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LETTER

On the proportionality between global temperature change and cumulative CO_2 emissions during periods of net negative CO_2 emissions

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Abstract

Recent research has demonstrated that global mean surface air warming is approximately proportional to cumulative CO_2 emissions. This proportional relationship has received considerable attention, as it allows one to calculate the cumulative CO_2 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_2 emissions. Negative CO_2 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_2, the temperature change (ΔT) versus cumulative CO_2 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_2. When corrected for this lagged response, or if the CO_2 decline is applied after the system has equilibrated with the previous CO_2 increase, the ΔT versus CE relationship is close to linear during periods of net negative CO_2 emissions. A proportionality constant—the transient climate response to cumulative carbon emissions (TCRE)—can therefore be calculated for both positive and net negative CO_2 emission periods. We find that in simulations with a symmetric 1% per year increase and decrease in atmospheric CO_2 the TCRE is larger on the upward than on the downward CO_2 trajectory, suggesting that positive CO_2 emissions are more effective at warming than negative emissions are at subsequently cooling. We also find that the cooling effectiveness of negative CO_2 emissions decreases if applied at higher atmospheric CO_2 concentrations.

1. Introduction

Recent research has established a near-proportional relationship between global mean surface air temperature change and cumulative CO_2 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_2 emissions is thought to arise from the compensation of different physical and biogeochemical processes: the increase in airborne fraction at higher cumulative CO_2 emissions, the saturation of radiative forcing of CO_2 at higher atmospheric CO_2 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_2 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_2 emissions persists when net negative CO_2 emissions are applied. Negative CO_2 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_2 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_2 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_2 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 0.3×10^{-4} m^2 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_2 simulations with CO_2 first increasing and then decreasing at 1% per year (referred to as 1% CO_2 simulations), zero CO_2 emissions simulations initialized from the point of peak CO_2 in the 1% CO_2 simulations, zero CO_2 emissions 'hiatus' simulations, whereby a 1% decrease in atmospheric CO_2 is prescribed from given points along a zero CO_2 emissions trajectory, and constant CO_2 concentration hiatus simulations, whereby a 1% decrease in atmospheric CO_2 is prescribed from given points along a constant CO_2 concentration trajectory.

The 1% CO_2 simulations were initialized from a pre-industrial spinup run. Atmospheric CO_2 was prescribed to increase at 1% per year until the time of doubling ($2\times CO_2$), tripling ($3\times CO_2$) and quadrupling ($4\times CO_2$) of the pre-industrial atmospheric CO_2 concentration, and then decrease at the same rate until the pre-industrial CO_2 concentration was restored (figure 1(a), solid lines).

The zero emissions (ZEs) simulations were initialized from the the point of peak CO_2 in the $2\times CO_2$ ($2\times CO_2$-ZE), $3\times CO_2$ ($3\times CO_2$-ZE) and $4\times CO_2$ ($4\times CO_2$-ZE) simulations, with zero prescribed CO_2 emissions after that time (figure 1(a), dotted lines).

The zero CO_2 emissions hiatus simulations were initialized from given points (50, 100, 250, 500 and 1000 years after the time of peak CO_2) along the $4\times CO_2$-ZE simulation. From these points, a 1% decrease in atmospheric CO_2 was prescribed until the pre-industrial atmospheric CO_2 level was restored. These simulations are referred to as $4\times CO_2$-ZE-h50, $4\times CO_2$-ZE-h100, $4\times CO_2$-ZE-h250, $4\times CO_2$-ZE-h500, and $4\times CO_2$-ZE-h1000, respectively. Note that the atmospheric CO_2 level from which the 1% CO_2 decrease was prescribed differs among simulations and therefore the CO_2 change between the beginning and the end of the prescribed CO_2 decrease period is also different (figure 4(a)).

