MODELING PERTURBATIONS OF THE GLOBAL CARBON CYCLE*

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Abstract

It appears the level of atmospheric carbon dioxide may not have increased almost exponentially since the beginning of the industrial revolution as is often portrayed. Preliminary calculations indicate that atmospheric carbon dioxide may have reached a local maximum, comparable to present levels, in about the year 1910 as a response to the pioneer agricultural expansion of the late nineteenth century. The corroboration of this hypothesis may rest upon a comparison of the resultant greenhouse effect with temperature records of the recent past for the northern hemisphere.

1. Introduction

The combustion of fossil fuels causes an inevitable increase in the level of atmospheric carbon dioxide. Reliable measurements of this increase have been made at several points on earth during the last two decades [1]-[4]. If these trends continue, then reasonable concern exists for possible effects on world climate [5],[6]. To compound matters, it now appears that at least in the recent past the terrestrial biosphere has been a source of atmospheric carbon dioxide [7]-[9]. During the latter half of the last century, the expansion of primarily the new world population gave rise to massive clear-cutting of forests for lumber and the development of agriculture. Although deforestation continues today, mostly in the South American rain forest, its effects on atmospheric carbon dioxide are probably masked by the magnitude of the fossil fuel consumption rate [10],[11].

Historical records for agriculture and silviculture are probably not accurate enough to determine the magnitude of the biospheric flux, hence an indirect method has been devised [11]. Because the age of the fossil fuels is much greater than the half-life of C-14 fossil fuel carbon dioxide is completely lacking in this radioactive carbon isotope. Thus, during the industrial revolution, starting in about 1860, the effect of fossil fuel combustion can be measured by the C-14/C-12 ratio in tree rings [12]. The release of carbon dioxide from the biosphere has little effect on the C-14 atmospheric level, mainly because of the relatively small deficiency (about 2%) in the C-14/C-12 ratio for biomass as compared with the complete deficiency of fossil fuels. The photosynthesis process discriminates against the uptake of the stable isotope C-13, hence the fossil fuels and biomass have approximately the same deficiencies (about 3%) in the C-13/C-12 ratio. Therefore, if the effect of fossil fuels on the C-13/C-12 ratio in the atmosphere can be computed, then any deviation from the C-13/C-12 ratio measurements in tree rings can be accounted for by an atmospheric input from the terrestrial biosphere. Recently, Stuiver [11] and Wilson [13] have made such calculations, and both have found the cumulative carbon dioxide biospheric input to the atmosphere between 1860 and 1950 to be approximately equal to that of the fossil fuel input from 1860 to present--that is, about 120 billion metric tonnes (BMT) of carbon. Their analyses are essentially the same, being based upon a steady-state input/output material balance for atmospheric carbon. This letter presents results of a dynamic analysis based upon models for C-12, C-13 and C-14 which represent the storages and flows of carbon throughout the global cycle. Computer simulations of this carbon model indicate the integrated biospheric flux is a little greater than twice the integrated fossil fuel flux over the time span of 1860 to 1974.

2. Model Description

The model used to describe the movement and storage of the three isotopes of carbon is of the basic compartmental type [14],[15]. The global cycle for each isotope is represented by an eight compartment submodel consisting of slow and rapid biosphere, atmosphere, mixed layer and deep ocean, and oceanic food chain boxes (see Figure 1). These submodels combine the structure and mass balance estimates of Bolin [16] for the world oceans with the terrestrial biosphere of Baes, et al. [6]. Because the main concern of this analysis is with the terrestrial biosphere, the essential two box ocean model was adopted instead of the multilayered structure often used in oceanographic studies as an approximation of diffusive carbon movement below the thermocline. Also, an oceanic food chain was included, in spite of inherently low carbon storages, because the high turnovers present in such a

