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LETTERS TO THE EDITOR

Reservoir time-scales for anthropogenic CO_2 in the atmosphere: commentary

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The recent paper by O'Neill et al. (1994) raised some interesting technical points concerning transit times and turnover times in non-steady-state systems. However, it may have generated more confusion than light with respect to the lifetime of anthropogenic CO_2. The authors point out that the empirical atmospheric turnover time for CO_2 produced by fossil fuel burning and land use changes over the past 3 decades is about 30–40 years. This is several times shorter than the $\sim$120-year lifetime often quoted for models of oceanic CO_2 uptake (Watson et al., 1990, henceforth the "IPCC" report). Part of the discrepancy between the CO_2 turnover time and its calculated lifetime is caused by uptake of CO_2 by the terrestrial biosphere, which appears to be growing as a consequence of reforestation at northern hemisphere midlatitudes and perhaps because of CO_2 and nitrogen fertilization (Tans et al., 1990; Sarmiento et al., 1995). The remaining discrepancy is caused by the mathematical difference between turnover time and lifetime. Turnover time is defined as the atmospheric reservoir size divided by the instantaneous removal rate. Expected lifetime is the average removal time for a pulse of CO_2 injected instantaneously into the atmosphere. The two time-scales are the same for a pulse input if the decay is exponential (which is *not* the case for anthropogenic CO_2).

This much is fine: we agree with the technical points raised by O'Neill et al. But, the authors further suggest that the empirically-determined turnover time for CO_2 may be used to predict future atmospheric CO_2 concentrations and climate. This suggestion is worded cautiously: "The model-independent turnover time, as a measure of the short-term removal rate of CO_2, may prove useful as part of an alternative measure of global warming potentials." In the politically-charged global change arena, however, such a statement is tantamount to an invitation to use the low empirical turnover time of CO_2 as an estimate of its future atmospheric residence time. For example, Nierenburg (1995) cites their paper as evidence that the decay time of atmospheric CO_2 is much shorter than previously believed. He then goes on to conclude that the atmospheric CO_2 concentration will respond linearly to changes in emission rates and that the long-term effects of global warming may be much smaller than previously anticipated.

We caution that "turnover time" is a poor quantity to use in estimating CO_2 effects because it can itself vary rapidly with time. This point is illustrated in Fig. 1, which shows the decay times of four different CO_2 pulses (panel a), along with the corresponding instantaneous turnover times for excess atmospheric CO_2 (panel b). These pulses were calculated with a carbon cycle model that contains an oceanic component based on Siegenthaler (1983) and a terrestrial biosphere component based on Sarmiento et al. (1995).

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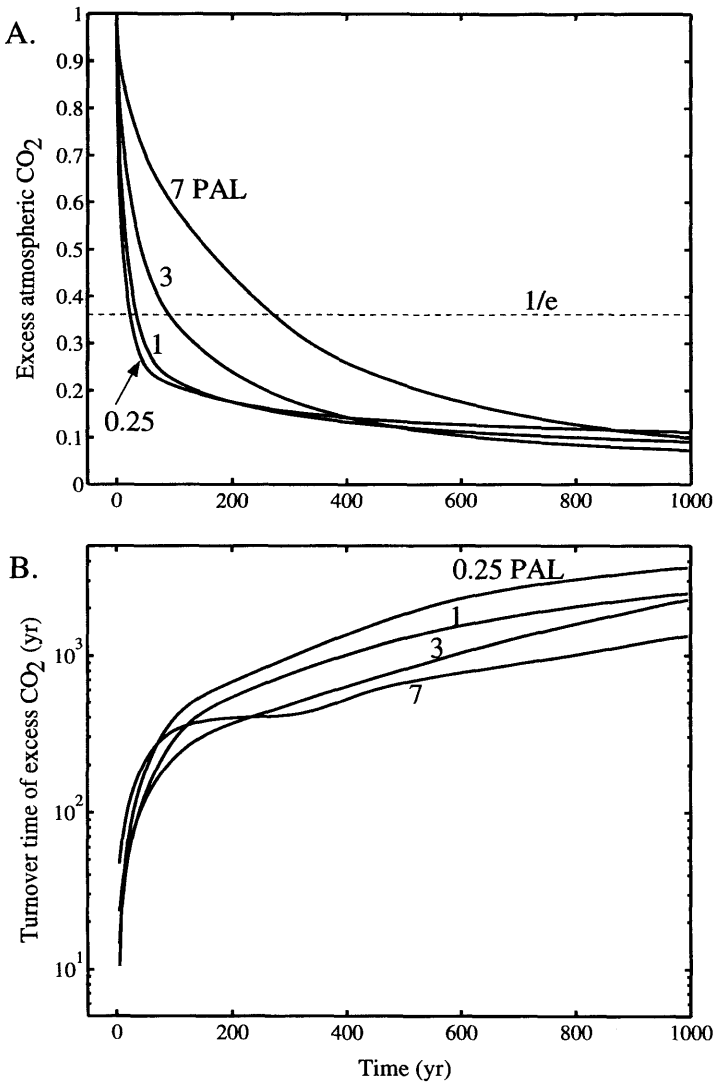