The constant CO_2 concentration hiatus simulations were initialized from given points (50, 100, 250, 500 and 1000 years after the time of peak CO_2) of a simulation with atmospheric CO_2 concentration held constant after the peak in the $4\times CO_2$ simulation. From these points, a 1% decrease in atmospheric CO_2

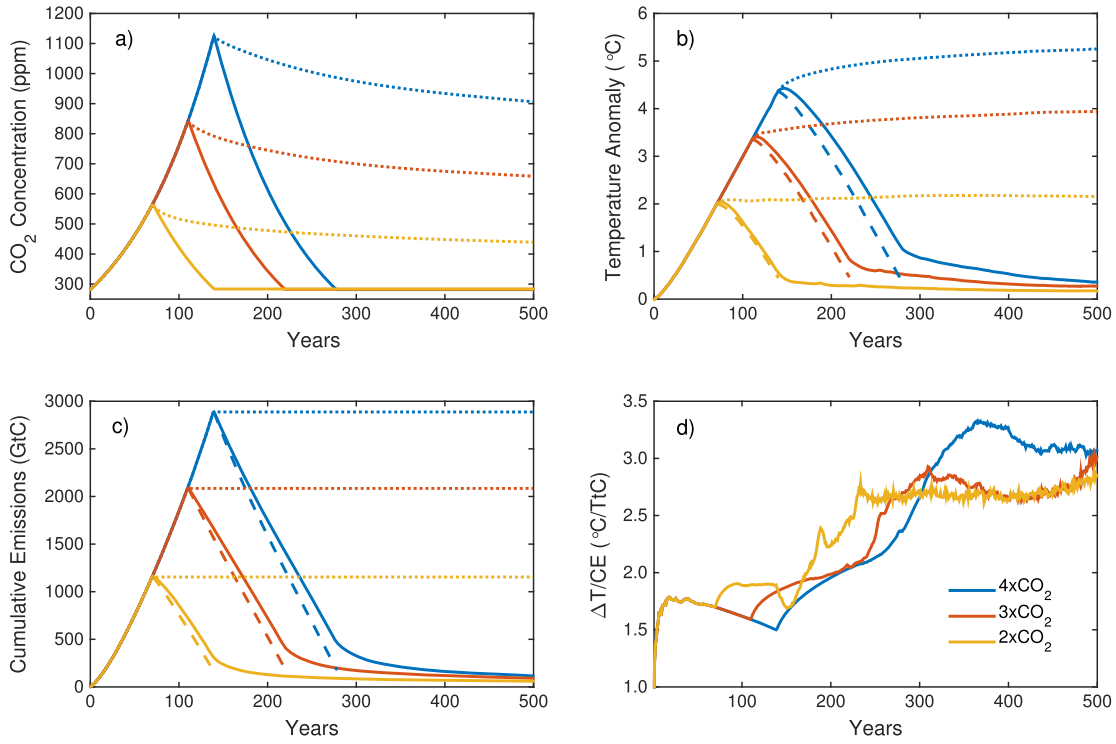

Figure 1. Time series of key climate model variables for 1% CO_2 and zero CO_2 emissions simulations. (a) Atmospheric CO_2 concentration, (b) surface-air temperature anomaly (relative to year 1), (c) cumulative CO_2 emissions, (d) ratio of surface air temperature anomaly (ΔT) to cumulative CO_2 emissions (CE) (TtC; 1 TtC = 10^3 GtC). Solid lines refer to 1% CO_2 simulations, dotted lines refer to simulations with zero CO_2 emissions after the time of peak CO_2 and dashed lines show the 1% CO_2 simulations corrected for the temperature and carbon sink response in the zero emissions simulations (cumulative emissions are corrected for the land and ocean carbon uptake after peak CO_2).

was prescribed, restoring atmospheric CO_2 to pre-industrial levels (supplementary figure 1). These simulations are referred to as 4×CO_2-CC-h50, 4×CO_2-CC-h100, 4×CO_2-CC-h250, 4×CO_2-CC-h500, and 4×CO_2-CC-h1000, respectively.

All simulations were forced with prescribed changes in atmospheric CO_2 or CO_2 emissions only. All other other forcings were held constant at their pre-industrial level. In simulations with prescribed atmospheric CO_2 concentration, CO_2 emissions were diagnosed from the rate of increase in atmospheric CO_2 and carbon fluxes to the land and the ocean as the residual term in the carbon mass balance.

