

## On the proportionality between global temperature change and cumulative CO<sub>2</sub> emissions during periods of net negative CO<sub>2</sub> emissions

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## Environmental Research Letters



## LETTER

On the proportionality between global temperature change and cumulative CO<sub>2</sub> emissions during periods of net negative CO<sub>2</sub> emissions

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Recent research has demonstrated that global mean surface air warming is approximately proportional to cumulative CO<sub>2</sub> emissions. This proportional relationship has received considerable attention, as it allows one to calculate the cumulative CO<sub>2</sub> emissions ('carbon budget') compatible with temperature targets and is a useful measure for model inter-comparison. Here we use an Earth system model to explore whether this relationship persists during periods of net negative CO<sub>2</sub> emissions. Negative CO<sub>2</sub> emissions are required in the majority of emissions scenarios limiting global warming to 2 °C above pre-industrial, with emissions becoming net negative in the second half of this century in several scenarios. We find that for model simulations with a symmetric 1% per year increase and decrease in atmospheric CO<sub>2</sub>, the temperature change ( $\Delta T$ ) versus cumulative CO<sub>2</sub> emissions (CE) relationship is nonlinear during periods of net negative emissions, owing to the lagged response of the deep ocean to previously increasing atmospheric CO<sub>2</sub>. When corrected for this lagged response, or if the CO<sub>2</sub> decline is applied after the system has equilibrated with the previous CO<sub>2</sub> increase, the  $\Delta T$  versus CE relationship is close to linear during periods of net negative CO<sub>2</sub> emissions. A proportionality constant—the transient climate response to cumulative carbon emissions (TCRE)—can therefore be calculated for both positive and net negative CO<sub>2</sub> emission periods. We find that in simulations with a symmetric 1% per year increase and decrease in atmospheric CO<sub>2</sub> the TCRE is larger on the upward than on the downward CO<sub>2</sub> trajectory, suggesting that positive CO<sub>2</sub> emissions are more effective at warming than negative emissions are at subsequently cooling. We also find that the cooling effectiveness of negative CO<sub>2</sub> emissions decreases if applied at higher atmospheric CO<sub>2</sub> concentrations.

**1. Introduction**

Recent research has established a near-proportional relationship between global mean surface air temperature change and cumulative CO<sub>2</sub> emissions [1–3]. The proportionality constant, referred to as the transient climate response to cumulative carbon emissions (TCRE) [4], combines the physical and biogeochemical response of the Earth system and has been suggested as a useful metric for model intercomparison [1, 3]. The TCRE is also of significance to climate policy, as it establishes a direct relationship between carbon emissions, upon which policy has control, and

temperature change, a widely used indicator of climate change. This direct relationship allows for the determination of a 'carbon budget' compatible with temperature targets, such as the 2 °C target adopted by the Paris agreement [4–6].

The near-constant nature of the TCRE has been demonstrated for a range of models of different complexity, from simple climate models [7, 8] to Earth system models of intermediate complexity [1, 9, 10] and atmosphere-ocean general circulation model-based Earth system models [3, 11], as well as for a range of different scenarios [12–14]. The near-proportional relationship between global mean temperature change

and cumulative CO<sub>2</sub> emissions is thought to arise from the compensation of different physical and biogeochemical processes: the increase in airborne fraction at higher cumulative CO<sub>2</sub> emissions, the saturation of radiative forcing of CO<sub>2</sub> at higher atmospheric CO<sub>2</sub> concentrations and the decline in the ability of the ocean to take up heat at higher radiative forcing [1, 7, 8, 10]. While the radiative properties of CO<sub>2</sub> are not related to ocean processes, and therefore any compensation between radiative and other processes must happen by chance, compensation between ocean heat and carbon uptake is thought to arise because both are governed by the same physical processes in the ocean [1, 10, 15].

Here, we explore whether the proportional relationship between global mean temperature change and cumulative CO<sub>2</sub> emissions persists when net negative CO<sub>2</sub> emissions are applied. Negative CO<sub>2</sub> emissions (also referred to as artificial ‘carbon dioxide removal’ or CDR) have been proposed as a measure for climate change mitigation and are included as mitigation option in the majority of emission scenarios limiting global warming to 2 °C (e.g. Representative Concentration Pathway 2.6). In several of these scenarios, CO<sub>2</sub> emissions become net negative in the second half of the 21st century. Negative emissions have also been proposed as a means to restore Earth’s climate to a safe state should the impacts of climate change become ‘dangerous’.

Several technologies have been proposed to achieve negative CO<sub>2</sub> emissions. These include land-based methods such as reforestation, afforestation and bio-energy production with carbon capture and storage (BECCS) [16]. Other options include technologies that capture CO<sub>2</sub> directly from ambient air [17] and methods to enhance carbon uptake by natural sinks (e.g. ocean fertilization [18]). None of these technologies have yet been applied at a large scale.

## 2. Methodology

### 2.1. Model description

We use version 2.9 of the University of Victoria Earth System Climate Model (UVic-ESCM) [19], a model of intermediate complexity with a horizontal grid resolution of 1.8° × 3.6°. This version of the UVic-ESCM includes a 3-D ocean general circulation model with isopycnal mixing and a Gent-McWilliams parameterization of the effect of eddy-induced tracer transport [20]. For diapycnal mixing, a Brian and Lewis [21] profile of diffusivity is applied, with a value of  $0.3 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$  in the pycnocline. The ocean model is coupled to a dynamic-thermodynamic sea-ice model and a single layer energy-moisture balance model of the atmosphere with dynamical feedbacks [22].

The land surface and vegetation are represented by a simplified version of the Hadley Centre’s MOSES land-surface scheme coupled to the dynamic vegetation

model TRIFFID. Land carbon fluxes are calculated within MOSES and are allocated to vegetation and soil carbon pools of the five plant functional types represented by the vegetation model [23]. Ocean carbon is simulated by means of a OCMIP-type inorganic carbon-cycle model [24] and a marine ecosystem/biogeochemistry model solving prognostic equations for nutrients, phytoplankton, zooplankton and detritus [25]. The marine ecosystem model also includes a representation of the nitrogen cycle. The version of the UVic ESCM used here includes a marine sediment component, which is based on [26].

