheric CO_2 content coupled with deforestation. This might suggest that model constructs can omit the biosphere to simplify calculations. However, omitting the biosphere may not be correct for predictions of future atmospheric CO_2 content; although the cumulative biospheric effect in our 200-yr model run is small, there are, according to the model result, periods dominated by considerable deforestation or regrowth. Most likely, such periods will also occur in the future, and if the two effects are not balanced during the time of consideration, the results will be incorrect for a model with the biosphere omitted. Therefore, it is necessary to comprehend rates of deforestation and regrowth on a global scale today so that we can make a reliable representation of the biospheric influence on the carbon cycle.

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APPENDIX 1

Model equations and steady-state conditions: N_i and S_j denotes the northern and the southern reservoirs (i, j = a, b, m, d); k_{ij} is the exchange coefficient from reservoir i to reservoir j; $\gamma(t)$ is the input function for fossil fuel; α is the "deforestation factor" and ξ is the sea buffer factor. An index o in N_{ao}, N_{mo}, etc denotes the steady-state content in the actual reservoir.

The model equations

$$\frac{dN_a}{dt} = -(k_{am} + k_{ab} + k_{aa})N_a + (k_{ba} + \alpha)N_b + k_{ma}(N_{mo}(1 - \xi) + \xi N_m) + k_{aa}S_a + \gamma(t)$$

$$\frac{dN_b}{dt} = -(k_{ba} + \alpha)N_b + k_{ab}N_a$$

$$\frac{dN_m}{dt} = -(k_{ma}(N_{mo}(1 - \xi) + \xi N_m) - k_{md}N_m + k_{am}N_a + k_{dm}N_d$$

$$\frac{dN_d}{dt} = -k_{dm}N_d + k_{md}N_m$$

$$\frac{dS_a}{dt} = -(k_{am} + k_{ab} + k_{aa})S_a + (k_{ba} + \alpha)S_b + k_{ma}(S_{mo}(1 - \xi) + \xi S_m) + k_{aa}N_a$$

$$\frac{dS_b}{dt} = -(k_{ba} + \alpha)S_b + k_{ab}S_a$$

$$\frac{dS_m}{dt} = -(k_{ma}(S_{mo}(1 - \xi) + \xi S_m) - k_{md}S_m + k_{am}S_a + k_{dm}S_d$$

$$\frac{dS_d}{dt} = -k_{dm}S_d + k_{md}S_m$$

The steady-state conditions

$$k_{am}N_{ao} = k_{ma}N_{mo}$$

$$k_{ab}N_{ao} = k_{ba}N_{bo}$$

$$k_{md}N_{mo} = k_{dm}N_{do}$$

$$k_{aa}N_{ao} = k_{aa}S_{ao}$$

$$k_{am}S_{ao} = k_{ma}S_{mo}$$

$$k_{ab}S_{ao} = k_{ba}S_{bo}$$

$$k_{md}S_{mo} = k_{dm}S_{do}$$