Negative CO_2 emissions are applied generically, without specifying any particular technology. We have assumed that the CO_2 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_2 emissions relationship

First, we examine the relationship between global mean surface air temperature change and cumulative CO_2 emissions for the 1% CO_2 ramp-up, ramp-down simulations (figure 1, solid lines). On the upward limb of the 1% CO_2 simulations, surface air temperature and cumulative CO_2 emissions increase nearly linearly in response to exponentially rising atmospheric CO_2 concentrations. Surface air temperature peaks a few decades after the peak in atmospheric CO_2, with a longer lag for simulations with higher peak atmospheric CO_2. 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_2 simulations. The lagged response of temperature to atmospheric CO_2 decrease is due to the slow thermal equilibration of the deep ocean. Cumulative CO_2 emissions start to decrease (i.e the rate of CO_2 emissions starts to become negative) right after the peak in atmospheric CO_2, indicating that the prescribed CO_2 decline cannot be achieved by CO_2 uptake by natural carbon sinks alone, but requires artificial removal of CO_2 from the atmosphere. Similarly to temperature, the decrease in cumulative emissions is slower than the increase on the upward limb of the 1% CO_2 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 (ΔT) and cumulative CO_2 emissions (CE) exhibits hysteresis behaviour: for a given amount of cumulative CO_2 emissions, ΔT (relative to year 1) is

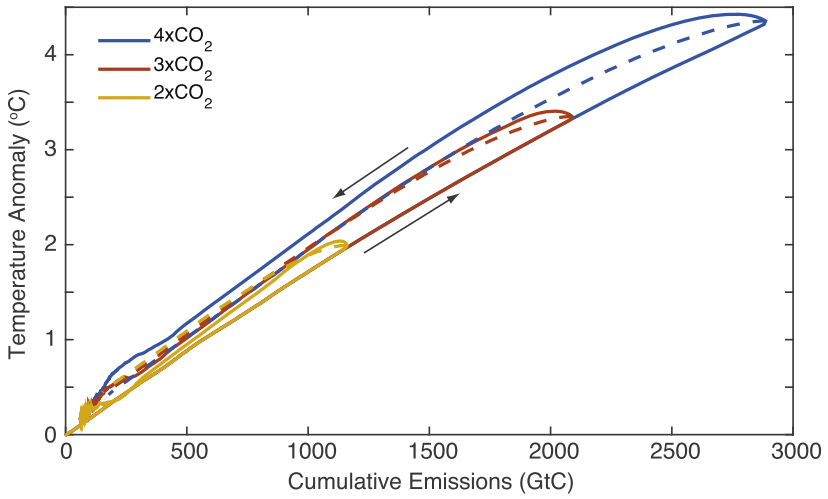

Figure 2. Surface-air temperature anomaly (relative to year 1) versus cumulative CO_2 emissions. Solid lines refer to the 1% CO_2 simulations, dashed lines refer to the 1% CO_2 simulations corrected for the temperature and carbon sink response in the zero CO_2 emissions simulations. The slope of the curves is the transient climate response to cumulative CO_2 emissions (TCRE).

larger on the upward than on the downward limb of the 1% CO_2 simulations (figure 2). Consistently with previous studies [1, 3, 4, 11], the ΔT versus CE relationship is approximately linear during the CO_2 ramp-up phase. During the CO_2 ramp-down phase, however, the ΔT versus CE curve is nonlinear, with larger nonlinearity for simulations with higher peak atmospheric CO_2 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_2 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_2 (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_2 levels start to decline, as the deep ocean is still equilibrating with past (positive) CO_2 emissions (figure 3(f)). On land, vegetation also continues to take up carbon for several years after atmospheric CO_2 starts to decline (figures 3(d) and (e)). This is mostly because of forest expansion at northern high latitudes, which lags atmospheric CO_2 due to the long timescales associated with vegetation shifts (not shown). The lag in the biogeochemical response to CO_2 decline is consistent with the results of [29, 30].

Ocean thermal and biogeochemical inertia affect the ΔT versus CE relationship on the downward limb of the 1% CO_2 simulations in opposite ways. This can be seen by separating the ratio $\Delta T/\mathrm{CE}$ into two terms [1]:

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

where ΔC_A is the change in atmospheric CO_2. Note that for the CO_2 ramp-up phase (positive emissions) changes are defined relative to year 1, whereas for the CO_2 ramp-down phase (negative emissions) changes are defined relative to the time of peak CO_2 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_2 (i.e. larger $\Delta C_A/\mathrm{CE}$), acting to *increase* the ratio $\Delta T/\mathrm{CE}$. On the other hand, thermal inertia results in a smaller temperature drop for the prescribed atmospheric CO_2 decline (i.e. smaller $\Delta T/\Delta C_A$) (figure 3(b)), which acts to *decrease* $\Delta T/\mathrm{CE}$. 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_2 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_2 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_2 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_2 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_2 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_2 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