Fig. 1. (a) Impulse response functions for CO_2 pulses of different magnitudes, as calculated by the combined ocean/terrestrial biosphere carbon cycle model. The pulse size has been normalized to unity for display purposes. "PAL" stands for "times the preindustrial level." (b) Calculated turnover times for the CO_2 pulses shown in panel 'a'. The turnover time was calculated by dividing the amount of excess CO_2 remaining in the atmosphere by the negative of its time derivative.

Bomb radiocarbon tuning was assumed for the ocean model. (This maximizes the rate of CO_2 uptake.) We have made several changes to the original ocean model, including: (1) replacing the parameterized buffer factors with explicit carbonate/borate chemistry, (2) adding particulate fluxes of carbonate and organic carbon, (3) adding in realistic ocean hypsometry, and (4) including weathering of terrestrial carbonate and silicate rocks. Despite the changes, the ocean model exhibits CO_2 uptake times similar to those calculated by Siegenthaler and Oeschger (1987) and Maier-Reimer and Hasselman (1987). The (normalized) pulses for the ocean model by itself reach

(1/*e*) of their initial value in times ranging from 100 years for the 0.25 PAL pulse to 430 years for the 7 PAL pulse. Here, "PAL" stands for "times the preindustrial atmospheric level" of 280 ppm. A 1 PAL pulse corresponds to an injection of 595 Gt(C). The estimated fossil fuel reserves contain about 5000 Gt(C) (Sundquist, 1986), equivalent to about 8.5 PAL of CO_2.

The impulse response functions shown in Fig. 1a decay more rapidly than this because a terrestrial biosphere model is included and because terrestrial productivity is assumed to be enhanced by CO_2 fertilization. The "*e*-folding" lifetime of the initial pulse varies from 22 years for the 0.25 PAL pulse to 266 years for the 7 PAL pulse. The lifetime increases with increasing pulse size because carbonate and borate become depleted in the upper parts of the ocean, thus reducing its buffering capacity, and because CO_2 fertilization is a nonlinear function of atmospheric CO_2. Note that the decay of the pulses is distinctly non-exponential. This is shown by the rapidly changing turnover times (Fig. 1b), which increase from a few decades at time zero to over a thousand years several centuries later.

Fig. 1b can be viewed as a warning that it would be unwise to use the present low turnover time of atmospheric CO_2 to predict its future Global Warming Potential. This point is made more directly in Fig. 2, where we compare future atmospheric CO_2 concentrations for a logistic CO_2 emission function of the form

$$E(t)=0.0241\left[1-\left(\frac{E_{\mathrm{tot}}(t)}{5000}\right)^{0.375}\right]E_{\mathrm{tot}}(t).$$

Here, $E(t)$ is the emission rate in Gt(C)/yr and $E_{\mathrm{tot}}(t)$ is the total amount of anthropogenic CO_2 emitted up to time $t[E_{\mathrm{tot}}(1990)=409$ Gt(C)]. The total amount of fossil fuel consumed over the entire integration is equivalent to 5000 Gt(C). The 2 upper curves show projected CO_2 concentrations for our own box-diffusion carbon cycle model, with and without the terrestrial biosphere component. The two lower curves show projections made using a parameterization that assumes that the injected CO_2 decays exponentially with turnover times of 120 years and 30 years, respectively.