### 2.2. Experiment design

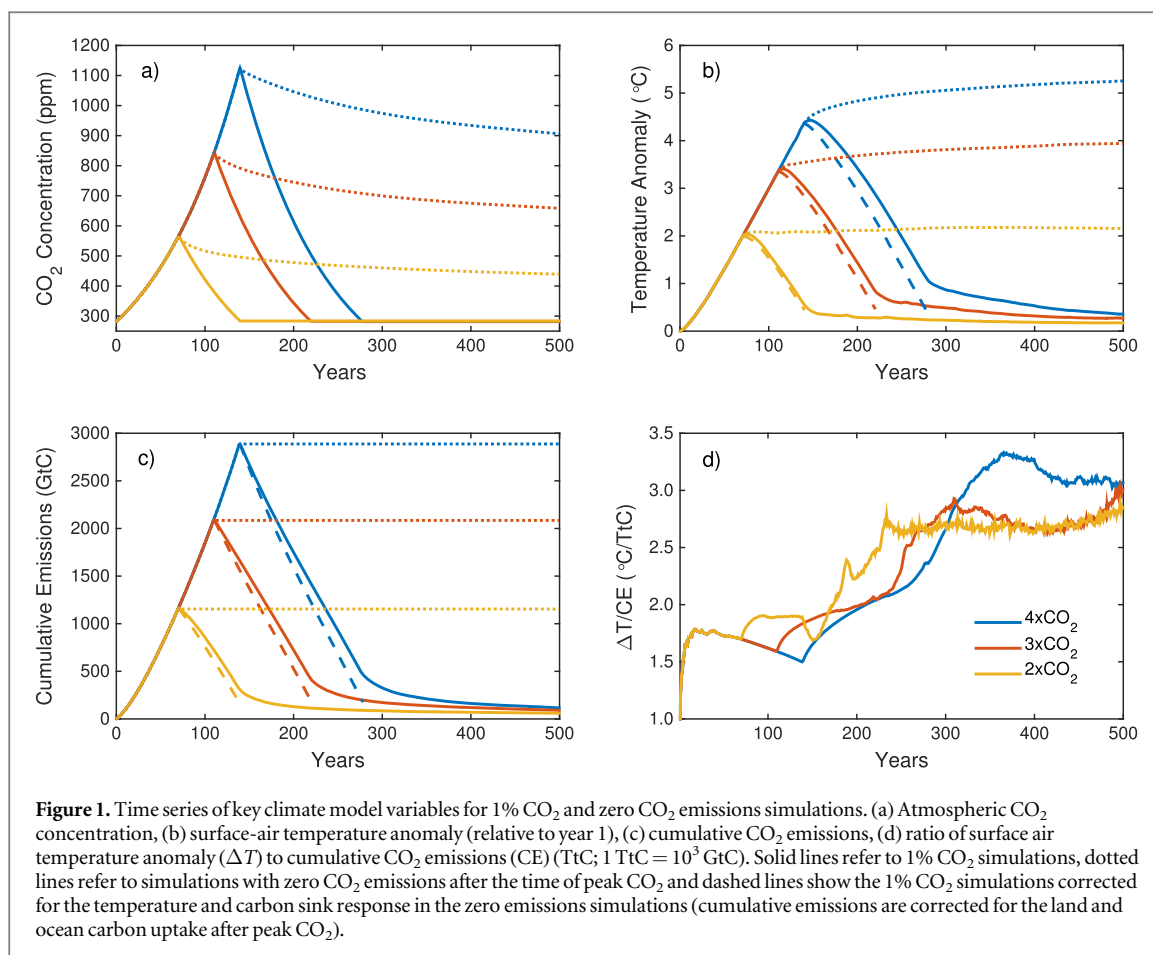
Several sets of simulations were run with the UVic ESCM: prescribed atmospheric CO<sub>2</sub> simulations with CO<sub>2</sub> first increasing and then decreasing at 1% per year (referred to as 1% CO<sub>2</sub> simulations), zero CO<sub>2</sub> emissions simulations initialized from the point of peak CO<sub>2</sub> in the 1% CO<sub>2</sub> simulations, zero CO<sub>2</sub> emissions ‘hiatus’ simulations, whereby a 1% decrease in atmospheric CO<sub>2</sub> is prescribed from given points along a zero CO<sub>2</sub> emissions trajectory, and constant CO<sub>2</sub> concentration hiatus simulations, whereby a 1% decrease in atmospheric CO<sub>2</sub> is prescribed from given points along a constant CO<sub>2</sub> concentration trajectory.

The 1% CO<sub>2</sub> simulations were initialized from a pre-industrial spinup run. Atmospheric CO<sub>2</sub> was prescribed to increase at 1% per year until the time of doubling (2×CO<sub>2</sub>), tripling (3×CO<sub>2</sub>) and quadrupling (4×CO<sub>2</sub>) of the pre-industrial atmospheric CO<sub>2</sub> concentration, and then decrease at the same rate until the pre-industrial CO<sub>2</sub> concentration was restored (figure 1(a), solid lines).

The zero emissions (ZEs) simulations were initialized from the the point of peak CO<sub>2</sub> in the 2×CO<sub>2</sub> (2×CO<sub>2</sub>-ZE), 3×CO<sub>2</sub> (3×CO<sub>2</sub>-ZE) and 4×CO<sub>2</sub> (4×CO<sub>2</sub>-ZE) simulations, with zero prescribed CO<sub>2</sub> emissions after that time (figure 1(a), dotted lines).

The zero CO<sub>2</sub> emissions hiatus simulations were initialized from given points (50, 100, 250, 500 and 1000 years after the time of peak CO<sub>2</sub>) along the 4×CO<sub>2</sub>-ZE simulation. From these points, a 1% decrease in atmospheric CO<sub>2</sub> was prescribed until the pre-industrial atmospheric CO<sub>2</sub> level was restored. These simulations are referred to as 4×CO<sub>2</sub>-ZE-h50, 4×CO<sub>2</sub>-ZE-h100, 4×CO<sub>2</sub>-ZE-h250, 4×CO<sub>2</sub>-ZE-h500, and 4×CO<sub>2</sub>-ZE-h1000, respectively. Note that the atmospheric CO<sub>2</sub> level from which the 1% CO<sub>2</sub> decrease was prescribed differs among simulations and therefore the CO<sub>2</sub> change between the beginning and the end of the prescribed CO<sub>2</sub> decrease period is also different (figure 4(a)).

The constant CO<sub>2</sub> concentration hiatus simulations were initialized from given points (50, 100, 250, 500 and 1000 years after the time of peak CO<sub>2</sub>) of a simulation with atmospheric CO<sub>2</sub> concentration held constant after the peak in the 4×CO<sub>2</sub> simulation. From these points, a 1% decrease in atmospheric CO<sub>2</sub>



was prescribed, restoring atmospheric CO<sub>2</sub> to pre-industrial levels (supplementary figure 1). These simulations are referred to as 4×CO<sub>2</sub>-CC-h50, 4×CO<sub>2</sub>-CC-h100, 4×CO<sub>2</sub>-CC-h250, 4×CO<sub>2</sub>-CC-h500, and 4×CO<sub>2</sub>-CC-h1000, respectively.

