Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

Geoscientific Model Development Discussions
Open Access EGU

Limitations of the 1% experiment as the benchmark idealized experiment for carbon cycle intercomparison in C^4MIP

Andrew H. MacDougall[1]

[1]Climate & Environment, St. Francis Xavier University, Antigonish, Nova Scotia, Canada.

Correspondence: AH MacDougall (amacdoug@stfx.ca)

Abstract. Idealized climate change simulations are used as benchmark experiments to facilitate the comparison of ensembles of climate models. In the Fifth Assessment Report of the IPCC the 1% per yearly compounded change in atmospheric CO_2 concentration experiment was used to compare Earth System Models with full representations of the global carbon cycle (C^4MIP). However this "1% experiment" was never intended for such a purpose and implies a rise in atmospheric CO_2 concentration at double the rate of the instrumental record. Here we examine this choice by using an intermediate complexity climate model to compare the 1% experiment to an idealized CO_2 pathway derived from a logistic function. The comparison shows that the logistic experiment has three key differences from the 1% experiment. (1) The Logistic experiment exhibits a transition of the land biosphere from a carbon sink to a carbon source, a feature absent from the 1% experiment. (2) The ocean uptake of carbon comes to dominate the carbon cycle as emissions decelerate, a feature that cannot be captured by the 1% experiment as emissions always accelerate in that experiment. (3) The permafrost carbon feedback to climate change in the 1% experiment is less than half the strength of the feedback seen in the logistic experiment. The logistic experiment also allows smooth transition to zero or negative emission states, allowing these states to be examined without sharp discontinuities in CO_2 emissions. The protocol for the CMIP6 iteration of C^4MIP again sets the 1% experiment as the benchmark experiment for model intercomparison, however clever use of the Tier 2 experiments may alleviate some of the limitations outlined here. Given the limitations of the 1% experiment as the benchmark experiment for carbon cycle intercomparisons, adding a logistic or similar idealized experiment to the protocol of the CMIP7 iteration of C^4MIP is recommended.

1 Introduction

Idealized climate change experiments are used as common framework to compare the output of ensembles of climate models (Houghton et al., 1996). These experiments are used to estimate standard Earth system metrics such as: Climate Sensitivity (Gregory et al., 2004), Transient Climate Response (Houghton et al., 2001; Raper et al., 2002), and Transient Climate Response to Cumulative Emissions (TCRE) (Gillett et al., 2013). Two of the idealized experiments outlined by the Climate Model Intercomparison Project (CMIP) and the Intergovernmental Panel on Climate Change (IPCC) prescribe changes only in atmospheric CO_2 concentration, the $4\times$ CO_2 experiment and the 1% per year compounded increased in atmospheric CO_2 experiment (hereafter referred to as the 1% experiment)(Meehl et al., 2007; Taylor et al., 2012; Eyring et al., 2016). Using either of these experiments allows for the study of the effect of CO_2 on the Earth system without having to account for the confounding effects of land-use-change, non-CO_2 greenhouse gases, and aerosols. The $4\times$ CO_2 experiment prescribes an instantaneous quadrupling of atmospheric CO_2 concentration (relative to pre-industrial concentration) and is principally used to estimate equilibrium climate sensitivity (Gregory et al., 2004; Rugenstein et al., 2016). The 1% experiment prescribes a rise in atmospheric CO_2 concentration from pre-industrial concentration at 1% a year compounded, resulting in a doubling of CO_2 concentration at year 70 of the simulation, and a quadrupling of CO_2 concentration at year 140 of the simulation. The 1% experiment has principally been used to derive the Transient Climate Response, defined as the temperature change at the time of atmospheric CO_2 doubling in a 1% experiment (Houghton et al., 2001; Collins et al., 2013). As part of CMIP phase 5 (CMIP5) the 1% experiment was used for to compare the carbon cycle feedbacks within Earth System Models (ESMs) (Taylor et al., 2012; Arora et al., 2013), and to derive values of TCRE and thus to compute carbon budgets compatible with various temperature targets (Gillett et al., 2013). A similar modelling protocol has been established for forthcoming CMIP6 simulations (Jones et al., 2016). However, a clear rationale for using the 1% experiment for analysis of the carbon cycle is absent from the literature. Here we critically examine this choice and propose a more suitable idealized experiment for examining carbon cycle feedbacks to climate change.

The first documented use of the 1% experiment was by Stouffer et al. (1989) where the experiment was used to force an early ocean-atmosphere general circulation model developed by the Geophysical Fluid Dynamics Laboratory [Personal Communication, R.J. Stouffer]. The 1% rate of increase was chosen to approximate the rate of increase of all anthropogenic greenhouse gasses observed at the time Stouffer et al. (1989) (while not accounting for cooling from aerosols, a process that was poorly quantified in the 1980s (Houghton et al., 2001)). The exponential functional form of the experiment was chosen because radiative forcing from CO_2 is approximately a logarithmic function of change in atmospheric CO_2 concentration. Therefore, an exponential rise in atmospheric CO_2 at 1% a year compounded results in a 1% a year linear increase in radiative forcing at the top of the atmosphere Stouffer et al. (1989). Thus the increase in CO_2 was intended to represent the rise in all greenhouse gases and it was well understood that CO_2 concentration rose much faster in the 1% experiment than it was expected to rise in the natural world. Since yearly records began in 1958 the annual rate of change in atmospheric CO_2 concentration has ranged between 0.09% in 1964 and 0.8% in 1998 with a mean of 0.43% from 1958 to 2016 (Figure 1). The numerical experiment of Stouffer et al. (1989) was included in the First Assessment Report of the IPCC Houghton et al. (1992) and by the time of the Second assessment report the 1% experiment had become a standard benchmark numerical experiment for climate model intercomparison Houghton et al. (1996). In preparation for the sixth assessment report of the IPCC (AR6) the 1% experiment has been incorporated into the CMIP Diagnostic, Evaluation and Characterization of Klima (DECK) protocol, (Eyring et al., 2016), intended to be the CMIP core set of experiments for the indefinite future (Eyring et al., 2016).

The development of Earth System Model (climate models including carbon cycles (Planton, 2013)) created a need for a transient CO_2-only experiment for use in model lncomparisons of this new class of model (Friedlingstein et al., 2006). In the first intercomparison of ESMs, a modified version of the Special Report on Emissions Scenarios A2 experiment was used, where non-CO_2 forcing and land-use-changes from the scenario where turned off for the simulation (Friedlingstein et al., 2006). However, later studies utilizing model output from the Coupled Climate–Carbon Cycle Model Intercomparison Project (C^4MIP) implicitly criticized the choice of the A2 scenario, calling for the 1% experiment to be used in place of a modified

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

scenario (Matthews et al., 2009). This recommendation was implemented with the CMIP5 protocols calling for benchmark carbon cycle experiments to be carried out using a 1% experiment Taylor et al. (2012). The protocol for the CMIP6 iteration of C^4MIP also calls for the 1% experiment to be used at the benchmark for carbon cycle model intercomparison, along with a selection of scenario based simulations (Jones et al., 2016).

The carbon cycle is classically subdivided into the terrestrial carbon cycle, dominated by plant and soil biology, and the oceanic carbon cycle, dominated by ocean carbonate chemistry but influenced by ocean biogeochemistry (Ciais et al., 2013). Together these processes remove over half of the carbon emitted to the atmosphere by burning of fossil fuels and land-use-change, greatly mitigating the effect of CO_2 emissions on climate change (e.g. Le Quéré et al., 2018). In the terrestrial domaine there are three major feedbacks that are induced by increases in atmospheric CO_2 concentration and resultant climate warming. The response of plants in CO_2 limited ecosystems to increased atmospheric concentration of CO_2 is the CO_2 fertilization effect, whereby primary productivity is increased leading to larger plant biomass and an increased flux of dead biomass into soils (e.g. Ciais et al., 2013). The rate of heterotrophic respiration of soil organic matter is strongly controlled by temperature (Jenkinson et al., 1991), such that warmer soil temperature tend to induce a faster overturn of soil organic matter and release of carbon to the atmosphere (Jenkinson et al., 1991). This enhanced soil respiration is especially significant in permafrost environments where the switch from dominantly frozen soils to dominantly thawed soils dramatically increases the rate of respiration and can lead to the release of long-sequestered pools of carbon (Schuur et al., 2015). The third major feedback affecting the terrestrial realm is ecosystem changes resulting from climate warming and can be either a positive or negative feedback depending on the region of the world (e.g. Malhi et al., 2009; Ciais et al., 2013).

In the ocean domain uptake of carbon is driven by the difference in the partial pressure of CO_2 (pCO_2) between the surface ocean and the atmosphere (e.g. Greenblatt and Sarmiento, 2004). Where atmospheric CO_2 concentration is higher than local sea surface pCO_2, atmospheric CO_2 will invade the ocean system. Due to ocean carbonate chemistry most of the carbon that enters the ocean is reacted to bicarbonate ions, with a relatively small fraction held as dissolved CO_2 – the species that controls ocean pCO_2 (e.g. Greenblatt and Sarmiento, 2004). Like most gases dissolved CO_2 has a higher partial pressure in warm water relative to colder water such that climate warming is expected to reduce the efficiency of ocean carbon uptake (Ciais et al., 2013). On centennial timescales the ocean has a relatively fixed alkalinity such that the ocean carbonate chemistry equilibrium will shift to a state where more carbon is held as dissolved CO_2, an effect which also reduces the efficiency of ocean carbon uptake (Broecker and Peng, 1982). Over longer time periods the ocean will increase its alkalinity by dissolving calcium carbonate from ocean sediments, allowing the ocean to absorb additional CO_2 from the atmosphere (Archer, 1996). Thus, the ocean is expected to become less efficient at absorbing carbon as CO_2 emissions continue but is expected to continue to be a carbon sink far into the future (Arora et al., 2013). However, feedbacks involving ocean biogeochemistry and changes in overturning circulation remain important but poorly quantified uncertainties (Jones et al., 2016).