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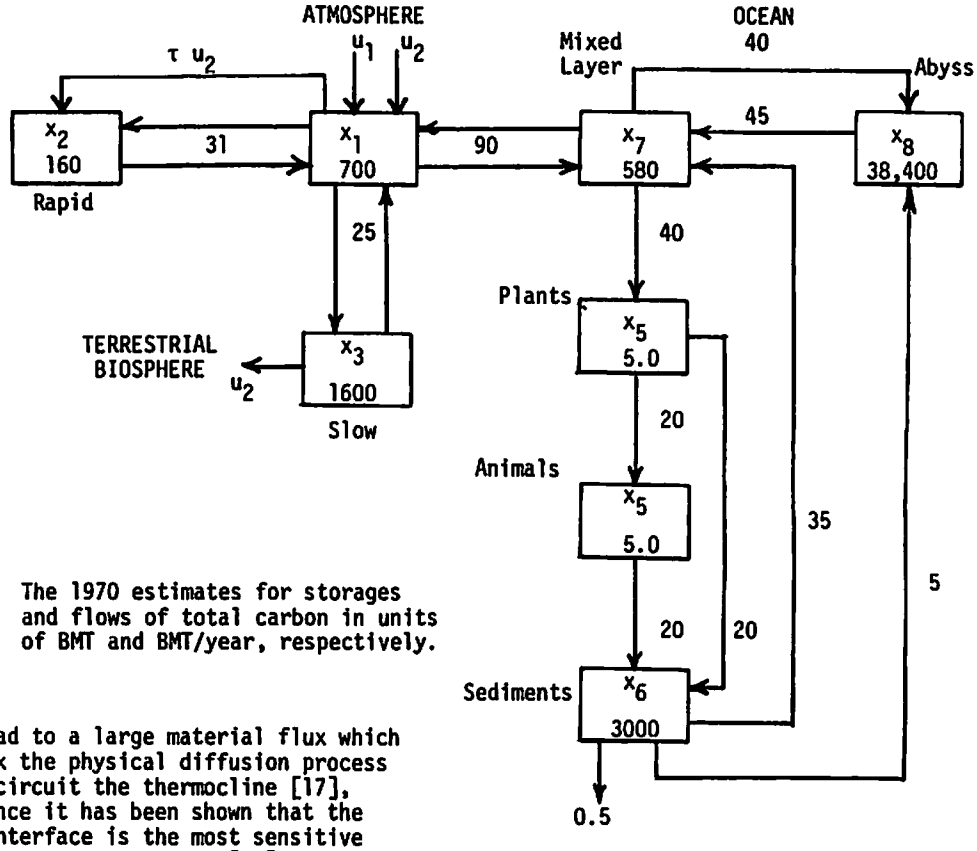

Figure 1. The 1970 estimates for storages and flows of total carbon in units of BMT and BMT/year, respectively.

subsystem could lead to a large material flux which would serve to mask the physical diffusion process and thereby short-circuit the thermocline [17], [18]. Finally, since it has been shown that the ocean/atmosphere interface is the most sensitive coupling in the model type described [15], the buffering of the carbonate system in seawater [19] was represented according to Oeschger et al. [20] by the parameter ξ which is adjusted to fit the model response to measured atmospheric carbon dioxide data.

For the C-12 submodel the compartmental storages and flows were taken from Bolin [16] and Baes et al [6]. The basic linear compartment model mass balance equations are:

$$\begin{aligned}
\dot{x}_1 &= u_1 + (1-\tau)u_2 - 0.208571\, x_1 + 0.19375\, x_2 \\
&\quad + 0.015625\, x_3 + 0.155172\, x_7 \\
\dot{x}_2 &= 0.044286\, x_1 - 0.19375\, x_2 - \tau\, u_2 \\
\dot{x}_3 &= 0.035714\, x_1 - 0.015625\, x_3 - u_2 \\
\dot{x}_4 &= 0.068965\, x_7 - 8.0\, x_4 \qquad (1) \\
\dot{x}_5 &= 4.0\, x_4 - 4.0\, x_5 \\
\dot{x}_6 &= 4.0\, x_4 + 4.0\, x_5 - 0.0135\, x_6 \\
\dot{x}_7 &= 0.128571\, x_1 + 0.011667\, x_6 + 0.001172\, x_8 \\
&\quad - 0.293103\, x_7 \\
\dot{x}_8 &= 0.001667\, x_6 + 0.068966\, x_7 - 0.001172\, x_8
\end{aligned}$$

where the rate coefficients are computed from the flux and storage data. For example, the rate of transfer from the slow terrestrial biosphere to the atmosphere is given by the ratio of the flow to the atmosphere divided by the slow biosphere storage:

$$a_{13} = 25/1600 = 0.15625 . \qquad (2)$$

The inputs to the model are prescribed by the historical time series for fossil fuel combustion (u_1) [21], and the yet to be determined biospheric contribution (u_2). The coefficient τ represents the conversion of slow biomass to rapid biomass which results from deforestation.

Since it has been shown that the ocean/atmosphere interface is the most sensitive coupling in the model type described [15], the buffering of the carbonate system in seawater [19] is represented according to Oeschger et al. [20] by the parameter ξ which is later adjusted to fit the model response to measured atmospheric carbon dioxide data. Thus, the atmospheric box equation in (1)

$$\dot{x}_1 = \ldots + a_{17}\, x_7, \qquad (3)$$

with $a_{17} = 0.155172$, is replaced by

$$\dot{x}_1 = \ldots + a_{17}\, x_7(0) + \xi\, a_{17}\, (x_7 - x_7(0)), \qquad (4)$$

as long as $x_7 \geq x_7(0)$. Equation (4) shows the buffering coefficient acting on the incremental increase in carbon level over that of the pre-industrial steady state. The additive buffering factor which appears in (4) is also subtracted from the mixed layer (ocean) box of (1) in order to maintain the mass balance.