Fig. 2 shows that for this particular emission scenario the "constant turnover time" model underpredicts the peak atmospheric CO_2 concentration by more than 25%, even when the assumed turnover time is set equal to the 120-year value taken from the 1990 IPCC report. Furthermore,

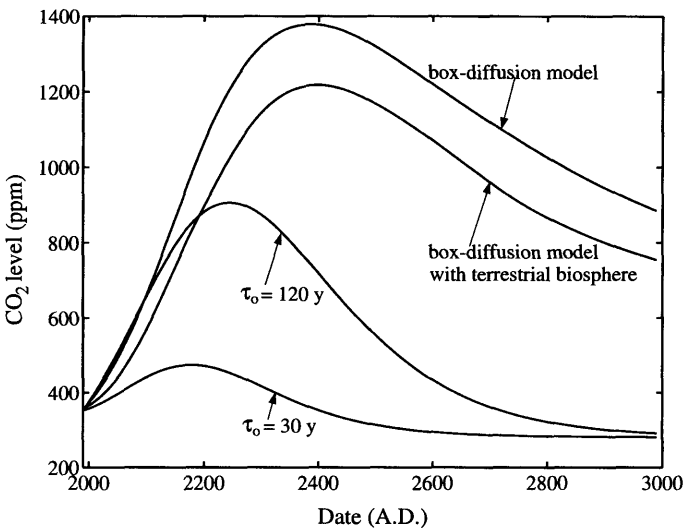

Fig. 2. Projected atmospheric CO_2 concentrations for the logistic CO_2 emission function given by eq. (1). The upper 2 curves were generated with the box-diffusion model described in this paper. The lower 2 curves were generated by a simple "constant turnover time" model, which assumes that the injected CO_2 decays exponentially with a time constant, τ_0.

the long-term decay is much too fast. After 1000 years of integration, the CO_2 concentration in the 'constant turnover time' model is nearly back to its preindustrial level, whereas the box-diffusion model predicts a concentration of ~ 800 ppm. Evidently, the effective turnover time of CO_2 in this simulation is significantly longer than 120 years, even when the terrestrial biosphere is included. Using a 30-year time constant in the 'constant turnover time' model yields projected atmospheric CO_2 concentrations that are far below the box-diffusion model predictions at all times. We should point out that our box-diffusion model predicts a CO_2 turnover time of about 30 years in 1990, which agrees with the empirical estimate made by O'Neill et al. (1994). In reality, our model may itself underestimate the lifetime of anthropogenic CO_2 because oceanic uptake may occur on the time-scale for uptake of natural radiocarbon, rather than bomb radiocarbon, and because CO_2 fertilization of the terrestrial biosphere may be less effective than assumed for reasons discussed by Sarmiento et al. (1995).

Thus, anthropogenic CO_2 may be expected to linger in the atmosphere for a long time, despite recent assertions to the contrary. This fact needs to be considered in computer models that attempt to simulate climate over the next few centuries. Current economic models (Nordhaus, 1992) that assume a 120-year CO_2 lifetime are already underestimating the magnitude of future global warming. (Nordhaus also assumes that 36% of the injected CO_2 goes immediately into the oceans, which further lowers his projected atmospheric CO_2 concentrations.) These models would be even less realistic if they used a shorter CO_2 lifetime.

Finally, to return to the question of the CO_2 global warming potential, we agree that this quantity should be re-evaluated periodically as our knowledge of the carbon cycle increases. In particular, attention needs to be given to the role of the terrestrial biosphere in future CO_2 uptake. But the sensible way to re-evaluate this quantity is by using better carbon cycle models, not by using empirically-determined CO_2 turnover times. The nonlinearities in the carbon cycle cannot be properly accounted for by relying on historical records of CO_2 uptake.

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