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Reply to "Reservoir timescales for anthropogenic CO_2 in the atmosphere: commentary"

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Kasting and Schultz's commentary is organized around the premise that in our original paper, we suggest using the relatively short historical turnover time to predict future atmospheric CO_2 concentrations. They demonstrate that this strategy would seriously underestimate CO_2 levels over the next 1000 years. However, nowhere did we propose using the turnover time for this purpose. They have misinterpreted our suggestion that the turnover time might be useful in an alternative Global Warming Potential (GWP) index. This suggestion is not equivalent to proposing its use in CO_2 projections. For example, the current formulation for the warming potential of CO_2 (Albritton et al., 1995) is based on an impulse response function that should not be used to project CO_2 concentrations, since no single response function captures the varying strength of carbon cycle nonlinearities through time. Likewise, a timescale used in a GWP should not necessarily be expected to accurately project future atmospheric concentrations since GWP's are intended to be simplified indexes.

Furthermore, we explicitly acknowledged the short-term nature of the turnover time, clearly differentiated it from the lifetime, emphasized that its value was subject to change in the future, and warned that timescale dynamics "must be understood to ensure their proper use in any economic index." Developing such an index continues to be a challenging task (Schmalensee, 1993; Eckhaus, 1992) and warrants consideration of both the long-term, irreversible effects of CO_2 emissions and short-term impacts.

Much of Kasting and Schultz's commentary is therefore devoted to knocking down a straw man. However, in so doing they raise several points worth further discussion.

For example, the authors warn that suggesting the use of the turnover time in a warming index invites its misuse as an estimate for the lifetime of CO_2. Indeed, this might continue to happen if timescales remain ambiguously defined and the climate change literature uses timescales such as turnover time, lifetime, and adjustment time interchangeably. However, we believe precisely defining, clearly explaining, and responsibly using a fundamental set of basic timescales is the best way to prevent their misinterpretation, and it was this spirit that motivated our paper.

For this reason, our main result (Fig. 1, O'Neill et al., 1994) showed illustrative calculations of the historical evolution of a number of timescales, not just the turnover time. The lifetime of the reversible portion of the effect of an emission on atmospheric concentrations was estimated to be 116 years, while about 15% of its effect was essentially irreversible. This timescale was clearly distinguished from the current 30-year turnover time, which measures only the net instantaneous removal rate of excess CO_2.

Kasting and Schultz point out that Nierenberg (1995) draws the wrong conclusion about how long it would take for the atmosphere to recover from fossil fuel emissions loading. But his mistake

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was not a result of our paper; he and others had been using timescales incorrectly before its publication (Nierenberg, 1994; Seitz, 1994; Starr, 1993). To us, these mistakes are examples of the need for more work, not less, on developing a consistent set of timescales to answer specific policy-relevant questions (O'Neill et al., submitted; Gaffin et al., 1995; Tubiello and Oppenheimer, 1995). It is more likely that the CO_2 lifetime will be underestimated in the political arena if timescales have no agreed-upon definitions within the scientific community than if they are clearly defined and consistently used.

Kasting and Schultz demonstrate the dangers of using the present relatively low turnover time to project future CO_2, a practice which we, too, advise against. The turnover time is an instantaneous measure and is likely to increase in the future as emissions deviate from their historical trend and as nonlinearities in the carbon cycle become more prominent, as we pointed out in our paper. Any equation based strictly on its present value will fail to reflect these changes.

However their claim that the turnover time's potential volatility rules out the use of any constant timescale model for CO_2 is overstated. Their Fig. 1B suggests that the turnover time increases by two orders of magnitude in response to instantaneous injections of hundreds or thousands of gigatons of carbon. But no such emissions event is likely to take place; our Fig. 1 shows the evolution of the turnover time in response to more plausible future emissions scenarios. It varies much more slowly than claimed by Kasting and Schultz, with an average value of about 60 years (about twice the current turnover time) over the next century. As a result, a model employing a constant turnover time of about 60 years applied only to the next century can reliably reproduce the response of much larger and more complicated carbon cycle models to a wide range of emissions.