Carbon cycle feedbacks are affected both by the concentration of atmospheric CO_2, air temperature, and the rates of change of these qualities (e.g. Greenblatt and Sarmiento, 2004). A faster rise in atmospheric CO_2 will increase the partial pressure gradient between the atmosphere and the ocean, tending to increase the rate of ocean carbon invasion, however the ocean will have less time to overturn the mixed layer tending to reduce the invasion rate. The CO_2 fertilization effect depends on CO_2

concentration but the buildup of carbon in soils from higher primary productivity and thus enhanced soil respiration depends on the rate of change of CO_2. Permafrost carbon feedbacks in particular are sensitive to the rate of change in temperature as it takes time to thaw soils and decay the highly recalcitrant permafrost carbon pool (e.g. Schuur et al., 2015). Thus using the 1% experiment as the benchmark for carbon cycle model intercomparison may be problematic given that CO_2 rises in the experiment at twice the historical rate. Such concerns are supported by a recent study utilizing an intermediate complexity ESM with a representation of the permafrost system, and forced with the 1% experiment. The study showed a permafrost carbon feedback strength evaluated at year 70 of the 1% experiment only $\sim$ 8% of the feedback strength evaluated in the year 2100 CE of the RCP 8.5 scenario with the same model (MacDougall et al., 2017; MacDougall and Knutti, 2016). MacDougall et al. (2017) concluded that the 1% experiment warmed too fast to allow permafrost to thaw. The study recommended a different idealized CO_2-only experiment be developed to help evaluate effect of permafrost carbon feedbacks on climate change. Here we develop such a new idealized scenario and compare it to the 1% experiment.

2 Methods

2.1 Model Description

The University of Victoria Earth System Climate Model (UVic ESCM) is a climate model of intermediate complexity that participate in both the original C[4]MIP and the CMIP5 iteration of C[4]MIP (Friedlingstein et al., 2006; Arora et al., 2013). The core of the model is a full three dimensional ocean general circulation model coupled to a simplified moisture and energy balance atmosphere (Weaver et al., 2001). The UVIC ESCM contains a detailed representation the global carbon cycle including oceanic and terrestrial components. The ocean carbonate chemistry is simulated following the protocols of the ocean carbon cycle model intercomparison project (Orr et al., 1999), and ocean biogeochemistry is represented using a nutrient-phytoplankton-zooplankton-detritus ocean biology scheme (Schmittner et al., 2008). The slow dissolution of ocean carbonate sediments follows (Archer, 1996). The terrestrial carbon cycle is represented using the Top-down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) dynamic vegetation model (Meissner et al., 2003; Matthews et al., 2004; Cox et al., 2001). The version of the model used in the present study is a modified variant of the frozen ground version of the UVic ESCM which includes a representation of the permafrost carbon pool (MacDougall and Knutti, 2016), and is the same version of the model used in MacDougall et al. (2017) where the limitations of the 1% experiment with respect to the permafrost carbon feedback were first encountered.

2.2 A new idealized experiment

We can conceptualize CO_2 emission pathways as having four possible stages: (1) accelerating emissions, that are captured by the 1% experiment and also by the modified A2 scenario used by the original C[4]MIP (Friedlingstein et al., 2006). (2) Decelerating emissions, the stage of emissions following peak emissions captured by many climate scenarios (Meinshausen et al., 2011). (3) Zero emissions, a stage used to investigate the behaviour of the carbon cycle after CO_2 emissions cease (e.g.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

Matthews and Weaver, 2010; Frölicher et al., 2014). And (4) negative emissions, a stage used to investigate the behaviour of the carbon cycle during a hypothesized mass deployment of artificial atmospheric CO_2 removal technology (e.g. Samanta et al., 2010; Boucher et al., 2012; Zickfeld et al., 2013). Thus an ideal idealized scenario should include both an acceleration and deceleration phase, and allow for a smooth transition to zero emissions or negative emission potentialities.

There are an infinite number of CO_2 pathways that could satisfy these core criteria.Thus two more constraints are added: that the pathway roughly follow the CO_2 trajectory of the historical record (Trans and Keeling, 2017), and the the pathway be an elementary function. Given these criteria a logistic function was settled upon:

$$C_A = \frac{C_{Ap}}{1+e^{-k(t-t_m)}} + C_{Ao} \quad (1)$$

where C_A is the atmospheric CO_2 concentration, C_{Ao} is the original atmospheric CO_2 concentration, C_{Ap} is peak atmospheric CO_2 concentration, t is time, t_m is the mid-point of the function, and k is a rate constant. k and t_m are found by fitting the function to the historical CO_2 record. C_{Ao} is taken to be 280 ppm and k and t_m values for $2\times$, $4\times$, and $8\times$ pathways are shown in Table 1, these pathways are displayed in Figure 2a. Logistic functions are common in nature and appear in systems where growth is limited by finite resources (e.g Reed and Berkson, 1929). Famously a logistic equation is one solution to the Verhulst-Lotka population growth equations (e.g Berryman, 1992), and RCP extension scenarios (except for the peak-and-decline RCP 2.6) resemble logistic functions (Moss et al., 2010).

The $4\times$ CO_2 logistic pathway is compared to the historical CO_2 trajectory, the $4\times$ CO_2 1% experiment pathway, and the pathway of Wigley and Schlesinger (1985) in figure 3. The Wigley and Schlesinger (1985) pathway was an early alternative to the 1% experiment the fell out of use before IPCC SAR. The figure demonstrates how fast CO_2 concentration grows in the 1% experiment relative to to the historical record and also how much closer the Wigley and Schlesinger (1985) pathway trends to the post 1985 historical record. Logistic functions asymptote towards their high and low bounds as the function approached positive and negative infinity, hence how close the function is to the peak and preindustrial CO_2 concentration depends on the match between the logistic function and the historical CO_2 record. Treating year 1850 as the preindustrial reference time and making the function symmetric about its mid-point leads to preindustrial and peak CO_2 values within 1 ppm of the target value for the three derived pathways.

2.3 Model experiments

The UVic ESCM was forced with three versions of the 1% experiment and three logistic CO_2 pathways, with CO_2 concentrations reaching a peak of $2\times$, $4\times$, and $8\times$ pre-industrial concentration. Following peak CO_2 concentration model experiments branch to a zero emissions scenario and a negative emissions scenario. In the zero emissions scenario the model is switched from prescribed atmospheric CO_2 to freely evolving CO_2 with fossil fuel emission rate set to zero such that natural sources and sinks determine atmospheric CO_2 concentration (Eby et al., 2009). In the negative emissions scenario CO_2 concentration return to pre-industrial concentration in a mirror image of their original rise (Figure 4). For the 1% experiment the negative emissions scenario is the 1% up, 1% down experiment used by several previous studies (Samanta et al., 2010; Boucher et al.,

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

2012; Zickfeld et al., 2013, 2016). In model simulations where atmospheric CO_2 concentration is prescribed, anthropogenic emissions are diagnosed from conservation of mass as the residual of the carbon cycle.

The UVic ESCM is being used here simply to illustrate the differences between the behaviour of the carbon cycle in the 1% and logistic experiments. Replication of the logistic experiment with different ESMs is necessary to confirm the result presented below. In particular the behaviour of the terrestrial carbon pool is likely to be different in different ESMs Friedlingstein et al. (2006); Arora et al. (2013).

3 Results

3.1 Accelerating & Decelerating Emissions

The evolution of atmospheric CO_2 concentration under the logistic and 1% experiments are shown in figure 2. The figure also shows the diagnosed emissions for each of the pathways. The emissions for the logistic experiment grow slowly for the first 100 years of the simulation, then enter a stage of rapid acceleration before reaching peak emissions and going into a deceleration phase. After the peak emissions decelerate rapidly before entering a long tail of low but persistent emissions. For the 1% experiment emissions monotonically increase through time, with the rate of change in emissions slowing as $2\times$ CO_2 is approached but accelerating again as $4\times$ CO_2 is approached. For the logistic experiments CO_2 emissions peak at 10, 17 and 28 Pg C a^{-1} respectively for the $2\times$, $4\times$, and $8\times$ pathways. For the 1% experiments emissions always peak at the termination of the experiment with values of 21, 29 and 48 Pg C a^{-1} respectively for the $2\times$, $4\times$, and $8\times$ pathways. For perspective recall that 2017 anthropogenic CO_2 emissions are 11 Pg C a^{-1} (Le Quéré et al., 2018).

A key purpose of carbon cycle models and related model intercomparison projects is to explore how the ocean system and land biosphere carbon sinks will operate under changed climate conditions (e.g. Friedlingstein et al., 2006). One way of visualizing these processes is through the fraction of emitted carbon that is stored in each of the main near-surface carbon reservoirs. Hence we can define airborne, ocean-borne and land-borne fractions of carbon. These can be defined either as instantaneous fractions, the fraction of carbon emitted this year that ends up in each reservoir, or as cumulative fractions – the fraction of carbon emitted since pre-industrial times held in the ocean, land, and atmosphere. Instant fractions give an immediate sense of how the Earth system is reacting to changes in CO_2 concentration and temperature but are not defined once emissions reach zero. Figure 5 shows the instantaneous and cumulative airborne, ocean-borne, and land-borne fractions of carbon for the logistic and 1% $4\times$ CO_2 experiments. The accelerating phase of the logistic experiment closely resembles the 1% experiment with closely matched ocean-borne and land-borne fractions early in the simulation, a gradual rise in the airborne fraction of carbon and decline in the land-borne fraction near the end of the acceleration phase. In the emission deceleration phase of the logistic experiment the carbon cycle behaves differently. As emissions slow the land system transitions from a carbon sink to a carbon source, while the ocean sink comes to dominate the system absorbing more carbon than the net emissions to the atmosphere.

