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Introduction

In this supplementary information, we present additional analysis of the climate-carbon response from model simulations. The climate-carbon response (CCR), as we have defined it in this paper, represents a new metric of the climate response to carbon emissions, which aggregates both climate sensitivity (the temperature response to increased atmospheric CO_2), a newly-defined carbon sensitivity (the airborne fraction of cumulative carbon emissions), and the effect of carbon cycle feedbacks on both the airborne fraction of emission and the resulting climate change. We have additionally shown that the CCR is approximately independent of both CO_2 concentration and its rate of change, concluding that this quantity could be widely applied both as a metric for inter-model comparison, and a tool to estimate allowable CO_2 emissions to achieve climate mitigation and policy targets.

Our analysis builds on a number of previous model studies of the temperature response to carbon emissions. Several studies have now shown that the temperature response to either a pulse carbon emission, or a zero-emissions commitment scenario (in which carbon emissions are set to zero at some point in time in a transient model simulation) is sustained for many centuries at either approximately constant, or slowly decreasing levels[3,4,6,7,8,12]. Shine and coauthors[6] further suggested that the temperature response to a small emission pulse (1 kg of CO_2 or other greenhouse gas) or a sustained constant emission level (1 kg per year) could be used as an alternative to the “Global Warming Potential,” which is typically used to compare the temperature response to forcing by different greenhouse gases. This study was limited, however, by the use of very simple analytical and energy-balance models, and the authors did not extend their analysis of the temperature response to carbon emissions beyond this very confined range of models and emissions scenarios. Nevertheless, the results presented by Shine et al. do complement the analysis we have provided here, and when converted to units of °C/TtC (degrees warming per 10^{18} grams or trillion tonnes of carbon emitted), the values of temperature response to carbon emissions generated by the simple models used by Shine et al. are consistent with the range of CCR values that we have found here across a wide variety of models and emission scenarios.

Model-based estimate of carbon-climate response

Supplementary Table 1 shows the calculated values of carbon-climate response (CCR) from the 11 C4MIP models[10], calculated as the decadal-average value of $\Delta T/E_T$ (the ratio of instantaneous temperature change to cumulative carbon emissions) at the time of CO_2 doubling. Model values of CCR range from 1.0 to 2.1 °C/TtC, with an ensemble mean value of 1.6 °C/TtC.

From this analysis, it is clear that some models are much more "optimistic" than others with respect to their projection of the climate response to CO_2 emissions. For example, CSM-1 and BERN-CC have the two lowest values of CCR (1.0 °C/TtC and 1.1 °C/TtC, respectively), whereas IPSL-CM4-LOOP and HADCM3LC have the two largest values (1.9/TtC °C and 2.1/TtC °C, respectively). In both cases, however, these pairs of models exhibit similar values of CCR for different reasons. CSM-1 has a lower transient climate response than BERN-CC, but this is compensated for to some extent by a higher carbon sensitivity, leading to a higher airborne fraction of emissions with overall weaker carbon sinks. Similarly, HadCM3LC has a lower transient climate response than IPSL-CM4-LOOP, but this is compensated for by a higher carbon sensitivity, resulting in a slightly higher value of CCR in HADCM3LC.

It is worth emphasizing that the carbon sensitivity defined here based on the airborne fraction of cumulative carbon emissions is not the same as the strength of the positive climate-carbon feedback as presented in the C4MIP study[10]. For example, UVIC-2.7 and CSM-1 have very similar carbon sensitivities (with airborne factions of 0.51 and 0.50 at the time of CO_2 doubling, respectively); however, these models exhibit very large differences in the strength of their respective climate-carbon feedbacks (feedbacks gains of 0.2 and 0.06, respectively[10]). The similar airborne fractions of UVIC-2.7 and CSM-1 can be explained by stronger carbon sinks in UVIC-2.7, which compensate for a stronger positive climate-carbon feedback. In this case the CCR values of these two models are very different, and this can be easily traced to differences in transient climate response. However, the analysis we have presented here, and the CCR calculated by this method, does not provide any direct information about the feedback between climate change and the carbon cycle—rather, the CCR of a given model reflects the model's climate sensitivity in combination with the net carbon cycle response to both atmospheric CO_2 and climate changes.