All simulations were forced with prescribed changes in atmospheric CO<sub>2</sub> or CO<sub>2</sub> emissions only. All other forcings were held constant at their pre-industrial level. In simulations with prescribed atmospheric CO<sub>2</sub> concentration, CO<sub>2</sub> emissions were diagnosed from the rate of increase in atmospheric CO<sub>2</sub> and carbon fluxes to the land and the ocean as the residual term in the carbon mass balance.

Negative CO<sub>2</sub> emissions are applied generically, without specifying any particular technology. We have assumed that the CO<sub>2</sub> captured from the atmosphere is removed permanently from the climate system (e.g. via underground storage).

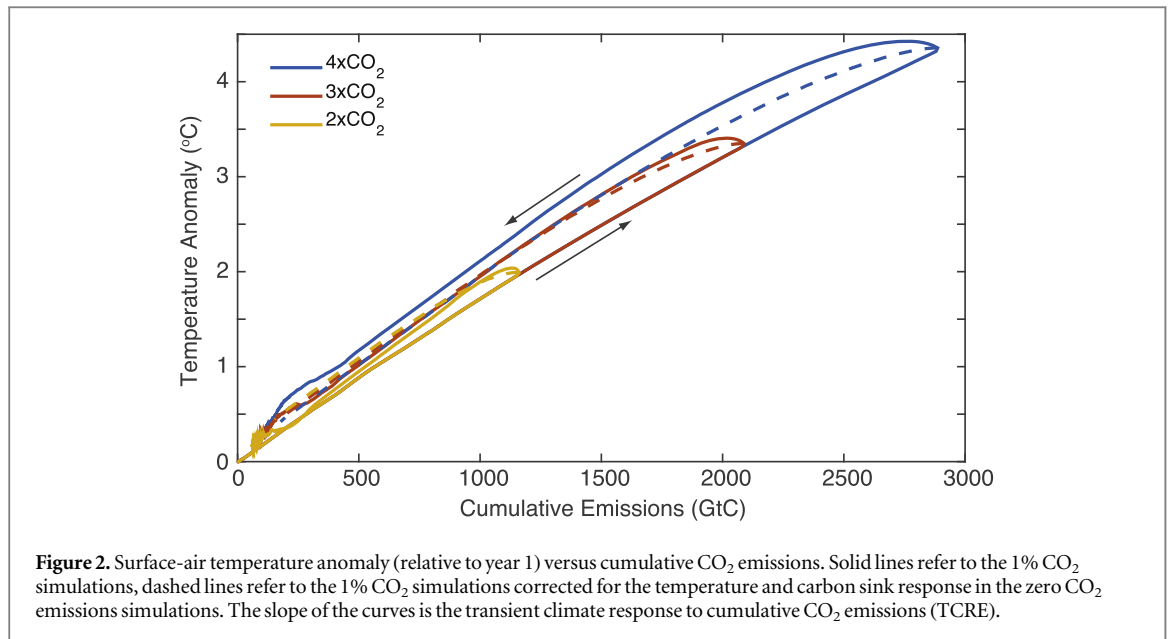
### 3. Results and discussion

#### 3.1. Linearity of temperature change versus cumulative CO<sub>2</sub> emissions relationship

First, we examine the relationship between global mean surface air temperature change and cumulative CO<sub>2</sub> emissions for the 1% CO<sub>2</sub> ramp-up, ramp-down simulations (figure 1, solid lines). On the upward limb of the 1% CO<sub>2</sub> simulations, surface air temperature

and cumulative CO<sub>2</sub> emissions increase nearly linearly in response to exponentially rising atmospheric CO<sub>2</sub> concentrations. Surface air temperature peaks a few decades after the peak in atmospheric CO<sub>2</sub>, with a longer lag for simulations with higher peak atmospheric CO<sub>2</sub>. After the peak, surface air temperature declines, albeit at a slower rate than the rate at which it increased on the upward limb of the 1% CO<sub>2</sub> simulations. The lagged response of temperature to atmospheric CO<sub>2</sub> decrease is due to the slow thermal equilibration of the deep ocean. Cumulative CO<sub>2</sub> emissions start to decrease (i.e. the rate of CO<sub>2</sub> emissions starts to become negative) right after the peak in atmospheric CO<sub>2</sub>, indicating that the prescribed CO<sub>2</sub> decline cannot be achieved by CO<sub>2</sub> uptake by natural carbon sinks alone, but requires artificial removal of CO<sub>2</sub> from the atmosphere. Similarly to temperature, the decrease in cumulative emissions is slower than the increase on the upward limb of the 1% CO<sub>2</sub> simulations. This ‘carbon inertia’ is largely due to the slow biogeochemical equilibration of the deep ocean, with a small contribution from the lagged response of the terrestrial biosphere, as will be discussed below.

The relationship between surface air temperature change ( $\Delta T$ ) and cumulative CO<sub>2</sub> emissions (CE) exhibits hysteresis behaviour: for a given amount of cumulative CO<sub>2</sub> emissions,  $\Delta T$  (relative to year 1) is



larger on the upward than on the downward limb of the 1% CO<sub>2</sub> simulations (figure 2). Consistently with previous studies [1, 3, 4, 11], the  $\Delta T$  versus CE relationship is approximately linear during the CO<sub>2</sub> ramp-up phase. During the CO<sub>2</sub> ramp-down phase, however, the  $\Delta T$  versus CE curve is nonlinear, with larger nonlinearity for simulations with higher peak atmospheric CO<sub>2</sub> concentration. This nonlinearity is due to the inertia in physical and biogeochemical climate processes mentioned in the previous paragraph. The lagged response of temperature to CO<sub>2</sub> decline is due to the slow thermal equilibration of the deep ocean, which continues to take up heat for several decades after the peak in atmospheric CO<sub>2</sub> (figure 3(c)), and is consistent with the results of earlier studies [27–29]. Biogeochemical inertia is largely due to the ocean, with a smaller contribution from the terrestrial biosphere. The ocean continues to take up carbon even after atmospheric CO<sub>2</sub> levels start to decline, as the deep ocean is still equilibrating with past (positive) CO<sub>2</sub> emissions (figure 3(f)). On land, vegetation also continues to take up carbon for several years after atmospheric CO<sub>2</sub> starts to decline (figures 3(d) and (e)). This is mostly because of forest expansion at northern high latitudes, which lags atmospheric CO<sub>2</sub> due to the long timescales associated with vegetation shifts (not shown). The lag in the biogeochemical response to CO<sub>2</sub> decline is consistent with the results of [29, 30].