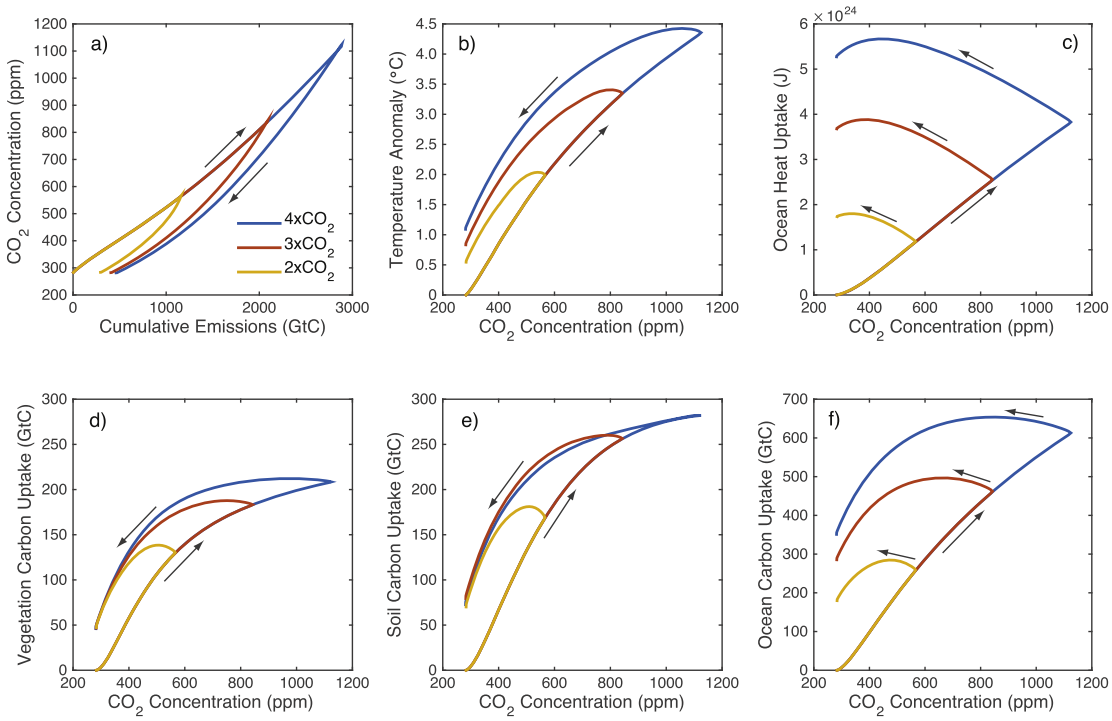

Figure 3. Climate variables as a function of atmospheric CO_2 concentration for 1% CO_2 simulations. (a) Atmospheric CO_2 versus cumulative CO_2 emissions, (b) surface-air temperature anomaly versus atmospheric CO_2 concentration, (c) ocean heat uptake versus atmospheric CO_2 concentration, (d) vegetation carbon uptake versus atmospheric CO_2 concentration, (e) soil carbon uptake versus atmospheric CO_2 concentration, (f) ocean carbon uptake versus atmospheric CO_2 concentration. Data is plotted for the periods of CO_2 increase and decrease only.

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_2 concentration to 4× pre-industrial levels and constant CO_2 concentration thereafter is largely independent of the mixing parameterization [31]. Therefore we expect this balance to be maintained also for zero end negative CO_2 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_2, which also exhibits larger thermal than biogeochemical inertia [29].

The system's response on the downward limb of the 1% CO_2 simulations results from the combination of the lagged response to positive CO_2 emissions prior to the decline in atmospheric CO_2, and the response to negative CO_2 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_2 (figure 1, dotted lines). Over the time of the CO_2 ramp down in the 1% CO_2 simulations (70, 110 and 140 years, respectively), atmospheric CO_2 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_2-ZE, 3×CO_2-ZE and 4×CO_2-ZE simulations, respectively. If the temperature and carbon cycle response on the downward limb of the 1% CO_2 simulations is corrected for the response in the ZE simulations, the ΔT 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_2, 3×CO_2 and 4×CO_2 simulations converge to a similar value. This suggests that the relationship between global mean temperature change and cumulative CO_2 emissions is approximately linear also during periods of net negative CO_2 emissions, provided that the negative emissions are applied from a state where the system is at equilibrium with past CO_2 emissions.