Figure 6 shows the evolution of the land carbon pool anomalies in the $4\times$ CO_2 1% and logistic experiments. The land pool is shown broken down into carbon held in living vegetation, soil carbon, and permafrost carbon (carbon that had been frozen

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

Geoscientific Model Development Discussions

in permafrost soil layers at the beginning of the simulation, which maintains distinct properties after being thawed in the UVic ESCM model scheme (MacDougall and Knutti, 2016)). The figure shows that in both experiments the permafrost carbon pool declines monotonically, and vegetation carbon increases with CO_2 concentration. However, in the logistic simulation the soil carbon pool increases to a peak anomaly of 259 Pg C before declining to near zero by the end of the simulation. Under the 1% experiment the soil carbon pool anomaly peaks but only just begins a decline before the simulation ends. Hence an enhanced soil respiration feedback is evident in the logistic experiment but not captured well in the 1% experiment.

The second key feature of the carbon cycle under decelerating emissions is the increase in the instantaneous ocean-borne fraction of carbon. The feature is explored in figure 7 which shows the absolute uptake of carbon by the land, ocean, and atmosphere. The figure shows that ocean carbon uptake does decline in the logistic experiment as the CO_2 emission rate decelerates, however the ocean remains a sink and by the end of the simulation is absorbing carbon at 1.3 Pg C a^{-1}. Given that in multi-millennial ESM simulations the ocean tends to absorb carbon for many centuries after emissions cease (e.g. Eby et al., 2009) this feature is not unexpected, but to our knowledge increasing ocean-borne fraction under decelerating emissions has not been explicitly pointed out in literature.

The motivation to create the logistic pathway experiments was the weak response on the permafrost carbon feedback under the 1% experiment relative to the feedback strength seen under the RCP scenarios (MacDougall et al., 2017). The response of carbon in the permafrost region (including both the modelled permafrost carbon pool and regular soil carbon in the active layer above the permafrost) is shown in figure 8. At the mid-point of the $4\times$ CO_2 simulations, where carbon cycle feedbacks are classically evaluated (e.g. Arora et al., 2013), the permafrost region has released 19 PgC under the 1% experiment and 55 PgC under the logistic experiment. By the end of each simulations the permafrost region releases 99 PgC under the 1% experiment and 238 PgC under the logistic experiment. Figure 8 demonstrates the importance of time in destabilizing permafrost carbon, with the slower warming logistic experiment having a higher release of carbon from permafrost regions at any given CO_2 concentration.

3.2 Zero Emissions

An important question posed to ESMs concerns evolution of atmospheric CO_2 concentration and global temperature following total cessation of net CO_2 emissions (e.g. Matthews and Weaver, 2010; Frölicher et al., 2014). Whether global temperature will increases, decreases, or stabilizes following cessation of emissions determines the final size of carbon budgets compatible with temperature targets, and has important policy implications (e.g. Frölicher et al., 2014). The change in temperature following cessation of CO_2 emissions is termed the Zero Emissions Commitment (ZEC) (Zickfeld et al., 2012). The evolution of atmosphere CO_2 and cumulative carbon fractions following cessation of emissions for the logistic and 1% experiments is shown in figure 9. In both experiments atmospheric CO_2 concentration drops after emissions cease, consistent with most other ESMs (Frölicher et al., 2014). The carbon fractions for both experiments are similar after emissions cease, with the airborne and land-borne fractions of carbon declining and the ocean-borne fraction of carbon increasing. The difference between the logistic and 1% experiments is most evident when emissions cease. The logistic experiment has a continuous behaviour as emissions accelerate, decelerate then reach zero, while the 1% experiment exhibits a sharp discontinuity in behaviour when

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

emissions cease (figure 9). The airborne fraction goes from increasing to decreasing, the ocean-borne fraction goes from stable to increasing, and the land-borne fraction goes from declining quickly to declining slowly. Figure 10 shows the evolution of the surface air temperature anomaly for the logistic and 1% experiments during the transient simulation and following cessation of emissions. Both experiments have positive ZEC, with the logistic experiment warming 0.6°C between cessation of emissions and year 1000 of the experiment, and the 1% experiment warming 1.5°C between cessation of emissions an year 1000. Despite having a smaller ZEC the logistic experiment is warmer than the 1% experiment in the year 1000 by 0.3°C.

3.3 Negative Emissions

Recent interest in the possibility of net negative CO_2 emissions being used to undo climate change through 'carbon remediation' (e.g. Shepherd, 2009) has lead to the formalization of the 1% up 1% down idealized experiment. In this experiment atmospheric CO_2 concentration follows the 1% experiment up to a given threshold, then is returned to preindustrial concentration in a mirrored path with -1% compounded reductions in CO_2 concentration each year (Samanta et al., 2010; Boucher et al., 2012; Zickfeld et al., 2013, 2016). Simulations of the 1% up 1% down experiment and the logistic equivalent for $2\times$, $4\times$, and $8\times$ CO_2 are shown in figure 4. This figure also shows CO_2 emissions diagnosed from these pathways. The logistic pathways exhibit a smooth transition to negative emissions, with declining rate of emissions simply continuing to decline once the zero emissions threshold is breached. The 1% up 1% down pathways create a transition from very high positive emissions to very large negative emissions over the course of a single year. For example, under the $4\times$ CO_2 1% up 1% down emissions go from 29 PgC a^{-1} in year 140 of the experiment to -21PgC a^{-1} in year 142 of the experiment. The abrupt change in emission rate also leads to an abrupt cooling of the climate as shown in figure 11. The figure shows that the 1% up 1% down experiment exhibits a linear increase in temperature followed by a fast but asymmetric cooling of temperature with a long tail of warming which dies out by about the year 500 of for the $4\times$ CO_2 simulation. The logistic mirrored experiment shows a far more asymmetric temperature curve, with temperature continuing to increase for over a century once CO_2 concentration begins to drop (consistent with the ZEC results) followed by a slow decline in temperatures, with temperature still 0.85 °C above preindustrial by the end of the simulation in model year 1200.

4 Discussion

A critical question from the early days of coupled carbon cycle modelling was whether the terrestrial carbon sink will transition to source of carbon to the atmosphere (e.g. Cox et al., 2001). One model in each of the two previous intercomparisons of the carbon cycles of ESMs exhibited a terrestrial sink to source transition, HadCM3LC in Friedlingstein et al. (2006), and MIROC-ESM in Arora et al. (2013). However, as all the other models in those intercomparisons did not exhibit a terrestrial sink to source transition this potentiality would appear possible but unlikely (Friedlingstein et al., 2006; Arora et al., 2013). Here we have shown that at least to some degree that the existence of a terrestrial sink to source transition is contingent on the choice of idealized experiment used to force a model. Had a logistic experiment been used in previous iterations of C^4MIP different conclusions about the robustness of the terrestrial carbon sink may have been drawn.

In order to meet the 2°C temperature target outlined in the Paris Agreement (United Nations, 2015) emissions of CO_2 should peak during the present decade (Rogelj et al., 2011; Friedlingstein et al., 2014). Even under less aggressive temperature targets emissions rate should peak in the early to mid 21st century (Rogelj et al., 2011; Friedlingstein et al., 2014). Thus examining the behaviour of the carbon cycle under conditions of decelerating emissions is a area of imminent importance. Here we have shown that the ocean comes to dominate the global carbon cycle as emissions decelerate. This feature of the carbon cycle has actually appeared in previous intercomparisons of intermediate complexity ESMs forced with multi-gas scenarios Zickfeld et al. (2013). However, ocean dominance has not been emphasized in literature. For example the summary for policy makers for the IPCC AR5 states that: “Based on Earth System Models, there is high confidence that the feedback between climate and the carbon cycle is positive in the 21st century; that is, climate change will partially offset increases in land and ocean carbon sinks caused by rising atmospheric CO_2. As a result more of the emitted anthropogenic CO_2 will remain in the atmosphere.” IPCC (2013). Although this statement is strictly true, carbon sinks are weaker in fully coupled models relative to biogeochemically coupled models Arora et al. (2013), the statement does not make clear that if emissions rate peaks then declines then a smaller fraction of emitted anthropogenic carbon will remain in the atmosphere. The more extensive discussion of carbon cycle feedbacks in Chapter 6 of AR5, also makes no mention of a higher ocean-borne fraction under decelerating emission rates Ciais et al. (2013). Thus examining the ocean carbon cycle as emissions decelerate should be a key priority when analyzing the model output of the CMIP6 iteration of C^4MIP.

A key priority of the CMIP6 iteration of C^4MIP is examining the strength of the permafrost carbon cycle feedback to climate change (Jones et al., 2016), as representations of permafrost carbon were absent from the models that participated in CMIP5 (Arora et al., 2013). Informal intercomparisons of the permafrost carbon feedback have thus far used year 2100 of RCP 8.5 as the point of comparison (Schuur et al., 2015). Given the results of the present study and MacDougall et al. (2017) changing the point of comparison to year 70 of the 1% experiment is likely to substantially underestimate the potential contribution of permafrost carbon to climate change. Thus the point of comparison and the lagged nature of the permafrost carbon cycle feedback must be explicitly acknowledged when analysis of the CMIP6 iteration of C^4MIP is conducted.