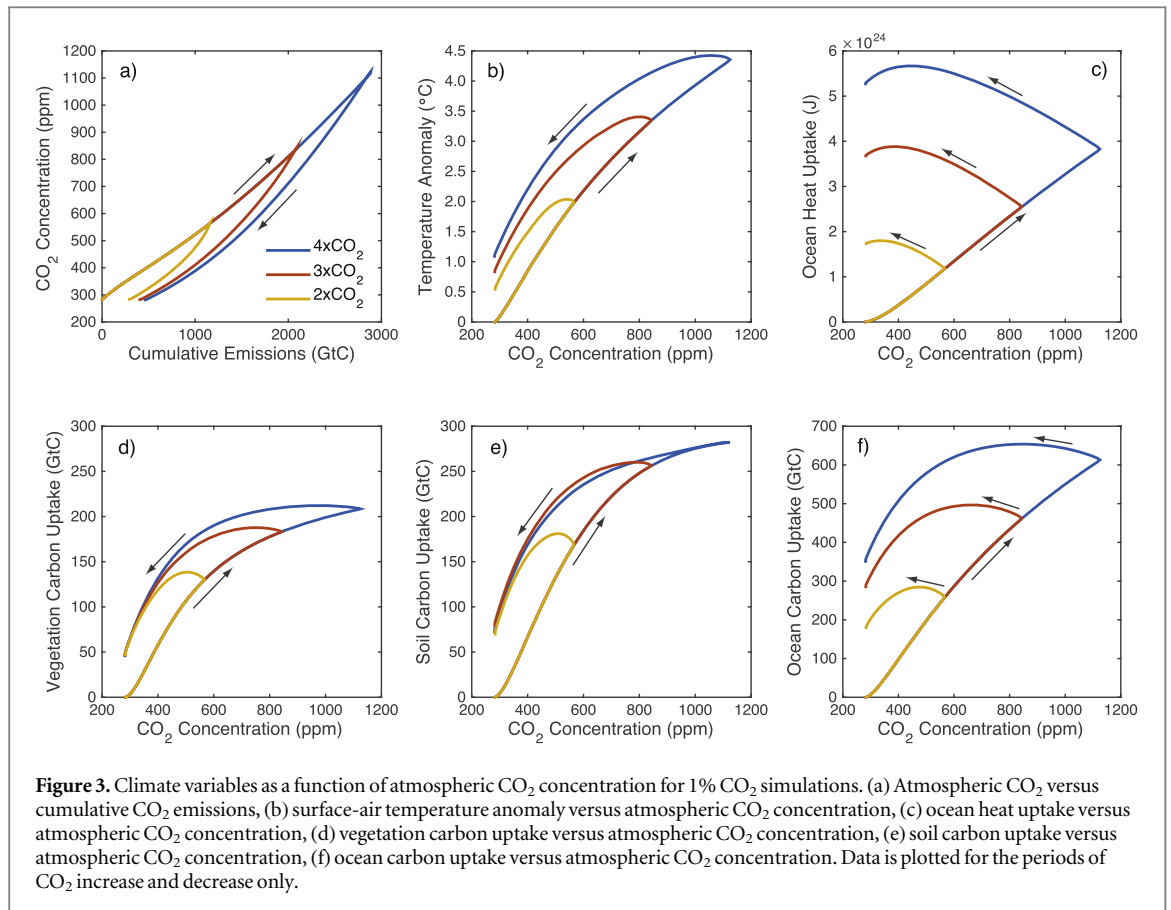
Ocean thermal and biogeochemical inertia affect the  $\Delta T$  versus CE relationship on the downward limb of the 1% CO<sub>2</sub> simulations in opposite ways. This can be seen by separating the ratio  $\Delta T/CE$  into two terms [1]:

$$\frac{\Delta T}{CE} = \frac{\Delta C_A}{CE} \frac{\Delta T}{\Delta C_A}, \quad (1)$$

where  $\Delta C_A$  is the change in atmospheric CO<sub>2</sub>. Note that for the CO<sub>2</sub> ramp-up phase (positive emissions)

changes are defined relative to year 1, whereas for the CO<sub>2</sub> ramp-down phase (negative emissions) changes are defined relative to the time of peak CO<sub>2</sub> concentration. As is evident in figure 3(a), biogeochemical inertia results in less cumulative negative emissions required to achieve the prescribed drop in atmospheric CO<sub>2</sub> (i.e. larger  $\Delta C_A/CE$ ), acting to *increase* the ratio  $\Delta T/CE$ . On the other hand, thermal inertia results in a smaller temperature drop for the prescribed atmospheric CO<sub>2</sub> decline (i.e. smaller  $\Delta T/\Delta C_A$ ) (figure 3(b)), which acts to *decrease*  $\Delta T/CE$ . As will be discussed later, the TCRE is smaller on the downward than on the upward limb, indicating that thermal inertia is slightly larger than biogeochemical inertia. This difference between thermal and biogeochemical inertia is the result of the different vertical profiles of heat and carbon in the ocean. Ocean heat and carbon uptake are governed by CO<sub>2</sub> and temperature gradients between the ocean mixed layer and the atmosphere, and the mixing with the deep ocean. Since the deep ocean is colder than the mixed layer throughout the 1% CO<sub>2</sub> simulations, mixing with the deep ocean cools the mixed layer, enhancing the temperature gradient at the atmosphere-ocean interface. This delays the reversal in air-sea heat flux to nearly the end of the CO<sub>2</sub> decline phase (figure 3(f)). On the other hand, since the deep ocean is enriched in carbon relative to the mixed layer, upward mixing of deeper waters acts to decrease the CO<sub>2</sub> gradient at the sea surface, causing the ocean to turn from a sink to a source of carbon only a few decades after the start of the CO<sub>2</sub> decline phase (figure 3(c)).

