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A modified impulse-response representation of the global response to carbon dioxide emissions

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This manuscript proposes a simple carbon cycle representation that involves a linear increase in integrated airborne fraction over time. Such a representation is useful for many purposes, including integrated assessment models that combine representations of the climate system and the economy. I assume that invited reviewers will cover the paper thoroughly so I will confine my remarks to a few concerns: the timescales and scenarios over which such a representation is useful, and how to make a valid comparison with the BEAM model described in Glotter et al 2014 (a paper on which I am a co-author).

Timescales and scenarios

The authors write: "We find that a simple linear increase in 100-year integrated airborne fraction with cumulative carbon uptake and global temperature change is both necessary and sufficient to represent the response of the climate system to CO2 on a range of timescales and under a range of experimental designs."

But, the airborne fraction does not increase linearly over long timescales in most realistic emissions scenarios. The figures in this paper focus on centennial timescales and on scenarios where CO_2 emissions are increasing at a constant growth rate. But if emissions decline, airborne fraction declines as well. (And over long timescales, cumulative airborne fraction continues to decline as the ocean comes into equilibrium.) This behavior can be shown by considering runs using the $A2^+$ emissions scenario, in which emissions rise as business-as-usual until 2100 and then drop linearly to zero by 2300 (Figure 1 below). The $A2^+$ scenario has been used with two intermediate-complexity Earth System Models (ESMs), UVic and CLIMBER-2. In these runs, airborne fraction rises initially but begins to drop as emissions slow, and continues dropping after emissions cease, reaching a final value of ~0.5. The authors of this manuscript need to be more specific about which conditions their model is able to capture.

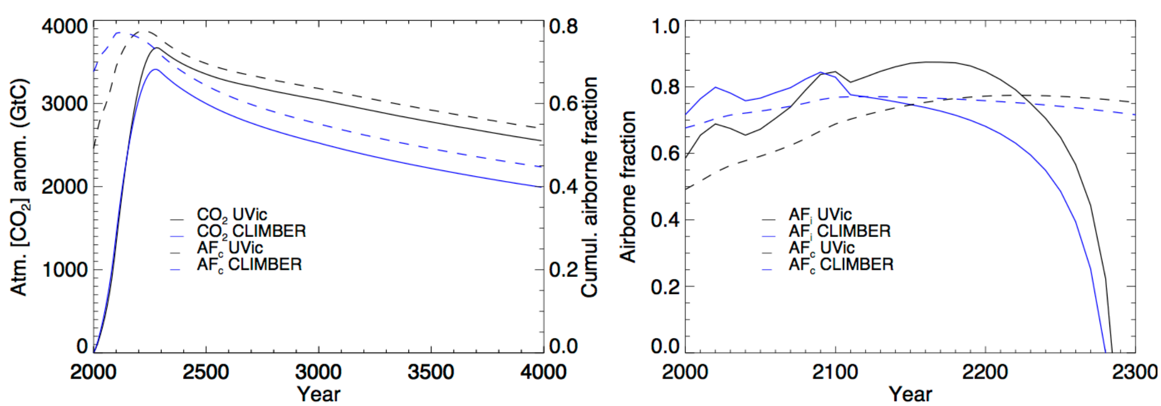

Figure 1: Atmospheric CO_2 (expressed as GtC anomaly over year 2000 values) and airborne fraction in CLIMBER and UVic run with the $A2^+$ emissions scenario. In both models airborne fraction first rises and then falls. Airborne fraction is defined in two ways. The "cumulative" or "integrated" airborne fraction is the atmospheric anomaly above pre-industrial divided by the total past emissions. The "instantaneous" airborne fraction is the amount of CO_2 added or lost from the atmosphere in one timestep, divided by the emissions in that timestep. Instantaneous airborne fraction becomes negative in this scenario shortly before emissions reach zero, when net loss of CO_2 from the atmosphere exceeds emissions. (It is obviously not meaningful when emissions reach zero.) Cumulative airborne fraction reflects the entire emissions history; in this scenario nearly 9% of final cumulative emissions occur between 1880 and 2000.

I confess that I find the writing of this paper very confusing, and Figure 1d does seem to imply an decrease in airborne fraction over time in certain experiments, though followed by a subsequent increase. This decrease is not explained well, but is different from the long-term decrease that comes in realistic emissions scenarios when emissions slow. Figure 1 is introduced before either the model or the experiments has been described, which makes it hard to understand.