Zero emissions scenarios and full mirroring of atmospheric CO_2 back to pre-industrial concentration are experiments outside the realm of C^4MIP (Jones et al., 2016), and generally investigated with Earth system models of intermediate complexity (e.g. Zickfeld et al., 2016) or with a single simulation with a full ESM (e.g. Zickfeld et al., 2012; Frölicher et al., 2014). Thus it is relatively simple for investigators studying these post-emissions states to switch to a logistic like experiment or a scenario which includes decelerating emissions. That the choice of which idealized experiment to use can drastically change results of ZEC or negative emissions experiments should should gravely concern investigators and reinforce the need for applying critical thought to experiment design. The 1% up, 1% down experiment in particular needs to be critically examined as an abrupt transition from very high positive emissions to very large negative emissions is deeply implausible. All idealized scenarios are implausible in some aspects but generally similar events could occur as a component of broader cataclysms. An abrupt transition from high to zero emissions as seen in the 1% to zero emissions experiment is consistent with a nuclear war obliterating the infrastructure of the fossil fuel economy (Turco et al., 1983). Even the abrupt release of CO_2, doubling or quadrupling atmospheric CO_2 concentration is more plausible than it may first appear. Paleoclimate evidence from the end-Cretaceous impact event suggests an increase in atmospheric CO_2 concentration of about this magnitude, originating from vaporized rock and global firestorms (MacLeod et al., 2018). However, there is no plausible way to decarbonize the global economy and deploy atmospheric CO_2 removal technology in a single year. Thus investigators considering using the 1% up 1% down experiment should carefully examine why they are conducting the experiment and whether some other CO_2 pathway would be more appropriate.

4.1 Recommendations for analysis of CMIP6 iteration of C^4MIP

The protocol for the CMIP6 iteration of C^4MIP is now set in stone (Jones et al., 2016). The two Tier 1 experiments required of all participating modelling groups are the 1% experiment and SSP5-8.5 scenario (the successor to RCP8.5) up to year 2100 CE. Both of these experiments prescribe monotonically increasing atmospheric CO_2 concentration and thus have no emission deceleration phase. However, two of the Tier two experiments, SSP5-8.5-BGC to 2300 and SSP5-3.4-Overshoot-BGC have deceleration phases and SSP5-3.4-Overshoot-BGC implies negative emissions (Jones et al., 2016). Although using complex multi-forcing scenarios to evaluate carbon cycle feedbacks is sub-ideal in many ways using the Tier 2 scenarios may allow a more complete evaluation of the carbon cycle than using only the 1% experiment. Therefore we recommend:

1. Evaluating the permafrost carbon cycle feedback to climate change using the SSP5-8.5 and SSP5-8.5-BGC scenarios, not at year 70 of the 1% experiment.

2. Examining the relative strength of ocean carbon uptake during the emission deceleration phases of SSP5-8.5-BGC to 2300 and SSP5-3.4-Overshoot-BGC

5 Conclusions

Idealized scenarios have a long history in the climate modelling community having been used for benchmark experiments and as a means of model intercomparison since the Second Assessment Report of the IPCC Houghton et al. (1996). In the Fifth Assessment Report the 1% experiment was used to compare the behaviour of models which included a representation of the global carbon cycle Ciais et al. (2013); Arora et al. (2013) and the 1% experiment will again be at the core of CMIP6 analysis of these systems (Jones et al., 2016). However, in the 1% experiment atmospheric CO_2 concentration rises far faster than the historical record and implies only monotonically increasing CO_2 emission rate. Therefore, the experiment does not facilitate examination of the carbon cycle under conditions of decelerating emission rates, nor does the experiment allow for smooth transitions to zero emissions or negative emission experiments. Using a logistic shaped CO_2 concentration pathway allows for study of accelerating, decelerating, zero emissions and negative emissions states, and also better matches the historical trajectory of atmospheric CO_2 concentration.

By comparing simulations under the 1% experiment to simulations forced with a logistic CO_2 pathway, leading to the same atmospheric CO_2 concentration, we find five key differences: (1) the logistic experiment has a terrestrial sink to source transition, while the 1% experiment does not; (2) Under the logistic experiment the ocean uptake of carbon comes to dominate the global carbon cycle as emissions decelerate; (3) Permafrost soils release less than half the carbon at the point of CO_2

doubling in the 4×CO_2 1% experiment relative to the 4×CO_2 logistic experiment; (4) Following cessation of CO_2 emissions the zero emissions commitment is much larger following a 1% experiment than following a logistic experiment; (5) The 1% up 1% down experiment exhibits a smaller warming tail than the equivalent mirrored logistic experiment. These differences suggest that the outcomes of many numerical climate experiments conducted with Earth systems models are contingent on the choice of CO_2 pathway used to force the model. Overall, we recommend that consideration be given to replacing the idealized 1% experiment with a more suitable idealized experiment when the protocols for the CMIP7 iteration of C^4MIP are drafted.

Code and data availability. Version 2.9 of the UVic ESCM is available for download from http://climate.uvic.ca/model/. The updated model code including the frozen ground version of the model can be downloaded from ftp://uvicgroup:MalahatPa$$@data.iac.ethz.ch. Forcing files containing the CO_2 trajectories used for the numerical experiments described here are available in the supplementary data. Output variables necessary to reproduce the above numerical experiments are identical to those described in the C^4MIP protocol. Refer to Section 4 of Jones et al. (2016) for detailed description.

Competing interests. Author declares no competing interests.

Acknowledgements. This research was supported by a grant from the NSERC Discovery Grant programme. I thank Compute Canada for super-computer resources and support. R.J. Stouffer graciously provided an account of the of the origin and original purpose of the 1% experiment.

References

Archer, D.: A data-driven model of the global calcite lysocline, Global Biogeochemical Cycles, 10, 511–526, 1996.

Arora, V. K., Boer, G. J., Friedlingstein, P., Eby, M., Jones, C. D., Christian, J. R., Bonan, G., Bopp, L., Brovkin, V., Cadule, P., andTatiana Ilyina, T. H., Lindsay, K., Tjiputra, J. F., and Wu, T.: Carbon-Concentration and Carbon-Climate Feedbacks in CMIP5 Earth System Models., Journal of Climate, 26, 2013.

Berryman, A. A.: The Origins and Evolution of Predator-Prey Theory, Ecology, 73, 1530–1535, 1992.

Boucher, O., Halloran, P. R., Burke, E. J., Doutriaux-Boucher, M., Jones, C. D., Lowe, J., Ringer, M. A., Robertson, E., and Wu, P.: Reversibility in an Earth System model in response to CO_2 concentration changes, Environmental Research Letters, 7, 024 013, 2012.

Broecker, W. and Peng, T.: Tracers in the Sea, Eldigio Press, 1982.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Quéé, C. L., Myneni, R. B., Piao, S., and Thornton, P.: Carbon and Other Biogeochemical Cycles, in: Working Group I Contribution to the Intergovernmental Panel on Climate Change Fifth Assessment Report Climate Change 2013: The Physical Science Basis, edited by Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P., Cambridge University Press, 2013.

Collins, M., Knutti, R., Arblaster, J. M., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Jr., W. J. G., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J., and Wehner, M.: Long-term Climate Change: Projections, Commitments and Irreversibility, in: Working Group I Contribution to the Intergovernmental Panel on Climate Change Fifth Assessment Report Climate Change 2013: The Physical Science Basis, Cambridge University Press, 2013.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., and Totterdell, I. J.: Modelling vegetation and the carbon cycle as interactive elements of the climate system, Proceedings of the RMS millennium conference, 2001.

Eby, M., Zickfeld, K., Montenegro, A., Archer, D., Meissner, K. J., and Weaver, A. J.: Lifetime of Anthropogenic Climate Change: Millennial Time Scales of Potential CO_2 and Surface Temperature Perturbations, Journal of Climate, 22, 2501–2511, https://doi.org/10.1175/2008JCLI2554.1, 2009.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geoscientific Model Development, 9, 1937–1958, 2016.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiy, M., Knorr, W., Lindsay, K., Matthews, H. D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K. G., Schnur, R., Strassmann, K., Weaver, A. J., Yoshikawa, C., and Zeng, N.: Climate–Carbon Cycle Feedback Analysis: Results from the C4MIP Model Intercomparison, Journal of Climate, 19, 3337–3353, 2006.

Friedlingstein, P., Andrew, R., Rogelj, J., Peters, G., Canadell, J., Knutti, R., Luderer, G., Raupach, M., Schaeffer, M., van Vuuren, D., et al.: Persistent growth of CO_2 emissions and implications for reaching climate targets, Nature Geoscience, 7, 709–715, 2014.

Frölicher, T. L., Sarmiento, J. L., Paynter, D. J., Dunne, J. P., Krasting, J. P., and Winton, M.: Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models, Journal of Climate, 28, 862–886, 2014.

Gillett, N. P., Arora, V. K., Matthews, D., and Allen, M. R.: Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations, Journal of Climate, 26, 6844–6858, 2013.

Greenblatt, J. B. and Sarmiento, J. L.: Variability and climate feedback mechanisms in ocean uptake of CO_2, in: The global carbon cycle, edited by Field, C. B. and Raupach, M. R., Island Press, 2004.

Gregory, J., Ingram, W., Palmer, M., Jones, G., Stott, P., Thorpe, R., Lowe, J., Johns, T., and Williams, K.: A new method for diagnosing radiative forcing and climate sensitivity, Geophysical Research Letters, 31, 2004.

Houghton, J. et al.: Climate change 2001: The scientific basis, vol. 881, Cambridge University Press Cambridge, 2001.

Houghton, J. T., Callander, B. A., and Varney, S. K.: Climate change 1992, Cambridge University Press, 1992.