To further test this idea, we examine the system's response in a set of simulations whereby the 1% atmospheric CO_2 decline is prescribed from different points along the 4×CO_2 ZE simulation (figure 4). The hypothesis is that the later the CO_2 ramp down is applied, i.e. the closer the system is to equilibrium with past emissions, the more linear the ΔT versus CE relationship. The linearity of the ΔT versus CE relationship is quantified as the relative deviation of $\Delta T/\mathrm{CE}$ from the slope of the line calculated by linear regression. Results indicate that the later the CO_2 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_2 simulation, where the CO_2 ramp down is applied instantly after peak CO_2 levels are reached, but only

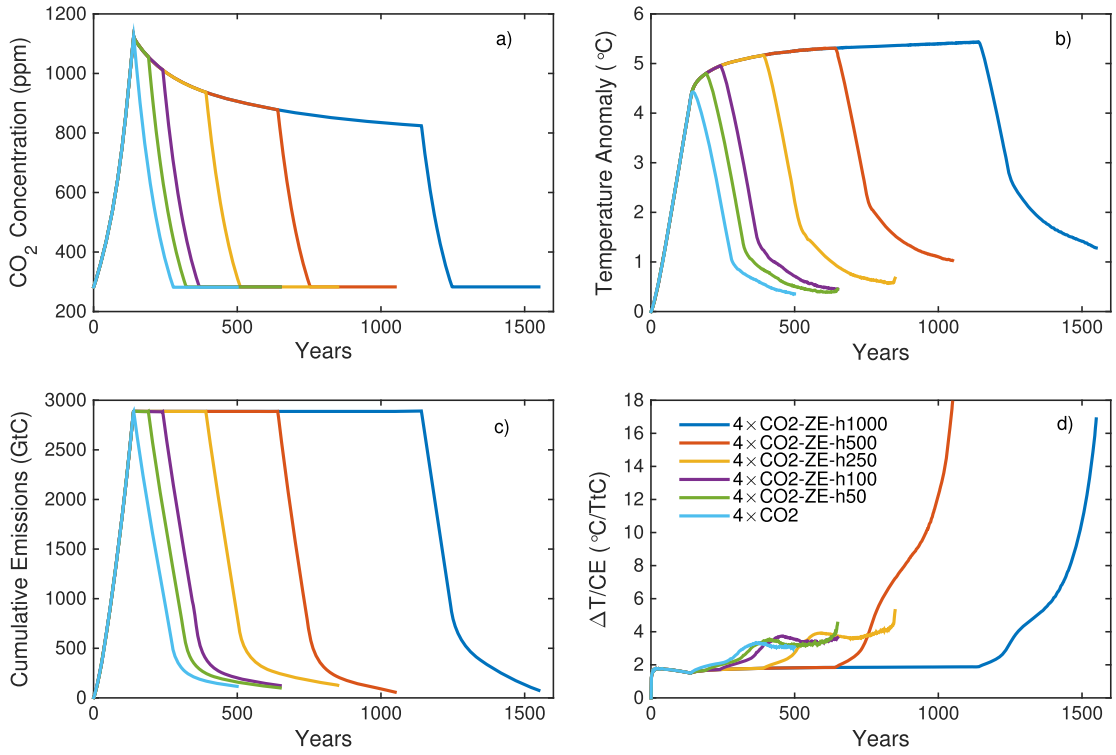

Figure 4. Time series of key climate model variables for $4\times CO_2$ zero emissions hiatus simulations. (a) Atmospheric CO_2 concentration. (b) Surface-air temperature anomaly (relative to year 1). (c) Cumulative CO_2 emissions. (d) Ratio of surface air temperature anomaly (ΔT) to cumulative CO_2 emissions (CE).