The balance between ocean thermal and biogeochemical inertia, which determines the width of the hysteresis in the global mean temperature change versus cumulative CO<sub>2</sub> emissions curve, is set by the timescale of mixing of heat and carbon into the deep ocean and could therefore be dependent on a model's ocean mixing parameterization. Simulations with the UVic ESCM using different mixing parameterizations and a

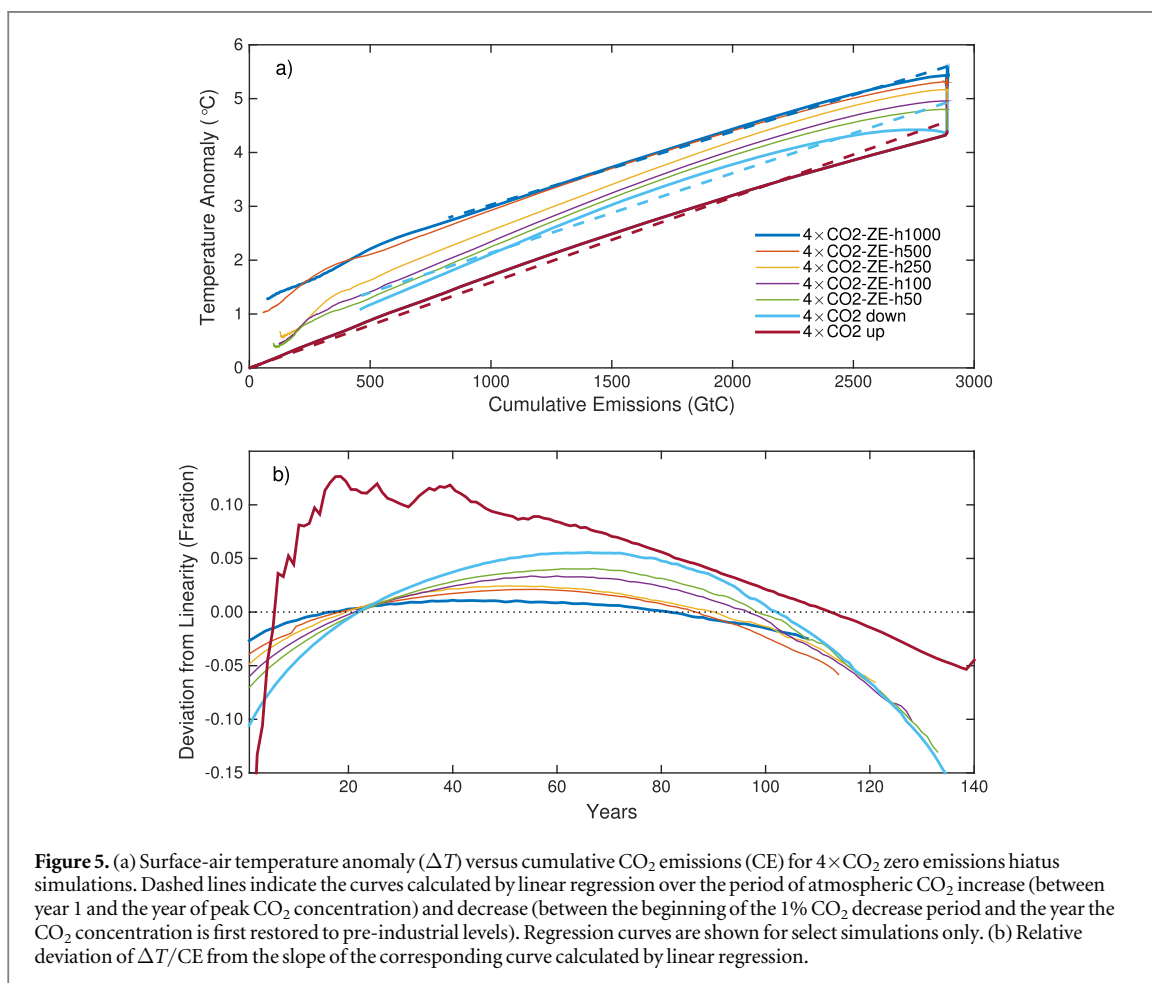
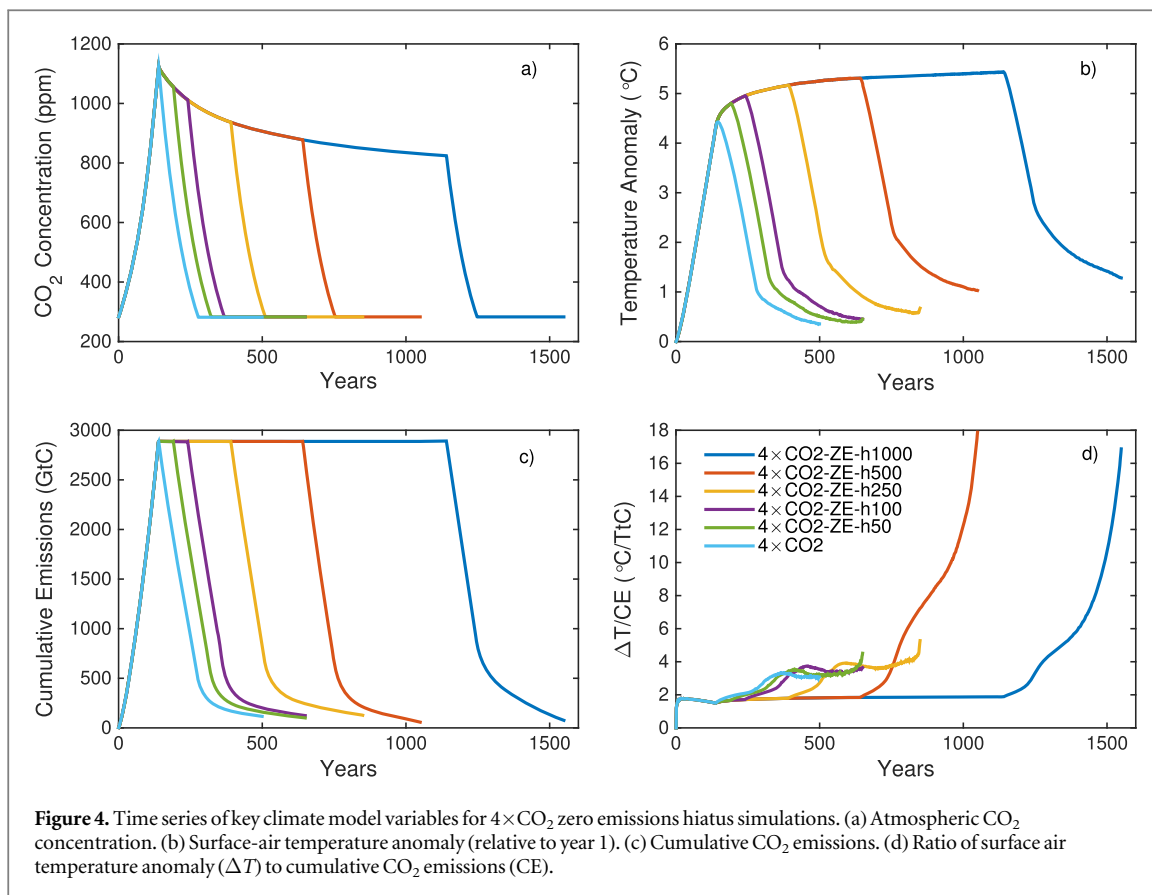