Houghton, J. T. et al.: Climate change 1995: The science of climate change: contribution of working group I to the second assessment report of the Intergovernmental Panel on Climate Change, vol. 2, Cambridge University Press, 1996.

IPCC: Summary for Policymakers, in: Working Group I Contribution to the Intergovernmental Panel on Climate Change Fifth Assessment Report Climate Change 2013: The Physical Science Basis, edited by Alexander, L., Allen, S., Bindoff, N. L., Bréon, F.-M., Church, J., Cubasch, U., Emori, S., Forster, P., Friedlingstein, P., Gillett, N., Gregory, J., Hartmann, D., Jansen, E., Kirtman, B., Knutti, R., Kanikicharla, K. K., Lemke, P., Marotzke, J., Masson-Delmotte, V., Meehl, G., Mokhov, I., Piao, S., Plattner, G.-K., Dahe, Q., Ramaswamy, V., Randall, D., Rhein, M., Rojas, M., Sabine, C., Shindell, D., Stocker, T. F., Talley, L., Vaughan, D., and Xie, S.-P., Cambridge University Press, 2013.

Jenkinson, D., Adams, D., and Wild, A.: Model estimates of CO_2 emissions from soil in response to global warming, Nature, 351, 304–306, 1991.

Jones, C. D., John, J. G., and Randerson, J. T.: C4MIP-The Coupled Climate-Carbon Cycle Model Intercomparison Project: experimental protocol for CMIP6, Geoscientific Model Development, 9, 2853, 2016.

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Jackson, R. B., et al.: Global carbon budget 2017, Earth System Science Data, 10, 405, 2018.

MacDougall, A. H. and Knutti, R.: Projecting the release of carbon from permafrost soils using a perturbed physics ensemble modelling approach, Biogeosciences, 13, 2123–2136, https://doi.org/10.5194/bg-13-2123-2016, 2016.

MacDougall, A. H., Swart, N. C., and Knutti, R.: The uncertainty in the transient climate response to cumulative CO_2 emissions arising from the uncertainty in physical climate parameters, Journal of Climate, 30, 813–827, 2017.

MacLeod, K., Quinton, P., Sepúlveda, J., and Negra, M.: Postimpact earliest Paleogene warming shown by fish debris oxygen isotopes (El Kef, Tunisia), Science, p. eaap8525, 2018.

Malhi, Y., Aragão, L., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., Sitch, S., McSweeney, C., and Meir, P.: Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest, Proceedings of the National Academy of Sciences, 106, 20 610–20 615, 2009.

Matthews, H. and Weaver, A.: Committed climate warming, Nature Geoscience, 3, 142–143, 2010.

Matthews, H. D., Weaver, A. J., Meissner, K. J., Gillett, N. P., and Eby, M.: Natural and anthropogenic climate change: incorporating historical land cover change, vegetation dynamics and the global carbon cycle, Climate Dynamics, 22, 461–479, https://doi.org/10.1007/s00382-004-0392-2, 2004.

Matthews, H. D., Gillett, N. P., Stott, P. A., and Zickfeld, K.: The proportionality of global warming to cumulative carbon emissions, Nature, 459, 829–832, https://doi.org/10.1038/nature08047, 2009.

Meehl, G. A., Covey, C., Taylor, K. E., Delworth, T., Stouffer, R. J., Latif, M., McAvaney, B., and Mitchell, J. F.: The WCRP CMIP3 multimodel dataset: A new era in climate change research, Bulletin of the American Meteorological Society, 88, 1383–1394, 2007.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M., Lamarque, J., Matsumoto, K., Montzka, S., Raper, S., Riahi, K., et al.: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, Climatic change, 109, 213–241, 2011.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

Geoscientific Model Development Discussions Open Access EGU

Meissner, K. J., Weaver, A. J., Matthews, H. D., and Cox, P. M.: The role of land–surface dynamics in glacial inception: A study with the UVic Earth System Model, Climate Dynamics, 21, 515–537, 2003.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747–754, https://doi.org/10.1038/nature08823, 2010.

Orr, J., Najjar, R., Sabine, C., and Joos, F.: Abiotic-how-to, internal OCMIP report, LSCE/CEA Saclay, 1999.

Planton, S.: Annex III: Glossary, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2013.

Raper, S. C. B., Gregory, J. M., and Stouffer, R. J.: The role of climate sensitivity and ocean heat uptake on AOGCM transient temperature response, Journal of Climate, 15, 124–130, 2002.

Reed, L. J. and Berkson, J.: The application of the logistic function to experimental data., The Journal of Physical Chemistry, 33, 760–779, 1929.

Rogelj, J., Hare, W., Lowe, J., Van Vuuren, D. P., Riahi, K., Matthews, B., Hanaoka, T., Jiang, K., and Meinshausen, M.: Emission pathways consistent with a 2° C global temperature limit, Nature Climate Change, 1, 413–418, 2011.

Rugenstein, M. A., Caldeira, K., and Knutti, R.: Dependence of global radiative feedbacks on evolving patterns of surface heat fluxes, Geophysical Research Letters, 43, 9877–9885, 2016.

Samanta, A., Anderson, B. T., Ganguly, S., Knyazikhin, Y., Nemani, R. R., and Myneni, R. B.: Physical climate response to a reduction of anthropogenic climate forcing, Earth Interactions, 14, 1–11, 2010.

Schmittner, A., Oschlies, A., Matthews, H. D., and Galbraith, E. D.: Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO_2 emission scenario until year 4000 AD, Global biogeochemical cycles, 22, GB1013, https://doi.org/10.1029/2007GB002953, 2008.

Schuur, E., McGuire, A., Schädel, C., Grosse, G., Harden, J., Hayes, D., Hugelius, G., Koven, C., Kuhry, P., Lawrence, D., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C., and Vonk, J. E.: Climate change and the permafrost carbon feedback, Nature, 520, 171–179, 2015.

Shepherd, J.: Geoengineering the climate: science, governance and uncertainty, Royal Society, 2009.

Stouffer, R., Manabe, S., and Bryan, K.: Interhemispheric asymmetry in climate response to a gradual increase of atmospheric CO2, Nature, 342, 660–662, 1989.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, Bulletin of the American Meteorological Society, 93, 485–498, 2012.

Trans, P. and Keeling, R.: Trends in Atmospheric Carbon Dioxide, https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html, 2017.

Turco, R. P., Toon, O. B., Ackerman, T. P., Pollack, J. B., and Sagan, C.: Nuclear winter: global consequences of multiple nuclear explosions, Science, 222, 1283–1292, 1983.

United Nations: Paris Agreement:Twenty-first conference of the parties of the United Nations Framework Convention on Climate Change, United Nations, 2015.

Weaver, A. J., Eby, M., Wiebe, E. C., ans P. B. Duffy, C. M. B., Ewen, T. L., Fanning, A. F., Holland, M. M., MacFadyen, A., Matthews, H. D., Meissner, K. J., Saenko, O., Schmittner, A., Wang, H., and Yoshimori, M.: The UVic Earth System Climate Model: Model description, climatology, and applications to past, present and future climates, Atmosphere–Ocean, 39, 1–67, 2001.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

Wigley, T. M. and Schlesinger, M. E.: Analytical solution for the effect of increasing CO_2 on global mean temperature, Nature, 315, 649–652, 1985.

Zickfeld, K., Arora, V., and Gillett, N.: Is the climate response to CO_2 emissions path dependent?, Geophysical Research Letters, 39, L05 703, 2012.

Zickfeld, K., Eby, M., Weaver, A. J., Alexander, K., Crespin, E., Edwards, N. R., Eliseev, A. V., Feulner, G., Fichefet, T., Forest, C. E., et al.: Long-Term Climate Change Commitment and Reversibility: An EMIC Intercomparison., Journal of Climate, 26, 2013.

Zickfeld, K., MacDougall, A. H., and Matthews, H. D.: On the proportionality between global temperature change and cumulative CO_2 emissions during periods of net negative CO_2 emissions, Environmental Research Letters, 11, 055 006, 2016.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

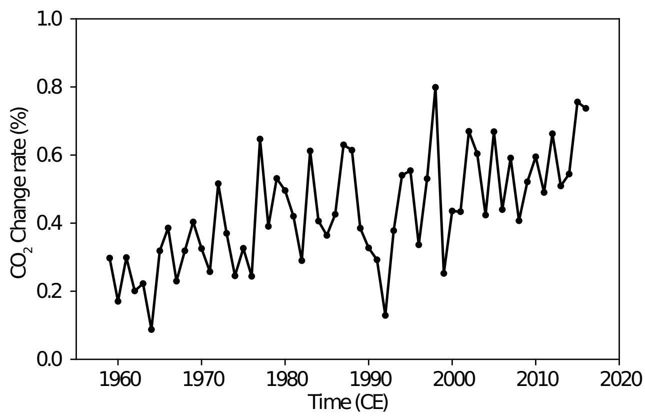

Figure 1. Historical yearly rate of atmospheric CO_2 change derived from the Mauna Loa record Trans and Keeling (2017). Note that the annual rate of increase has never breached 1% a year, and has averaged 0.46 a^{-1} over the historical record.