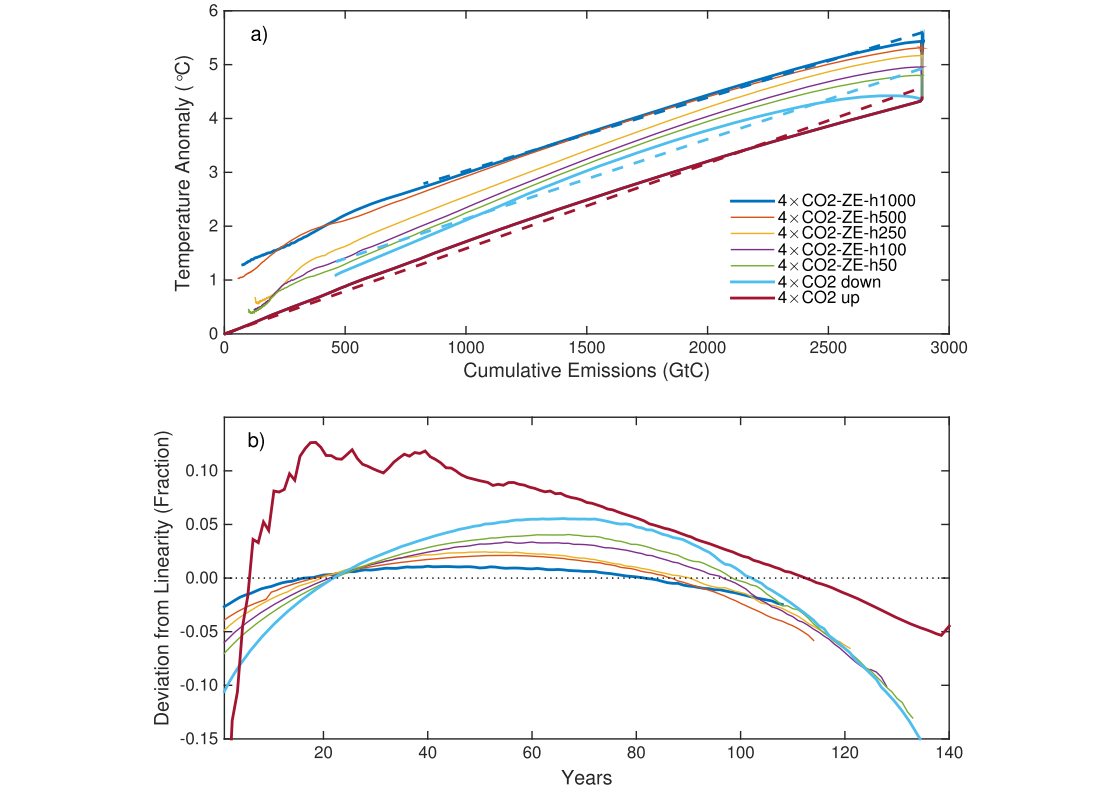

Figure 5. (a) Surface-air temperature anomaly (ΔT) versus cumulative CO_2 emissions (CE) for $4\times CO_2$ zero emissions hiatus simulations. Dashed lines indicate the curves calculated by linear regression over the period of atmospheric CO_2 increase (between year 1 and the year of peak CO_2 concentration) and decrease (between the beginning of the 1% CO_2 decrease period and the year the CO_2 concentration is first restored to pre-industrial levels). Regression curves are shown for select simulations only. (b) Relative deviation of $\Delta T/CE$ from the slope of the corresponding curve calculated by linear regression.

Table 1. Transient climate response to cumulative carbon emissions (TCREs) and ratio of surface air temperature anomaly (ΔT) to cumulative CO_2 emissions (CE). For positive emissions, TCRE is calculated by regressing the ΔT/CE curve over the period of CO_2 increase (between year 1 and the time of peak CO_2), with the regression line forced trough the origin. For negative emissions, TCRE− is calculated over the period of CO_2 decline (between the year CO_2 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_2 concentration. ΔT and CE for periods of CO_2 increase (positive emissions) are calculated at the year of peak CO_2 relative to year 1. ΔT and CE for periods of CO_2 decrease (negative emissions) are calculated between the start and the end of the 1% CO_2 decrease period. ΔT_c and CE_c denote values of ΔT and CE corrected for the temperature and carbon sinks response in the zero emissions simulations ($2\times CO_2$-ZE, $3\times CO_2$-ZE and $4\times CO_2$-ZE, respectively). CE estimates are rounded to the nearest tenth.