BEAM comparison

The second concern involves the comparison with the BEAM model. The version of BEAM used here is the default framework described in Glotter 2014; the authors write that BEAM was "run with parameters as given in Glotter et al. (2014), which are tuned for long time-scales". We see BEAM only as a framework that can capture the response of more complex models, and we would strongly prefer that parameters be chosen appropriate to the models being compared. Several of the parameters used in Glotter et al 2014 were in some sense placeholders, and we suggested that the users adjust them as needed to represent individual complex carbon cycle models. In retrospect we should have emphasized that need more clearly, and provided examples. It is evident from the manuscript figures here that default BEAM parameters do not capture short-term dynamics well. We are glad to provide code and discussion to ensure that the comparison of models is done appropriately.

While most of the parameters in BEAM have strong physical foundation, three are highly uncertain, those that relate the sizes and timescales of the reservoirs in the three-box models. These parameters seek to aggregate behavior globally that is not well-measured even locally. They are 1) δ, the ratio between the upper and lower oceans, represented as distinct reservoirs; 2) k_d, the exchange time between them; and 3) k_a, the exchange time between atmosphere and upper ocean. In the presentation of BEAM in Glotter 2014 we (in retrospect, unwisely) left these values as the fairly arbitrary choices of Bolin and Eriksson 1959 ($\delta = 50$, $k_d = .05$, and $k_d = .2$), and suggested (in appendix A.2) that users should adjust them as needed to best represent more complex ocean models. We had assumed that the primary use for BEAM would be in simple Integrated Assessment Models that consider long timescales and require relatively crude representations of the physical climate system. The Bolin and Eriksson values seemed acceptable for this purpose, as resulting temperature differences between BEAM and the ESMs are no more than 0.23 K in the first 100 years, and thereafter the two ESMs bracket BEAM temperatures.

However, the Bolin and Erikkson parameters describe a relatively shallow mixed-layer upper ocean, equivalent to about 75 meters depth, with a rapid exchange timescale of $1/k_d = 20$ years. In this configuration, even very small CO_2 uptake can alter the acidity of the shallow mixed layer substantially, so that the parameter B, which describes the ratio of dissolved CO_2 to total inorganic carbon, rises strongly. That rise means that very little CO_2 uptake is required to keep the mixed layer in equilibrium with the atmosphere, and atmospheric CO_2 drawdown is driven predominantly by transfer of inorganic carbon to the deep ocean. The result is a very high initial instantaneous airborne fraction, which drops only when emissions growth slows.

BEAM output can be readily matched to that of more complex climate models by adjusting the ratio of ocean reservoir volume δ and their exchange timescale k_d. (The upper ocean exchange timescale is sufficiently fast that it is less relevant at centennial timescales.) Figure 2 below shows CO_2 and airborne fraction under the $A2^+$ scenario, as in Figure 1, but here we compare output from UVic with that of BEAM with a variety of parameter settings: the Bolin and Eriksson value, a global optimized value to best capture UVic behavior, and output with k_d optimized for various values of δ. Results show that UVic is best emulated with a larger mixed layer volume and a longer exchange timescale. With this representation a given amount of CO_2 uptake produces smaller acidity changes, so that more uptake is required to bring the upper ocean to equilibrium with the atmosphere.

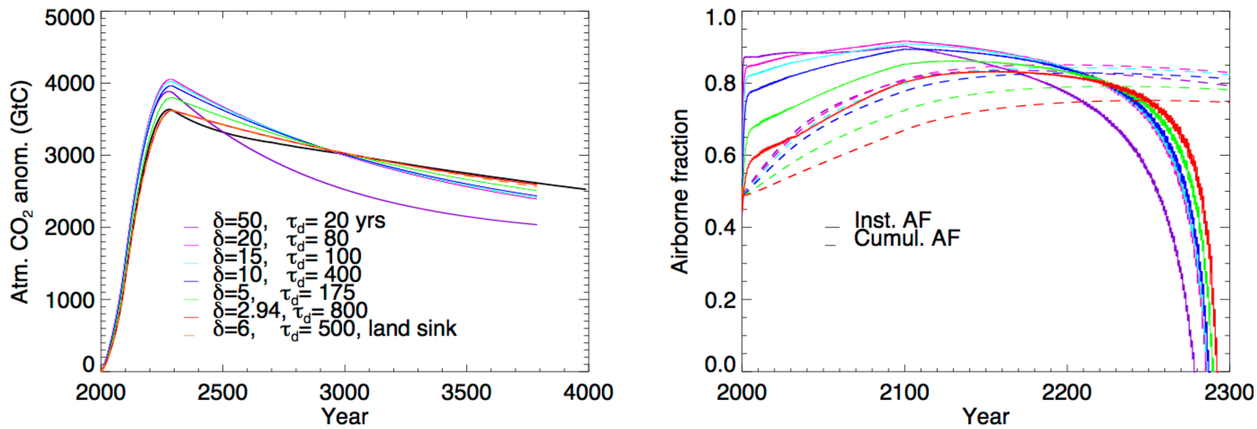

Figure 2: Optimizing the fit of BEAM to UVic output by adjusting the parameters δ and k_d (The exchange timescale $\tau d = 1/k_{d.}$) The very high instantaneous airborne fractions noted by the authors here are the result of an upper ocean mixed layer that is too shallow. The optimized parameters (red) describe a very deep mixed layer with a long exchange timescale. Adding a linearly declining land sink (orange, indistinguishable from red) produces an equally faithful reproduction of UVic output but with a more realistic mixed layer.