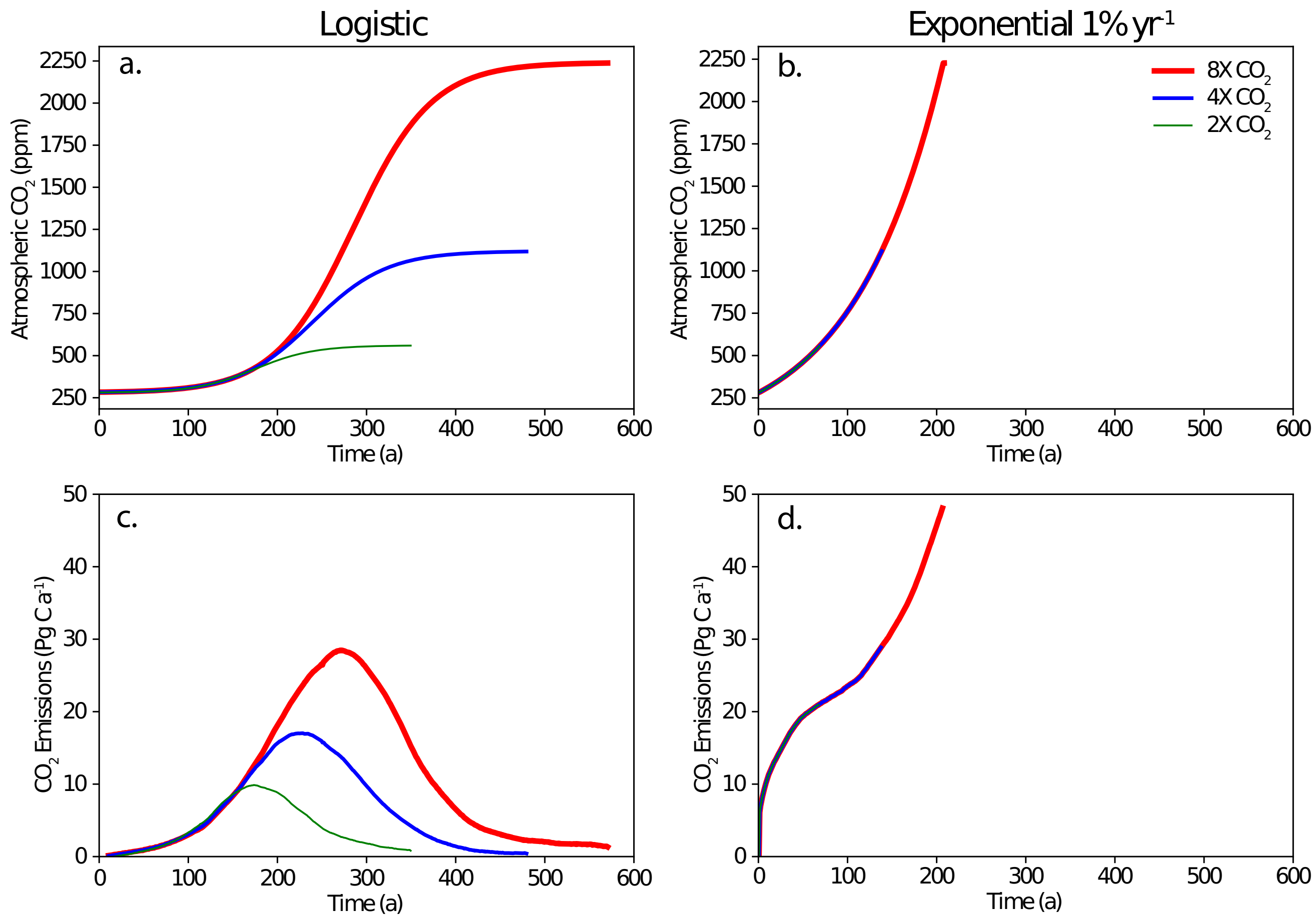

Figure 2. CO_2 pathways and diagnosed emissions for logistic and 1% experiment 2×, 4×, and 8× CO_2 pathways. Note that the logistic CO_2 pathways extend over a much longer period of time than the 1% experiments.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

Geoscientific Model Development
Discussions
Open Access

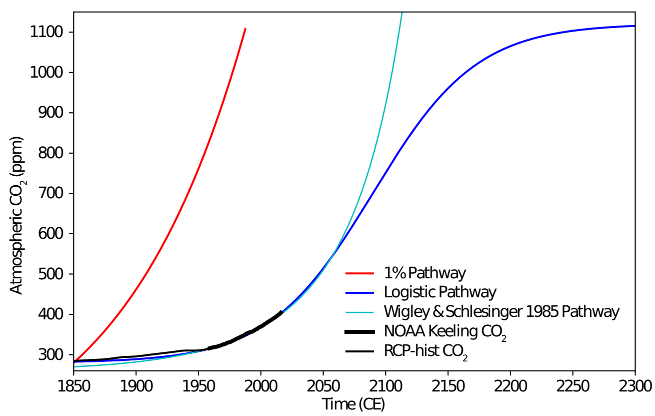

Figure 3. Historical atmospheric CO_2 trajectory and three idealized CO_2 pathways. Historical trajectories are from CMIP5 RCP-Historical archive for 1850 to 1958 (Moss et al., 2010) and from the National Oceanic & Atmospheric Administration (NOAA) record from Mauna Loa for 1959 to 2017 (Trans and Keeling, 2017). In addition to the $4\times CO_2$, 1% and logistic pathways the pathway of Wigley and Schlesinger (1985) (an abandoned alternative to the 1% experiment) is shown.

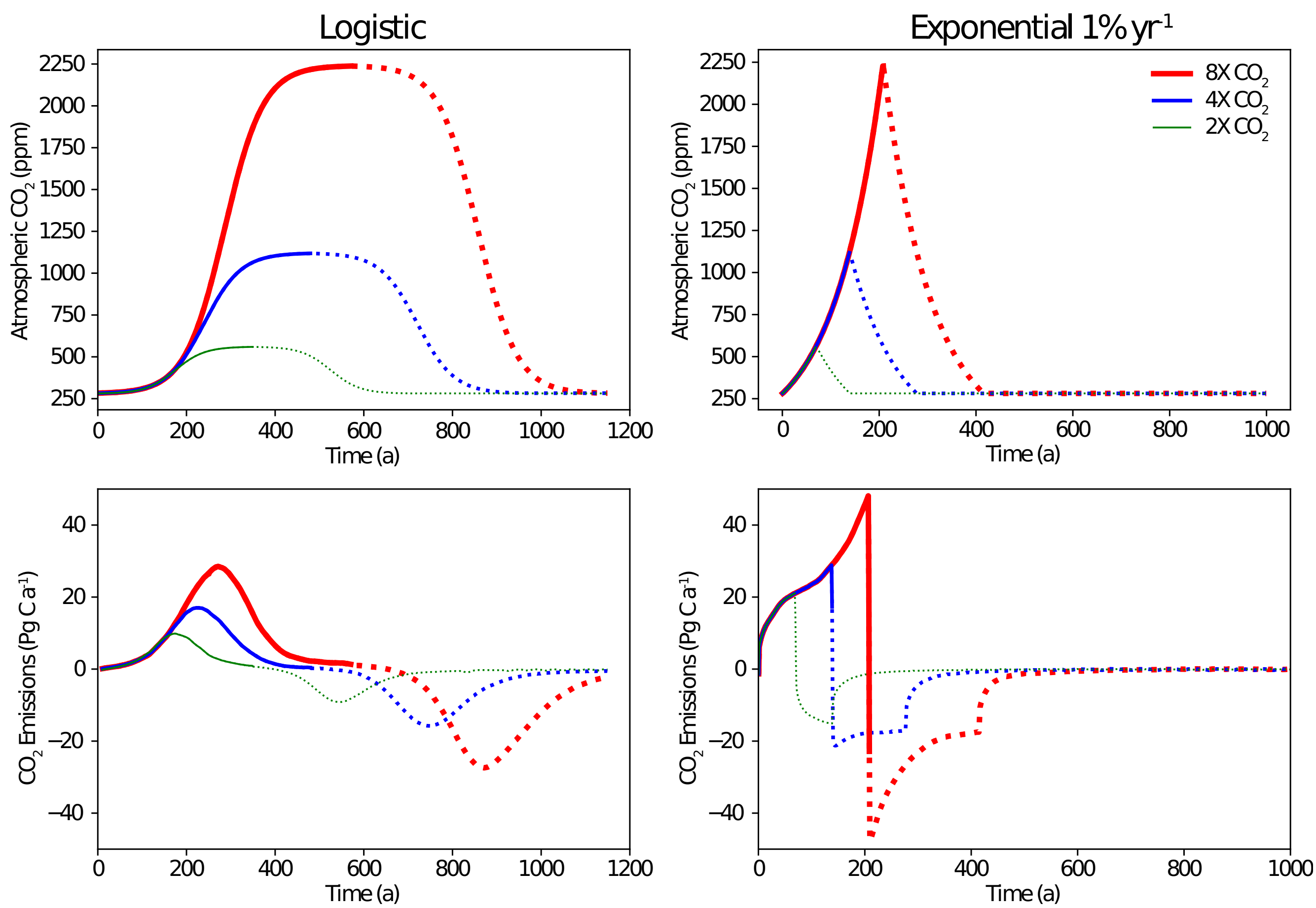

Figure 4. CO_2 pathways and diagnosed emissions for logistic and 1% experiment 2×, 4×, and 8× CO_2 mirrored pathways. Solid lines are the increasing CO_2 phase of the simulation and dotted lines are the atmospheric CO_2 removal phase of the pathways. Note that the logistic CO_2 pathways extend over a much longer period of time than the 1% experiments. Also note that the diagnosed emissions are smooth under the mirrored logistic pathway, while emissions undergo a sharp discontinuity under the 1%up 1% down experiment.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