range of mixing parameters indicate that the balance between ocean heat and carbon uptake in simulations with a 1% per year increase in atmospheric CO<sub>2</sub> concentration to 4× pre-industrial levels and constant CO<sub>2</sub> concentration thereafter is largely independent of the mixing parameterization [31]. Therefore we expect this balance to be maintained also for zero end negative CO<sub>2</sub> emissions scenarios, and the results discussed above to be robust against the choice of mixing parameterization. This inference is further supported by simulations with a complex Earth system model with a symmetric 1% per year increase and subsequent decrease in atmospheric CO<sub>2</sub>, which also exhibits larger thermal than biogeochemical inertia [29].

The system's response on the downward limb of the 1% CO<sub>2</sub> simulations results from the combination of the lagged response to positive CO<sub>2</sub> emissions prior to the decline in atmospheric CO<sub>2</sub>, and the response to negative CO<sub>2</sub> emissions. The continued warming and carbon uptake in response to past positive emissions can be quantified in simulations with prescribed zero emissions after peak atmospheric CO<sub>2</sub> (figure 1, dotted lines). Over the time of the CO<sub>2</sub> ramp down in the 1% CO<sub>2</sub> simulations (70, 110 and 140 years, respectively), atmospheric CO<sub>2</sub> levels drop by 67 ppm, 106 ppm, 138 ppm and surface air temperature increases by 0.1 °C, 0.4 °C, 0.7 °C in the 2×CO<sub>2</sub>-ZE, 3×CO<sub>2</sub>-ZE and 4×CO<sub>2</sub>-ZE simulations, respectively. If the temperature and carbon cycle response on the

downward limb of the 1% CO<sub>2</sub> simulations is corrected for the response in the ZE simulations, the  $\Delta T$  versus CE relationship is closer to linear (figure 2, dashed lines): the 'bulge' at the beginning of the return path is reduced, and the curves for the 2×CO<sub>2</sub>, 3×CO<sub>2</sub> and 4×CO<sub>2</sub> simulations converge to a similar value. This suggests that the relationship between global mean temperature change and cumulative CO<sub>2</sub> emissions is approximately linear also during periods of net negative CO<sub>2</sub> emissions, provided that the negative emissions are applied from a state where the system is at equilibrium with past CO<sub>2</sub> emissions.

To further test this idea, we examine the system's response in a set of simulations whereby the 1% atmospheric CO<sub>2</sub> decline is prescribed from different points along the 4×CO<sub>2</sub> ZE simulation (figure 4). The hypothesis is that the later the CO<sub>2</sub> ramp down is applied, i.e. the closer the system is to equilibrium with past emissions, the more linear the  $\Delta T$  versus CE relationship. The linearity of the  $\Delta T$  versus CE relationship is quantified as the relative deviation of  $\Delta T/CE$  from the slope of the line calculated by linear regression. Results indicate that the later the CO<sub>2</sub> decline is applied, the smaller the deviation from linearity (figure 5). The maximum deviation from nonlinearity is about 10% on the downward limb of the 4×CO<sub>2</sub> simulation, where the CO<sub>2</sub> ramp down is applied instantly after peak CO<sub>2</sub> levels are reached, but only



**Table 1.** Transient climate response to cumulative carbon emissions (TCREs) and ratio of surface air temperature anomaly ( $\Delta T$ ) to cumulative CO<sub>2</sub> emissions (CE). For positive emissions, TCRE is calculated by regressing the  $\Delta T$ /CE curve over the period of CO<sub>2</sub> increase (between year 1 and the time of peak CO<sub>2</sub>), with the regression line forced through the origin. For negative emissions, TCRE<sub>−</sub> is calculated over the period of CO<sub>2</sub> decline (between the year CO<sub>2</sub> starts to decline and the year it is first restored to pre-industrial levels), with the regression line forced through the point of peak CO<sub>2</sub> concentration.  $\Delta T$  and CE for periods of CO<sub>2</sub> increase (positive emissions) are calculated at the year of peak CO<sub>2</sub> relative to year 1.  $\Delta T$  and CE for periods of CO<sub>2</sub> decrease (negative emissions) are calculated between the start and the end of the 1% CO<sub>2</sub> decrease period.  $\Delta T_c$  and CE<sub>c</sub> denote values of  $\Delta T$  and CE corrected for the temperature and carbon sinks response in the zero emissions simulations (2×CO<sub>2</sub>-ZE, 3×CO<sub>2</sub>-ZE and 4×CO<sub>2</sub>-ZE, respectively). CE estimates are rounded to the nearest tenth.

Simulation	TCRE (°C/TtC)	$\Delta T$ (°C)	CE (GtC)	$\Delta T_c$ (°C)	CE <sub>c</sub> (GtC)	$\Delta T$ /CE (°C/TtC)
2×CO <sub>2</sub> up	1.72	2.0	1160	—	—	1.71
3×CO <sub>2</sub> up	1.65	3.4	2090	—	—	1.60
4×CO <sub>2</sub> up	1.59	4.4	2890	—	—	1.51
2×CO <sub>2</sub> down	1.80	−1.4	−890	−1.5	−1010	1.67
3×CO <sub>2</sub> down	1.62	−2.5	−1680	−2.9	−1910	1.50
4×CO <sub>2</sub> down	1.48	−3.3	−2430	−3.9	−2710	1.35
4×CO <sub>2</sub> -ZE-h50	1.55	−3.5	−2380	—	—	1.31
4×CO <sub>2</sub> -ZE-h100	1.55	−3.5	−2340	—	—	1.33
4×CO <sub>2</sub> -ZE-h250	1.52	−3.3	−2270	—	—	1.45
4×CO <sub>2</sub> -ZE-h500	1.38	−3.1	−2300	—	—	1.48
4×CO <sub>2</sub> -ZE-h1000	1.36	−2.7	−2070	—	—	1.47
4×CO <sub>2</sub> -CC-h50	1.51	−3.6	−2530	—	—	1.43
4×CO <sub>2</sub> -CC-h100	1.50	−3.7	−2610	—	—	1.42
4×CO <sub>2</sub> -CC-h250	1.44	−3.8	−2740	—	—	1.38
4×CO <sub>2</sub> -CC-h500	1.34	−3.6	−2850	—	—	1.28
4×CO <sub>2</sub> -CC-h1000	1.21	−3.5	−2990	—	—	1.15

2% in the simulation where 1000 years elapse before the CO<sub>2</sub> decline is applied (4×CO<sub>2</sub>-ZE-h1000).