Carbon-climate response based on carbon pulse simulations

Supplementary Figure 1 shows the temperature response per unit carbon emitted, in the UVic Earth System Climate Model (UVic ESCM), for a series of pulse-carbon emission simulations. Carbon pulses of between 0.32 and 5.12 TtC were added to the atmosphere instantaneously following a transient spin-up to year 2000 atmospheric CO_2 levels, and the model was run for 1000 years with zero additional carbon emissions[8]. Other natural and anthropogenic forcings were held constant at pre-industrial levels.

From these simulations, we can quantify approximate limits to the time and scenario independence of the carbon-climate response within an individual model. First, it is clear that temperature change per unit carbon emitted is not as constant with time in the extreme case of a carbon-pulse simulation, as it is under smoothly changing forcing (e.g. a 1% per year CO_2 increase) or under constant forcing (e.g. doubled CO_2). Further, the time-independence of the instantaneous temperature change per unit carbon emitted holds most strongly for emissions between 1 and 2 trillion tonnes of carbon. For smaller emission pulses, temperature tends to peak and then decrease with time, whereas for larger emission pulses, temperature tends to increase more slowly to a maximum value many centuries after the emission pulse. In addition, for emission pulses greater than about 2 trillion tonnes, there tends to be a decreasing temperature change per unit carbon emitted, as the logarithmic dependence of radiative forcing on CO_2 concentration dominates the effect of carbon sink saturation at higher emission levels.

Limitations of a constant carbon-climate response

Based on the UVic model pulse-response simulations presented above, we argue that the instantaneous temperature change per unit carbon emitted (and hence the carbon-climate response) is approximately constant with respect to time and emission scenario over timescales of 20 to 1000 years, and for total cumulative emissions of up to about 2 TtC. Subject to these time and scenario constraints, the temperature response per unit carbon emitted in the UVic model ranges from about 1.6 to 1.9 °C/TtC, representing variations in CCR from one model of about ±10%. While not negligible, this uncertainty is small relative to the inter-model variation discussed above.

Analysis of the C4MIP model simulations shows that the constancy of CCR holds across a range of different models. However, the range of climate sensitivities represented by this ensemble of models does not encompass the full range of possible climate sensitivities generated by some observationally-based estimates[1]. In particular, it is possible that for equilibrium climate sensitivities greater than about 5 °C (which is outside the C4MIP model range), the CCR may increase with time due to a slower climate system response time to forcing. Despite this caveat, we have shown here that the CCR is approximately constant across a likely range of both climate and carbon sensitivities.

Finally, it is worth noting that the constancy of CCR would not hold in the case of dramatic non-linear climate responses to forcing. An example of this can be seen at around the year 900 of the temperature response in the UVic ESCM to a 1.92 TtC pulse emission (Supplementary Figure 1), in which atmospheric temperature increased abruptly in response to an abrupt change in the Southern Ocean deep water circulation. It would be expected that CCR would not remain constant in the case of (for example) a complete collapse of the meridional overturning circulation, or other similarly globally-significant abrupt climate change. However, not all abrupt climate responses would necessarily result in a non-constant CCR. For example, in the HadCM3CL model simulation, the Amazon forest collapsed around the mid-21st century; however, this particular non-linear climate system response was not sufficient to affect the linearity of the temperature response in HadCM3LC to cumulative carbon emissions.