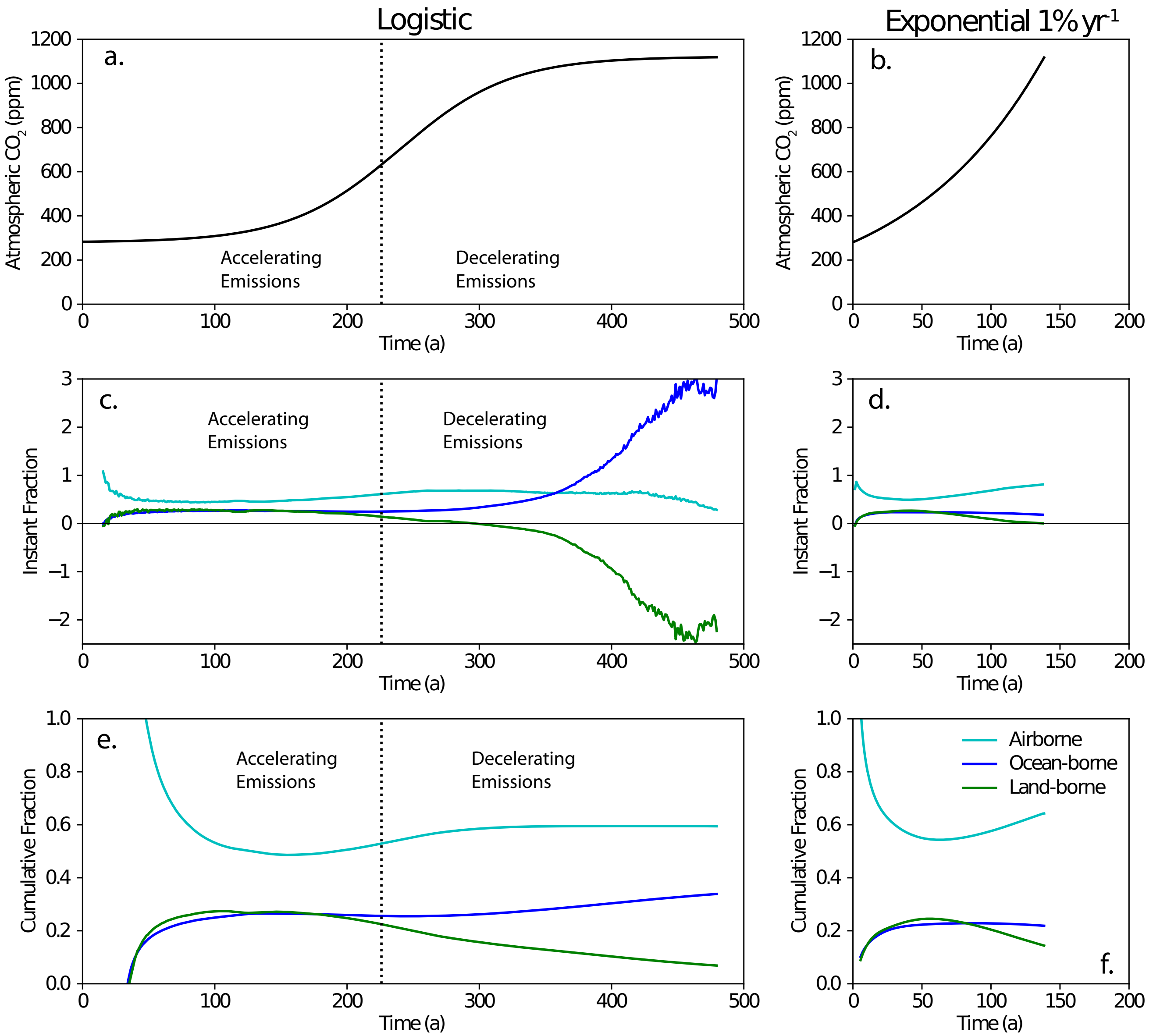

Figure 5. CO_2 concentration (a & b), instantaneous carbon fractions (c & d), and cumulative carbon fractions (e & f) for the 4× CO_2 logistic and 1% experiments.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

Geoscientific Model Development Discussions
Open Access

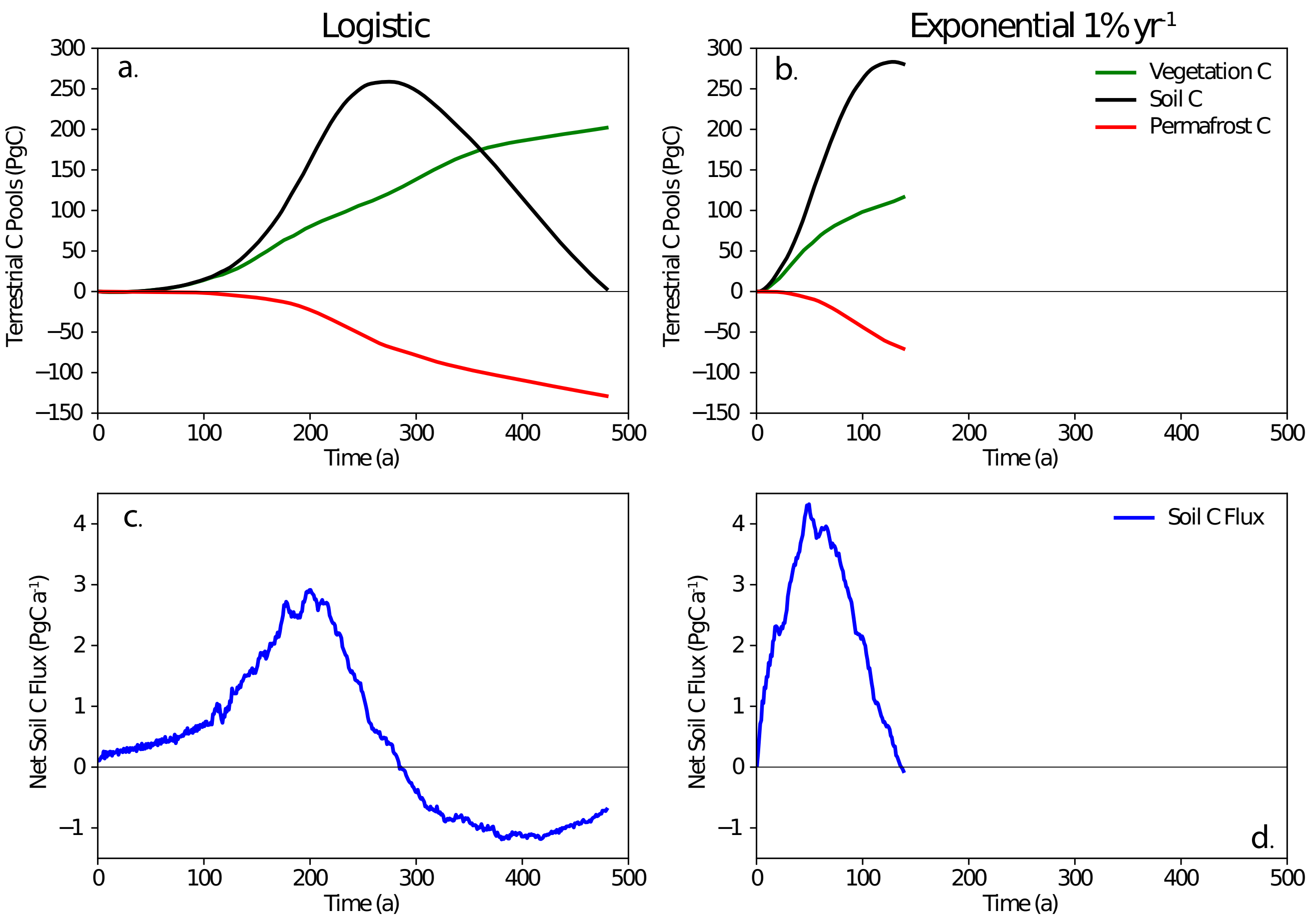

Figure 6. a,b – Evolution of terrestrial carbon pool anomalies in the logistic and 1% experiments. c,d – Flux of carbon into the soils computed from litter-fall minus heterotrophic soil respiration (excluding the permafrost carbon pool). Note that in the logistic experiment the enhanced soil respiration feedback overwhelms the increased flux of litter from vegetation leading soils to loose carbon – triggering a carbon sink to source transition on land.

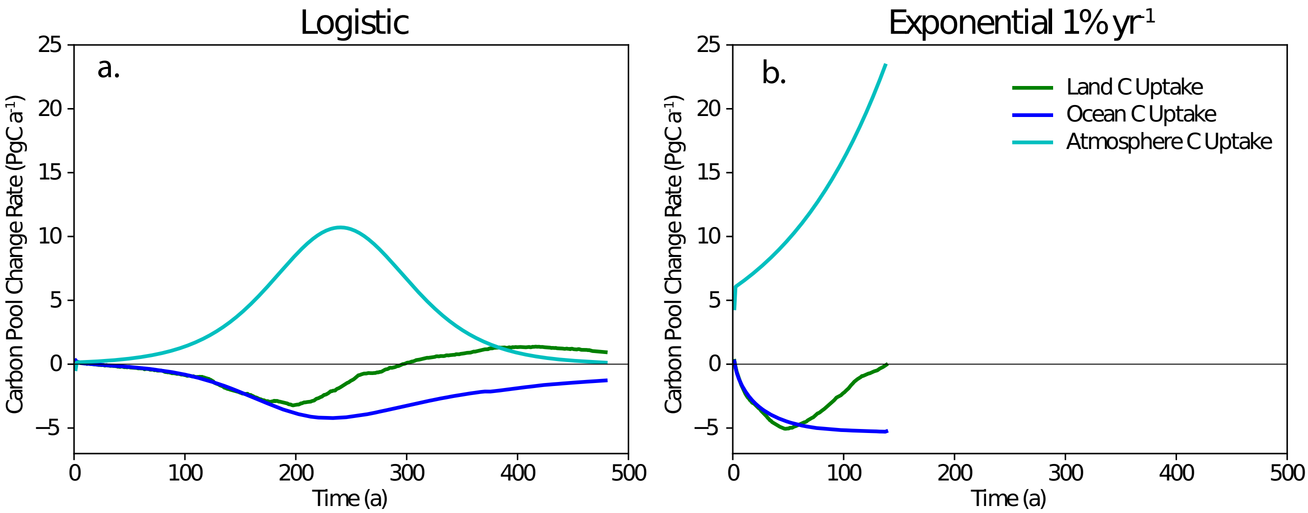

Figure 7. Uptake of carbon by the atmosphere, oceans and land systems in the logistic and 1% experiments.