### 3.2. Quantifying the $\Delta T$ versus CE relationship for net negative CO<sub>2</sub> emissions

Given that a near-proportional relationship exists between global mean temperature change and cumulative CO<sub>2</sub> emissions during periods of net negative CO<sub>2</sub> emissions, a proportionality constant can be defined, similarly to the TCRE for positive emissions. This proportionality constant will in the following be referred to as TCRE<sub>−</sub> to distinguish it from the TCRE during periods of positive emissions. Both TCRE and TCRE<sub>−</sub> are calculated by linear regression of the  $\Delta T$  versus CE curve (table 1; see caption for details about the calculation). On the upward limb of the 1% CO<sub>2</sub> simulations, TCRE is lowest for the simulation with the largest peak atmospheric CO<sub>2</sub> concentration (4×CO<sub>2</sub>), consistent with previous studies that show a lower TCRE at higher cumulative emissions (e.g. [13]). On the downward limb of the 1% CO<sub>2</sub> simulations, TCRE is also lowest for the simulation with the largest peak atmospheric CO<sub>2</sub> concentration, suggesting that negative emissions are less effective at cooling if applied at higher atmospheric CO<sub>2</sub> concentration. In the 4×CO<sub>2</sub> ZE hiatus simulations, TCRE<sub>−</sub> is lowest for the simulation in which the CO<sub>2</sub> decline is applied from the latest point on the zero CO<sub>2</sub> emissions trajectory, i.e. when the system is closer to equilibrium with past emissions (4×CO<sub>2</sub>-ZE-h1000). As discussed in the previous section, this is also the simulation for which the  $\Delta T$

versus CE relationship is closest to linear. Therefore, it can be expected that the TCRE<sub>−</sub> for the 4×CO<sub>2</sub>-ZE-h1000 simulation (1.4 °C/TtC) is closest to the ‘true’ TCRE<sub>−</sub> value (i.e. the value that would result if the CO<sub>2</sub> decline were applied when the system is fully equilibrated with past CO<sub>2</sub> emissions). This value is somewhat lower than the TCRE on the upward limb of the 4×CO<sub>2</sub> simulation (1.6 °C/TtC), suggesting that negative CO<sub>2</sub> emissions are less effective at cooling than prior positive emissions are at warming. It should be noted that this difference does likely not arise from an asymmetry in the response of the climate-carbon cycle system to positive and negative CO<sub>2</sub> emissions, but rather from differences in the background atmospheric CO<sub>2</sub> concentration from which the positive and negative CO<sub>2</sub> emissions are applied. This state dependence can be explained by the stronger ocean stratification at 4×CO<sub>2</sub>, from which the CO<sub>2</sub> decline is applied, compared to pre-industrial CO<sub>2</sub> levels, from which the CO<sub>2</sub> increase is applied. Due to this stronger stratification, it takes longer to mix heat upward into the ocean mixed layer than it took to mix heat downward during the period of CO<sub>2</sub> increase.

In the following, we examine  $\Delta T$  and CE for the period of atmospheric CO<sub>2</sub> increase (between year 1 and the year of peak CO<sub>2</sub>) and decrease (between the start of the CO<sub>2</sub> decline and the year of restoration of the pre-industrial CO<sub>2</sub> concentration) for the various simulations (table 1). The magnitude of both  $\Delta T$  and CE is larger on the upward than on the downward limb of the 1% CO<sub>2</sub> simulations. For instance, the climate warms by 4.4 °C if atmospheric CO<sub>2</sub> is ramped



up to  $4\times\text{CO}_2$ , but cools only by  $3.3\text{ }^\circ\text{C}$  if atmospheric  $\text{CO}_2$  is ramped down to pre-industrial levels at the same rate. Also, cumulative  $\text{CO}_2$  emissions consistent with ramping up atmospheric  $\text{CO}_2$  to  $4\times\text{CO}_2$  are 2890 GtC, whereas 2430 GtC need to be removed to restore atmospheric  $\text{CO}_2$  from  $4\times\text{CO}_2$  to pre-industrial levels. The lower  $\Delta T$  and CE on the downward limb of the 1%  $\text{CO}_2$  simulations are associated with the continued warming and  $\text{CO}_2$  uptake in response to past positive  $\text{CO}_2$  emissions discussed in the previous section. If  $\Delta T$  and CE are corrected for the warming and  $\text{CO}_2$  uptake in the ZE simulations, both the amount of cooling and the required negative  $\text{CO}_2$  emissions are larger during the  $\text{CO}_2$  ramp-down phase ( $3.9\text{ }^\circ\text{C}$  and 2710 GtC for the  $4\times\text{CO}_2$  simulation). It should be noted, however, that additional negative  $\text{CO}_2$  emissions are required to maintain atmospheric  $\text{CO}_2$  at the pre-industrial level.

Consistent with the TCRE discussed in the previous paragraph, the ratio  $\Delta T/\text{CE}$  on both upward and downward limbs of the 1%  $\text{CO}_2$  simulations decreases with higher peak  $\text{CO}_2$  levels. The value for  $\Delta T/\text{CE}$  on the upward limb is very similar to the TCRE calculated by linear regression, reflecting the near-linear relationship between  $\Delta T$  and CE. On the other hand, the value for  $\Delta T/\text{CE}$  on the downward limb is smaller than TCRE— reflecting the nonlinear  $\Delta T$  versus CE curve (the ‘bulge’ in the curve steepens the slope calculated by linear regression).

In the  $4\times\text{CO}_2$  ZE hiatus simulations, both  $\Delta T$  and CE are smaller for simulations which are more closely equilibrated with past  $\text{CO}_2$  emissions. This is a result of the smaller  $\text{CO}_2$  decrease during the  $\text{CO}_2$  ramp-down phase (figure 4) for simulations which follow the  $4\times\text{CO}_2$  ZEs trajectory for longer (for instance, atmospheric  $\text{CO}_2$  decreases by 230 ppm less in  $4\times\text{CO}_2$ -ZE-h1000 than in the  $4\times\text{CO}_2$ -ZE-50 during the  $\text{CO}_2$  ramp-down phase). The ratio  $\Delta T/\text{CE}$  is larger the longer the system follows the  $4\times\text{CO}_2$ -ZE trajectory, which is inconsistent with the decrease in TCRE—, a result of the different  $\Delta\text{CO}_2$  during the  $\text{CO}_2$  ramp-down phase in the different simulations.