Models for the stable isotope C-13 and the radioactive C-14 isotope can be constructed from (1). For C-14 a decay rate equal to $-\lambda z_i$ (i=1 to 8) where z_i is the C-14 level of compartment i, is added to each equation in (1). Also, since many physical and biological processes are known to discriminate against the heavier isotopes of carbon, the following fractionation coefficients, as defined in [14], are used to multiply the flows of Figure 1:

$\alpha_{21} = 0.964$ atmosphere to rapid biosphere

$\alpha_{31} = 0.964$ atmosphere to slow biosphere

$\alpha_{71} = 0.972$ atmosphere to mixed layer

$\alpha_{47} = 0.966$ mixed layer to plankton

$\alpha_{17} = 0.955$ mixed layer to atmosphere.

In a way similar to radiocarbon, the model for C-13 is obtained from that of C-12. However, the isotope C-13 is stable so no additional loss factor is used, but fractionation does take place. The variables y_i (i=1 to 8) define the C-13 concentration of the i-th compartment.

Estimates of fossil fuel usage for the years 1860 to 1974, obtained from Keeling [22] and Rotty [23], prescribe the C-12 model input u_1 as a time series. Since the half-life of C-14 is short compared with the age of the fossil fuels, no corresponding input to the C-14 submodel exists. For the C-13 submodel a time function, denoted by $\gamma(t)$, was constructed from the historical fossil fuel usage pattern which estimates the relative proportions of coal, petroleum, and natural gas combusted [24] in terms of the respective per mil C-13 deficiencies: -24 for coal, -28.5 for oil, and -41.5 for gas (see Fig. 2). The functions γ and u_1 then define the C-13 submodel fossil fuel input:

$$v_1 = \gamma(t)\, u_1 \qquad (5)$$

where the C-13/C-12 ratio given by $\gamma(t)$ is expressed in terms of the $\delta^{13}C$ standard defined by

$$\delta^{13}C \text{ per mil} = [R/R_s - 1]\, 1000 \qquad (6)$$

for which R is the C-13/C-12 ratio and $R_s = 0.01$.

Figure 2 defines the estimate of the C-13 content of combusted fossil fuels with respect to their historical use pattern. The change in relative defficiency beginning in the early part of this century and continuing to the present time indicates the shift from coal to petroleum and later to natural gas. This curve serves to resolve part of the defficiency in C-13 in tree ring data due to fossil fuel combustion.

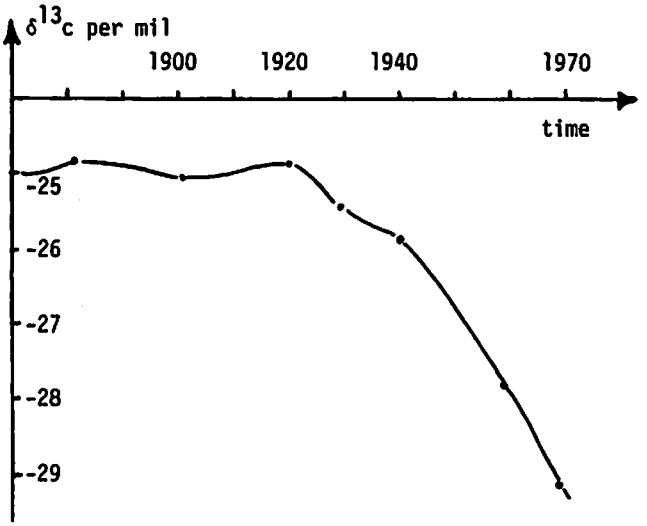

Figure 2. Estimated $\delta^{13}C$ for Combusted Fossil Fuels

Tree ring measurements [11],[13] for C-13 suggest a model input function u_2 for the deforestation rate to be of the form:

$$u_2 = (K/\sqrt{2\pi}\sigma)\, \exp[-(t-t_m)^2/2\sigma^2] \qquad (7)$$

where K is the total C-12 transferred from the terrestrial biosphere to the atmosphere, t_m=1890 is the year of peak rate of transfer, and σ=20 defines the inflection points. The biospheric inputs to the C-13 and C-14 submodels are obtained by multiplying u_2 by the instantaneous y_3/x_3 and z_3/x_3 ratios obtained from the model compartments representing slow terrestrial biomass. This provides a nonlinear coupling between submodels.

The initial conditions for the C-12 and C-13 models were obtained by taking the atmospheric C-12 level equal to 616 BMT and a y_1/x_1 ratio of $\delta^{13}C = -7$ per mil, and computing the other compartment levels assuming a preindustrial (before 1860) steady-state, i.e. all inputs null. For the C-14 submodel, the pre-industrial steady-state is established by a constant input of 8.96×10^3 g C-14/yr which represents the background level [21]. These calculations are valid for all model compartments except the slow terrestrial biosphere where deforestation pre-empts a steady-state. The initial slow biosphere level x_3 is assumed to be a model parameter adjusted to fit the model response to atmospheric carbon dioxide data.