Supplementary Table 1: C4MIP model results

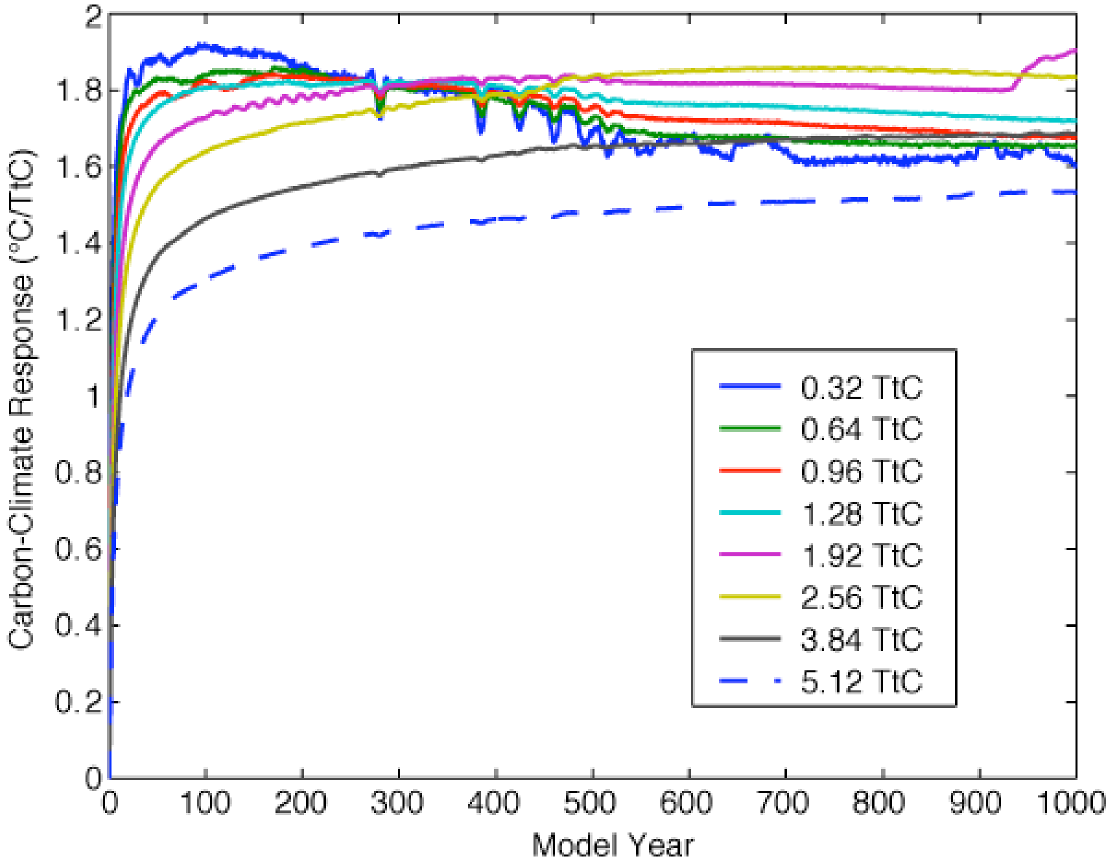
Model Name	**TCR*[a] (°C)**	**AF[b]**	**CCR[c] (°C/TtC)**
BERN-CC	1.5	0.45 (0.39)	1.1
CSM-1	1.1	0.50 (0.48)	1.0
CLIMBER2-LPJ	1.8	0.52 (0.48)	1.5
FRCGC	2.0	0.52 (0.44)	1.7
HADCM3LC	2.4	0.55 (0.45)	2.1
IPSL-CM2C	2.3	0.43 (0.38)	1.7
IPSL-CM4-LOOP	2.6	0.44 (0.43)	1.9
LLNL	2.2	0.40 (0.36)	1.4
MPI	2.3	0.47 (0.42)	1.9
UMD	1.6	0.63 (0.56)	1.6
UVIC-2.7[d]	2.2	0.51 (0.44)	1.9
Ensemble Mean	2.0	0.49 (0.44)	1.6

[a] TCR* is an estimate of the transient climate response for each model, representing the value for temperature change taken at the year of doubled CO_2 in each model.

[b] AF is the airborne fraction of cumulative emissions, calculated at the same year as the TCR*. Values in parentheses give the airborne fraction from the associated "uncoupled" simulations, in which climate change did not affect the carbon cycle[10].

[c] CCR was calculated using the 10-year average of temperature and cumulative emissions from each model at the time of CO_2 doubling. In this case, CCR can also be calculated as the product of TCR* and AF, divided by the change in atmospheric CO_2 (in TtC) at the time of doubling.

[d] UVic-2.7 has a higher CCR than version 2.8 due to a higher climate sensitivity in this version of the model and a stronger climate-carbon feedback.



Supplementary Figure 1: Temperature change per unit carbon emitted, simulated by the UVic ESCM in response to instantaneous pulse-carbon emissions from 0.32 to 5.12 TtC, followed by zero additional emissions. On timescales of 20 to 1000 years, and for emissions up to about 2 TtC, the instantaneous temperature response per unit carbon emitted is between about 1.6 and 1.9 °C/TtC.