Simulation	TCRE (°C/TtC)	ΔT (°C)	CE (GtC)	ΔT_c (°C)	CE_c (GtC)	ΔT/CE (°C/TtC)
$2\times CO_2$ up	1.72	2.0	1160	—	—	1.71
$3\times CO_2$ up	1.65	3.4	2090	—	—	1.60
$4\times CO_2$ up	1.59	4.4	2890	—	—	1.51
$2\times CO_2$ down	1.80	−1.4	−890	−1.5	−1010	1.67
$3\times CO_2$ down	1.62	−2.5	−1680	−2.9	−1910	1.50
$4\times CO_2$ down	1.48	−3.3	−2430	−3.9	−2710	1.35
$4\times CO_2$-ZE-h50	1.55	−3.5	−2380	—	—	1.31
$4\times CO_2$-ZE-h100	1.55	−3.5	−2340	—	—	1.33
$4\times CO_2$-ZE-h250	1.52	−3.3	−2270	—	—	1.45
$4\times CO_2$-ZE-h500	1.38	−3.1	−2300	—	—	1.48
$4\times CO_2$-ZE-h1000	1.36	−2.7	−2070	—	—	1.47
$4\times CO_2$-CC-h50	1.51	−3.6	−2530	—	—	1.43
$4\times CO_2$-CC-h100	1.50	−3.7	−2610	—	—	1.42
$4\times CO_2$-CC-h250	1.44	−3.8	−2740	—	—	1.38
$4\times CO_2$-CC-h500	1.34	−3.6	−2850	—	—	1.28
$4\times CO_2$-CC-h1000	1.21	−3.5	−2990	—	—	1.15

2% in the simulation where 1000 years elapse before the CO_2 decline is applied ($4\times CO_2$-ZE-h1000).

3.2. Quantifying the ΔT versus CE relationship for net negative CO_2 emissions

Given that a near-proportional relationship exists between global mean temperature change and cumulative CO_2 emissions during periods of net negative CO_2 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− to distinguish it from the TCRE during periods of positive emissions. Both TCRE and TCRE− are calculated by linear regression of the ΔT versus CE curve (table 1; see caption for details about the calculation). On the upward limb of the 1% CO_2 simulations, TCRE is lowest for the simulation with the largest peak atmospheric CO_2 concentration ($4\times CO_2$), consistent with previous studies that show a lower TCRE at higher cumulative emissions (e.g. [13]). On the downward limb of the 1% CO_2 simulations, TCRE is also lowest for the simulation with the largest peak atmospheric CO_2 concentration, suggesting that negative emissions are less effective at cooling if applied at higher atmospheric CO_2 concentration. In the $4\times CO_2$ ZE hiatus simulations, TCRE− is lowest for the simulation in which the CO_2 decline is applied from the latest point on the zero CO_2 emissions trajectory, i.e. when the system is closer to equilibrium with past emissions ($4\times CO_2$-ZE-h1000). As discussed in the previous section, this is also the simulation for which the ΔT versus CE relationship is closest to linear. Therefore, it can be expected that the TCRE− for the $4\times CO_2$-ZE-h1000 simulation (1.4 °C/TtC) is closest to the 'true' TCRE− value (i.e. the value that would result if the CO_2 decline were applied when the system is fully equilibrated with past CO_2 emissions). This value is somewhat lower than the TCRE on the upward limb of the $4\times CO_2$ simulation (1.6 °C/TtC), suggesting that negative CO_2 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_2 emissions, but rather from differences in the background atmospheric CO_2 concentration from which the positive and negative CO_2 emissions are applied. This state dependence can be explained by the stronger ocean stratification at $4\times CO_2$, from which the CO_2 decline is applied, compared to pre-industrial CO_2 levels, from which the CO_2 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_2 increase.

In the following, we examine ΔT and CE for the period of atmospheric CO_2 increase (between year 1 and the year of peak CO_2) and decrease (between the start of the CO_2 decline and the year of restoration of the pre-industrial CO_2 concentration) for the various simulations (table 1). The magnitude of both ΔT and CE is larger on the upward than on the downward limb of the 1% CO_2 simulations. For instance, the climate warms by 4.4 °C if atmospheric CO_2 is ramped

up to 4×CO_2, but cools only by 3.3 °C if atmospheric CO_2 is ramped down to pre-industrial levels at the same rate. Also, cumulative CO_2 emissions consistent with ramping up atmospheric CO_2 to 4×CO_2 are 2890 GtC, whereas 2430 GtC need to be removed to restore atmospheric CO_2 from 4×CO_2 to pre-industrial levels. The lower ΔT and CE on the downward limb of the 1% CO_2 simulations are associated with the continued warming and CO_2 uptake in response to past positive CO_2 emissions discussed in the previous section. If ΔT and CE are corrected for the warming and CO_2 uptake in the ZE simulations, both the amount of cooling and the required negative CO_2 emissions are larger during the CO_2 ramp-down phase (3.9 °C and 2710 GtC for the 4×CO_2 simulation). It should be noted, however, that additional negative CO_2 emissions are required to maintain atmospheric CO_2 at the pre-industrial level.