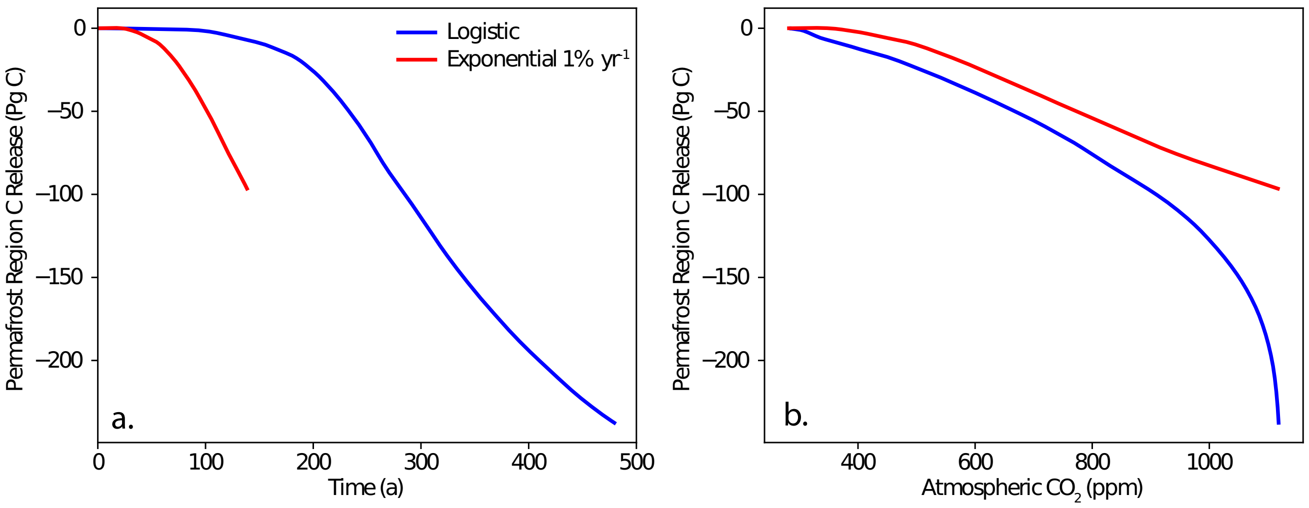

Figure 8. Release of carbon from permafrost region under logistic and 1% experiments. Release include both carbon from the permafrost carbon pool and soil carbon from the overlying active layer. Panel **a** compares the simulations with respect to time, and panel **b** with respect to atmospheric CO_2 concentration.

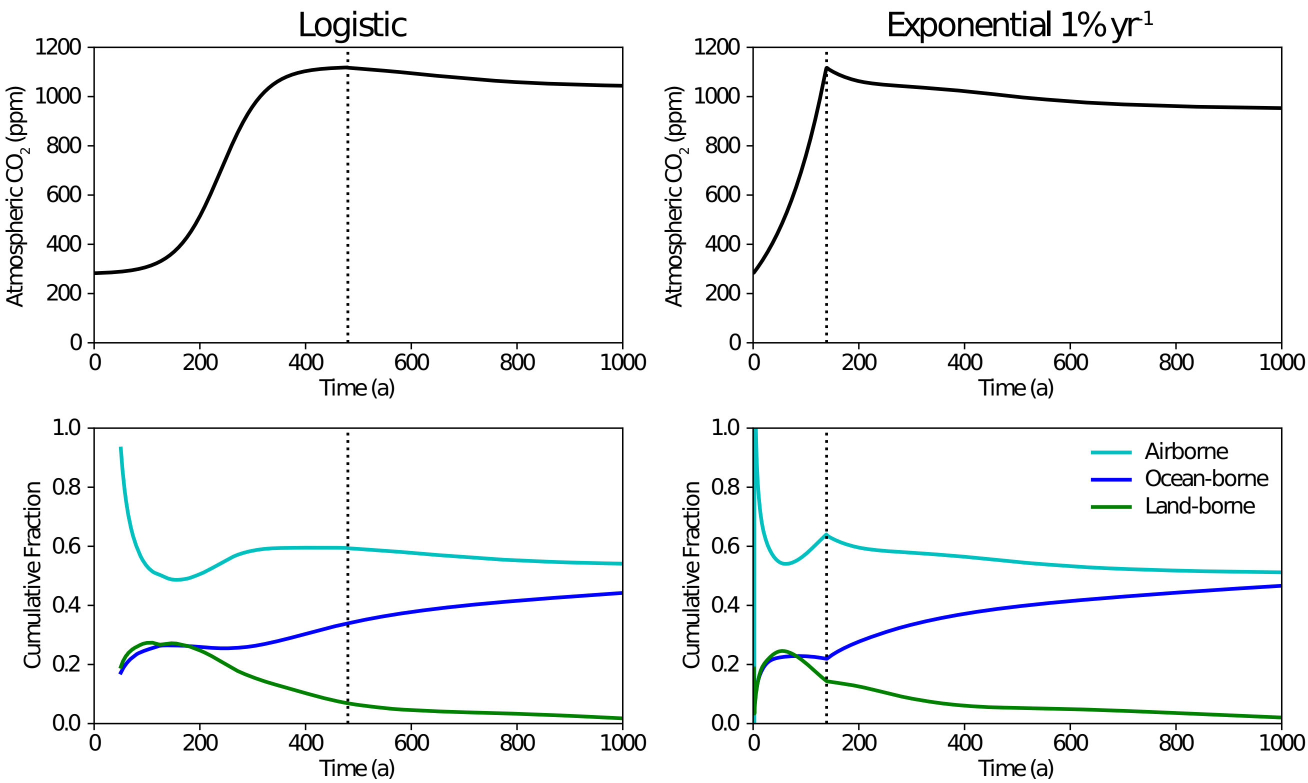

Figure 9. Evolution of atmospheric CO_2 concentration and cumulative carbon fractions for logistic and 1% experiments followed by net zero CO_2 emissions. Vertical dotted lines mark transition from prescribed atmospheric CO_2 concentration to zero emissions with free-evolving atmospheric CO_2 concentrations. Recall that instantaneous carbon fractions are not defined when emissions are zero (i.e. division by 0).

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

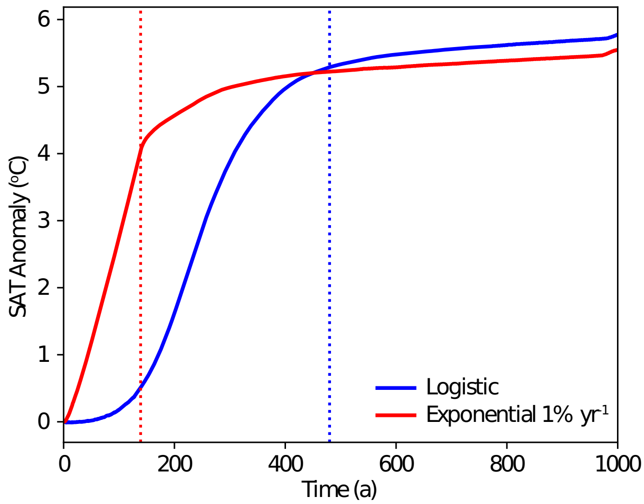

Figure 10. Evolution of global Surface Air Temperature (SAT) anomaly during transient run and zero emissions phase of logistic and 1% 4×CO_2 experiment. Vertical dotted lines mark transition from prescribed atmospheric CO_2 concentration to zero emissions with free-evolving atmospheric CO_2 concentrations.

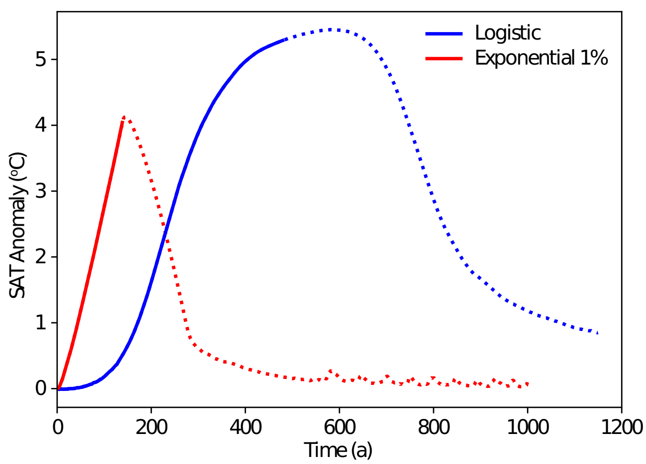

Figure 11. Evolution of global Surface Air Temperature (SAT) anomaly during 4×CO_2 1% up 1% down and mirrored logistic experiments. Solid lines are the increasing CO_2 phase of the simulation and dotted lines are the atmospheric CO_2 removal phase of the pathways.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-150
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 16 July 2018

Geoscientific Model Development Discussions
Open Access
EGU

Table 1. Parameter values for Logistic CO_2 pathways

Pathway	Rate of Change k (year)$^{-1}$	Year of mid-point t_m (year)
$2\times CO_2$	0.030	174.7
$4\times CO_2$	0.024	239.7
$8\times CO_2$	0.023	285.4