This fact does not imply that the lifetime of CO_2 is 60 years, or that it will take 60 years for atmospheric CO_2 to achieve equilibrium once emissions cease—those are separate questions answered by different (and much longer) time-

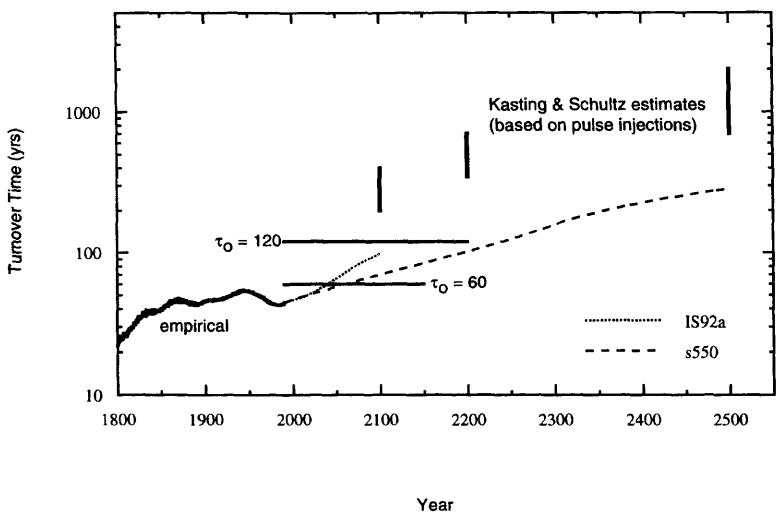

Fig. 1. The solid line plotted from 1800–1990 shows the empirically determined turnover time, based on atmospheric CO_2 concentration data, estimates of fossil fuel emissions, and net emissions from land use change determined from an inverse carbon cycle model run. The dotted and dashed lines show the evolution of the turnover time derived from output of a carbon cycle model forced with the IS92a "business as usual" emissions scenario and emissions leading to an atmosphere stabilized at 550 ppm (F. Joos, personal communication). Each is representative of the turnover times resulting from the full set of business as usual and stabilization scenarios developed by the IPCC. Both grow much more slowly than implied by the estimates of Kasting and Schultz (indicated by the heavy vertical bars, see their Fig. 1B), whose estimates are one to several hundred years higher at all times. Note that a 60-year turnover time is a rough average for the IS92 scenarios over the next century, while a 120-turnover time may not be surpassed for the next two centuries.

scales. Conversely, a long lifetime for CO_2 does not mean that the current instantaneous removal rate is slow.

While a simplified model based on one time constant would not be useful for exploring geophysical problems, it does have uses in other disciplines. Integrated assessment models, whose range of uncertainty does not warrant the incorporation of detailed geophysical models, often contain single-equation representations of the carbon cycle. Since no clear guidelines exist for CO_2 timescales, these models have sometimes employed inaccurate equations. Kasting and Schultz point out that the model used by Nordhaus (1992), containing a 120-year timescale, underestimates future CO_2. While this is true, it is not for the reasons they suppose. Fig. 1 implies that a 120-year turnover time would actually *overestimate* CO_2 concentrations for the next two centuries, and indeed Kasting and Schultz's Fig. 2 demonstrates this result explicitly. Nordhaus underestimates CO_2 levels because in order to make his model fit historical data, he added a correction factor to his emissions term, which lowered the model's effective turnover time to close to its historical value. We believe that a clear presentation of available timescales and their limits can help avoid similar problems in the future.

In summary, different aspects of the behavior of greenhouse gases in the atmosphere are described by different timescales. In simple systems, dynamics are controlled by a single rate constant, and all timescales are equal to the inverse of that constant. But in more complicated systems like the carbon cycle, the timescales are generally unequal. No single number or model result can answer all of the questions important to policymakers and other users of climate change science. We believe that a set of clearly defined timescales, used consistently, can begin to provide scientifically sound answers to these questions and will therefore be a valuable tool for bridging the science and policy of global warming.

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