To remediate the problem of different  $\Delta\text{CO}_2$  in  $4\times\text{CO}_2$ -ZE-h simulations, we examine  $\Delta T$  and CE for  $4\times\text{CO}_2$  constant concentration hiatus simulations ( $4\times\text{CO}_2$ -CC-h), whereby a 1% decrease in atmospheric  $\text{CO}_2$  is prescribed from given points along a constant  $4\times\text{CO}_2$  concentration simulation (which results in the same  $\text{CO}_2$  decline for all simulations). The cooling over the  $\text{CO}_2$  decline phase exhibits non-monotonic behaviour as a function of the time  $\text{CO}_2$  is held constant before the 1%  $\text{CO}_2$  decline is applied (referred to as ‘hiatus’): it increases up to a hiatus of 250 years and then decreases (table 1). In contrast, the amount of negative cumulative emissions required to restore atmospheric  $\text{CO}_2$  from  $4\times\text{CO}_2$  to pre-industrial levels increases with the length of the hiatus. The ratio  $\Delta T/\text{CE}$  decreases with the length of the hiatus, consistently with the decrease in TCRE— for these simulations, with the

value of  $\Delta T/\text{CE}$  being similar to the TCRE— value for simulations with longer hiatus. The  $\Delta T$  and CE behaviour in  $4\times\text{CO}_2$ -CC-h simulations can be understood in terms of two competing processes: the equilibration with past positive  $\text{CO}_2$  emissions, which, based on the discussion above, can be expected to lead to a larger cooling and larger cumulative negative  $\text{CO}_2$  emissions in simulations with longer hiatus; and the equilibration with  $4\times\text{CO}_2$  levels, which leads to reduced cooling and larger required negative  $\text{CO}_2$  emissions in simulations with longer hiatus. The longer the system is exposed to constant  $4\times\text{CO}_2$  levels, the warmer and more carbon rich the deep ocean, such that an imposed decline in atmospheric  $\text{CO}_2$  is less effective at cooling (as the water that mixes to the surface from the deep ocean from the deep ocean is warmer) and requires larger amounts of negative emissions to attain a desired (lower)  $\text{CO}_2$  level.

So far, we have examined  $\Delta T$  and CE only over the period of atmospheric  $\text{CO}_2$  decline. If we consider a longer time period (400 years from the start of the  $\text{CO}_2$  decline, with atmospheric  $\text{CO}_2$  restored to pre-industrial concentrations for several centuries), we find that in the  $4\times\text{CO}_2$  ZE hiatus simulations the amount of cooling is smallest and the temperature is furthest away from pre-industrial the longer the system is left to equilibrate with past  $\text{CO}_2$  emissions (figure 4). The amount of negative emissions is also largest for simulations with the longest ZE hiatus. These results indicate that the later along the zero  $\text{CO}_2$  emissions trajectory the  $\text{CO}_2$  decline is prescribed, the longer it takes to restore global mean surface air temperature to pre-industrial levels.

#### 4. Summary and conclusions

In this study, we explored the relationship between global mean temperature change and cumulative  $\text{CO}_2$  emissions during periods of both positive and net negative  $\text{CO}_2$  emissions. Our results suggest that in Earth system model simulations with a symmetric 1% atmospheric  $\text{CO}_2$  increase and decrease (with the  $\text{CO}_2$  decrease applied right after the time of peak  $\text{CO}_2$ ), the temperature change ( $\Delta T$ ) versus cumulative  $\text{CO}_2$  emissions (CE) relationship is nonlinear. This non-linearity largely arises from the lagged response of the deep ocean to past (positive)  $\text{CO}_2$  emissions, which results in continued warming and ocean  $\text{CO}_2$  uptake after the start of negative  $\text{CO}_2$  emissions.

If the atmospheric  $\text{CO}_2$  decline is prescribed several centuries after the system is left to equilibrate with past  $\text{CO}_2$  emissions, the  $\Delta T$  versus CE relationship is approximately linear. A proportionality constant can therefore be calculated, and compared to the TCRE for periods of positive emissions. We find that in simulations with a symmetric 1% per year atmospheric  $\text{CO}_2$  increase and decrease, the TCRE is larger on the upward than on the downward trajectory, suggesting that positive  $\text{CO}_2$  emissions are more effective at warming than

negative emissions are at subsequently cooling. This difference arises from a dependence of the climate-carbon cycle response on the atmospheric CO<sub>2</sub> level from which the positive/negative emissions are applied.

The cooling effectiveness of net negative emissions as quantified by the TCRE applies to the hypothetical case where net negative emissions are implemented after the system has come to equilibrium with prior (positive) CO<sub>2</sub> emissions. In the real world, if CO<sub>2</sub> emissions are ever to become net negative, this will likely happen when the system is in a state of disequilibrium. This study suggests that in such a situation the effectiveness of net negative CO<sub>2</sub> emissions at lowering global mean temperature will depend on the emission trajectory taken up to the point CO<sub>2</sub> emissions become net negative, with the amount of cooling per unit negative emission decreasing with increasing levels of peak atmospheric CO<sub>2</sub> concentration. The hysteresis in the global mean temperature change versus cumulative CO<sub>2</sub> emission relationship, which arises when net negative CO<sub>2</sub> emissions are implemented right after a period of positive emissions, also has implications for net carbon budgets following overshoot and return to a temperature target. As discussed in [32], these ‘overshoot net carbon budgets’ are path dependent and consistently smaller than the conventional budgets, suggesting that if the carbon budget for a given climate target is exceeded, more carbon needs to be removed from the atmosphere than the magnitude of the overshoot, if a return to the target is desired. Finally, the results from this study may be useful for informing the design of future studies on the effectiveness of net negative CO<sub>2</sub> emissions at lowering the atmospheric CO<sub>2</sub> concentration and reversing climate change. To date, few studies with Earth systems models have explored the response of the Earth system to net negative CO<sub>2</sub> emissions [29, 33–36], but it can be expected that more such studies will be carried out in the future given that atmospheric CDR is receiving increased attention in the climate research community. For instance, a CDR model inter-comparison project (CDR-MIP) has been launched for CMIP6, and our analysis here of the TCRE and the overall climate response to negative emissions can serve as a benchmark to inform this proposed model inter-comparison.

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