Consistent with the TCRE discussed in the previous paragraph, the ratio $\Delta T/\mathrm{CE}$ on both upward and downward limbs of the 1% CO_2 simulations decreases with higher peak CO_2 levels. The value for $\Delta T/\mathrm{CE}$ on the upward limb is very similar to the TCRE calculated by linear regression, reflecting the near-linear relationship between ΔT and CE. On the other hand, the value for $\Delta T/\mathrm{CE}$ on the downward limb is smaller than TCRE− reflecting the nonlinear ΔT versus CE curve (the 'bulge' in the curve steepens the slope calculated by linear regression).

In the 4×CO_2 ZE hiatus simulations, both ΔT and CE are smaller for simulations which are more closely equilibrated with past CO_2 emissions. This is a result of the smaller CO_2 decrease during the CO_2 ramp-down phase (figure 4) for simulations which follow the 4×CO_2 ZEs trajectory for longer (for instance, atmospheric CO_2 decreases by 230 ppm less in 4×CO_2-ZE-h1000 than in the 4×CO_2-ZE-50 during the CO_2 ramp-down phase). The ratio $\Delta T/\mathrm{CE}$ is larger the longer the system follows the 4×CO_2-ZE trajectory, which is inconsistent is with the decrease in TCRE−, a result of the different ΔCO_2 during the CO_2 ramp-down phase in the different simulations.

To remediate the problem of different ΔCO_2 in 4×CO_2-ZE-h simulations, we examine ΔT and CE for 4×CO_2 constant concentration hiatus simulations (4×CO_2-CC-h), whereby a 1% decrease in atmospheric CO_2 is prescribed from given points along a constant 4×CO_2 concentration simulation (which results in the same CO_2 decline for all simulations). The cooling over the CO_2 decline phase exhibits non-monotonic behaviour as a function of the time CO_2 is held constant before the 1% 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 CO_2 from 4×CO_2 to pre-industrial levels increases with the length of the hiatus. The ratio $\Delta T/\mathrm{CE}$ decreases with the length of the hiatus, consistently with the decrease in TCRE− for these simulations, with the value of $\Delta T/\mathrm{CE}$ being similar to the TCRE− value for simulations with longer hiatus. The ΔT and CE behaviour in 4×CO_2-CC-h simulations can be understood in terms of two competing processes: the equilibration with past positive CO_2 emissions, which, based on the discussion above, can be expected to lead to a larger cooling and larger cumulative negative CO_2 emissions in simulations with longer hiatus; and the equilibration with 4×CO_2 levels, which leads to reduced cooling and larger required negative CO_2 emissions in simulations with longer hiatus. The longer the system is exposed to constant 4×CO_2 levels, the warmer and more carbon rich the deep ocean, such that an imposed decline in atmospheric 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) CO_2 level.

So far, we have examined ΔT and CE only over the period of atmospheric CO_2 decline. If we consider a longer time period (400 years from the start of the CO_2 decline, with atmospheric CO_2 restored to pre-industrial concentrations for several centuries), we find that in the 4×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 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 CO_2 emissions trajectory the 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 CO_2 emissions during periods of both positive and net negative CO_2 emissions. Our results suggest that in Earth system model simulations with a symmetric 1% atmospheric CO_2 increase and decrease (with the CO_2 decrease applied right after the time of peak CO_2), the temperature change (ΔT) versus cumulative CO_2 emissions (CE) relationship is nonlinear. This nonlinearity largely arises from the lagged response of the deep ocean to past (positive) CO_2 emissions, which results in continued warming and ocean CO_2 uptake after the start of negative CO_2 emissions.

If the atmospheric CO_2 decline is prescribed several centuries after the system is left to equilibrate with past CO_2 emissions, the ΔT 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 CO_2 increase and decrease, the TCRE is larger on the upward than on the downward trajectory, suggesting that positive 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_2 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_2 emissions. In the real world, if CO_2 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_2 emissions at lowering global mean temperature will depend on the emission trajectory taken up to the point CO_2 emissions become net negative, with the amount of cooling per unit negative emission decreasing with increasing levels of peak atmospheric CO_2 concentration. The hysteresis in the global mean temperature change versus cumulative CO_2 emission relationship, which arises when net negative CO_2 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 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_2 emissions at lowering the atmospheric CO_2 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_2 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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