3. Model Simulation

The carbon model described has been simulated on a digital computer, and the time series output of the simulation for atmospheric carbon has been compared with the Mauna Loa data for various values of the model parameters ξ, K and x_3. The best least squares fit of the model output to the Mauna Loa data is provided by K = 260 BMT for the total

carbon transferred from the biosphere to the atmosphere, x_3 = 1515 BMT for the 1860 value of the slow terrestrial biosphere compartment and ξ = 10.0 for the ocean buffering coefficient. The model output for atmospheric C-12 levels, shown in Figure 3, illustrates a deforestation induced peak level in 1908 of a magnitude of 704 BMT. This 1908 level compares with estimates of the 1974 level of approximately 700 BMT of carbon. An extrapolated exponential curve fit to measured data is shown (dashed curve) for reference purposes only. Up until now many investigators (for example see [11],[25] and [26]) have presumed a monotonic, almost exponential increase in atmospheric carbon dioxide from the onset of the industrial era until the present time, however the model described shows an alternative time history.

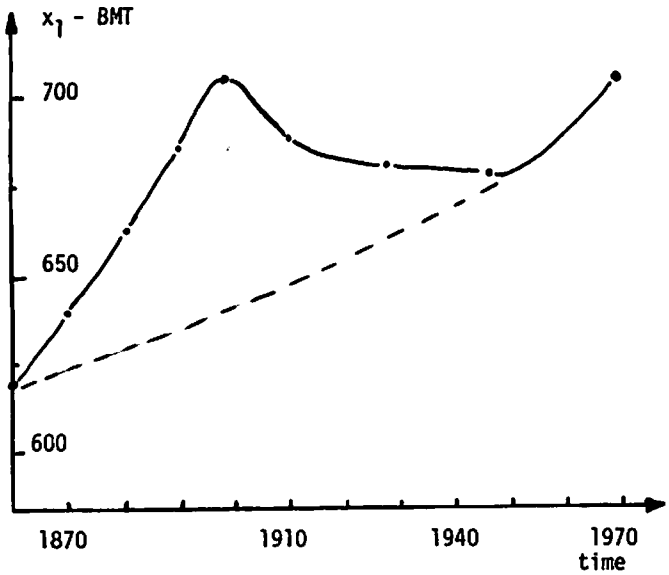

Figure 3. Simulated atmospheric carbon level (solid curve) showing a peak level of 704 BMT in 1908 as a response to deforestation. An extrapolated exponential curve fit to measured data is shown (dashed curve) for reference purposes only.

It should be noted that the model simulation of C-13 for the slow terrestrial biosphere compartment closely resembles the tree ring data measured by Stuiver [11] and Wilson [13]. Indeed, the change of about 0.7 to 0.8 of the per mil ratio of (6) before 1900 to after 1900 agrees remarkably well with the tree ring data. However, it is hard to discern whether the decline in the simulated C-13 values after 1960, which also appears in the measured data presented by Stuiver and Wilson, is due to increased use of natural gas (see Figure 2) or continued deforestation. Since the carbon added to the atmosphere during the pioneer agricultural expansion takes place early in the twentieth century when the fossil fuel use pattern is stable with respect to C-13, the postulated indirect fit of u_2 to the C-13 tree ring data discussed remains valid.

Finally, as an independent validation of the carbon model, the simulation produced a $\Delta^{14}C$ value for the atmosphere of 36.4 per mil in 1950 which agrees with other data and simulation [14]. Also, the model responded to nuclear weapons testing as a C-14 input and produced a $\Delta^{14}C$ equal to 80.4 percent in 1964 which is close to the value sited by Stuiver [11].

4. Conclusion

Through the greenhouse effect, increased levels of atmospheric carbon dioxide are believed to give rise to increased surface temperatures for the earth. The surface temperature trend for the northern hemisphere from 1870 to 1970, presented by Brinkmann [27], shows a pronounced increase in temperature of about 0.5°C starting in 1920, peaking in 1940, and declining slowly after that. Both the incremental temperature rise and the time scale of action may correlate well with the atmospheric carbon dioxide level predicted by the model output presented in this paper. However, climate is a very complicated natural phenomenon with a variability that may be larger than any possible anthropogenic changes in this century.

It is interesting to note that using a temperature rise of 3°C for a doubling of atmospheric carbon dioxide, as computed by Manabe and Wetherald [28], the resultant temperature rise due to the model output of Figure 3 is 0.6°C. If there is an artifact of the pioneer agricultural exapnsion in the temperature records for the earth, then it is important to make use of this phenomenon to calibrate predicting the future temperature the earth due to the combustion of fossil fuels.

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