Note that the optimized parameters are still not the most physically reasonable, as the optimization exercise forces an ocean-only model to reproduce atmospheric CO_2 from ESMs that include land carbon sinks as well. That is, in BEAM the ocean is forced to account for all the uptake of the present-day land sink as well, which is believed to be comparable in magnitude to the ocean sink. The authors here state that BEAM cannot be compared to models that include land sinks, but it is a trivial to add one. Of course, the long-term evolution of the land sink is highly uncertain and differs even in sign in more complex models, so the exercise is most useful for studies that focus on the short term. As a demonstration, we have added a land sink that begins at 2.5 GtC/year in the present day (year 2000) and declines linearly to zero in 300 years and calculated optimized parameter values. The exercise yields slightly larger δ and k_d and again matches UVic CO_2 trajectories well (Figure 2). This formulation may be best to use when comparing across emission scenarios, since the more physically rational the representation, the better able the model will be to capture responses to differing emissions trajectories. Again, we are happy to provide code if that is helpful.

Additional confusions

I am confused about the author's definition of "cumulative uptake" and "cumulative airborne fraction" in Figure 1. In this figure BEAM output is shown as beginning with ~300 ppm and zero cumulative uptake. But the initial conditions suggested in Glotter et al 2014 begin BEAM after historical emissions from 1800-2000, so that starting atmospheric CO2 is over 380 ppm, and substantial emissions and uptake have occurred already.

In addition, given those initial conditions, the starting "cumulative airborne fraction" is ~0.5 and rises only slowly over time even when ocean uptake is small and instantaneous airborne fraction is high. Here the cumulative airborne fraction is shown as reaching 0.9 nearly immediately.

Finally, I was confused by statements implying that different emissions scenarios can be captured by a model that represents airborne fraction as a function of cumulative emissions (and temperature). Again the writing is confusing and I may have misunderstood, but airborne fraction seems quite sensitive to the emissions scenario (Figure 3 below). It seems that a figure is needed to explicitly validate this assertion.

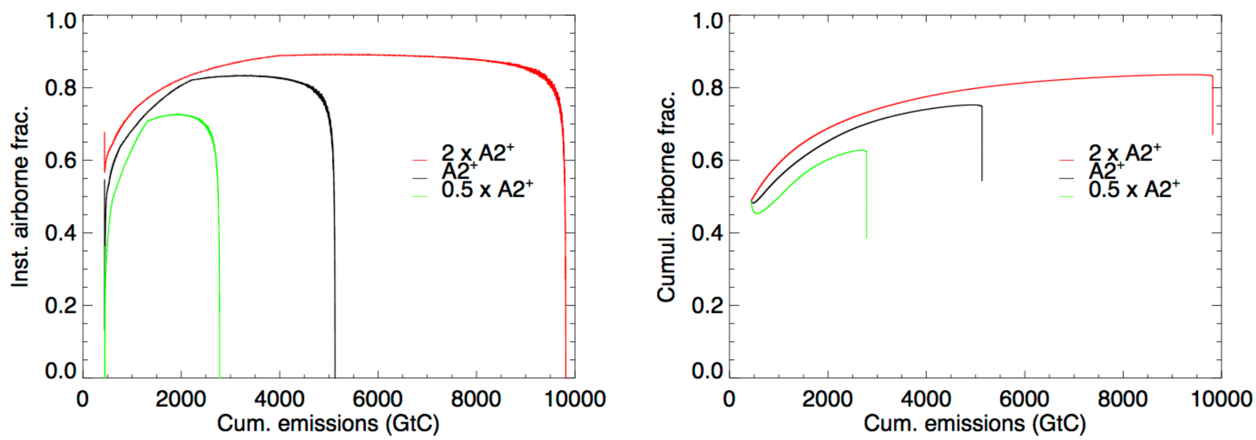

Figure 3: Instantaneous and cumulative airborne fraction in BEAM under three emissions scenarios, A2$^+$ and scenarios with A2$^+$ emissions doubled or halved. The version of BEAM is that optimized for reproducing UVic, with an assumed land carbon sink beginning at 2.5 GtC/year and linearly declining over 300 years. Airborne fraction is dependent on emissions scenario in both short and long terms. The vertical lines in the right panel represent the period when emissions have ceased but atmospheric CO_2 slowly declines over thousands of years.