Response to reviews of manuscript:

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

I appreciate the thoughtful comments of both reviewers and have responded to each comment below. The reviews are copied verbatim and are italicized. Author responses are in regular font. Changes made to the manuscript are blue.

Response to Reviewer 1:

Review of "Limitations of the 1% experiment as the benchmark idealised experiment for carbon cycle inter comparison in C4MIP", by Andrew MacDougall.

This is a well written, clear description of a proposed alternative experiment to the now standard 1% experiments often used to quantify and compare carbon cycle feedbacks in coupled climate carbon cycle models (so-called C4MIP experiments).

I found this a useful and thoughtful paper which makes some very salient comments about existing experimental design and offers some insights into the limitations of the standard experiments compared to new "logistic" CO2 pathways. The paper show cases the new pathways using the UVIC EMIC.

In general, both personally and as a co-chair of C4MIP, I find this level of analysis and engagement very pleasing to see, and it will certainly help drive the further evolution of C4MIP in the future (I'm not yet ready to think about CMIP7 though!). C4MIP is explicitly aimed at ESMs, although we welcome EMIC participation. But perhaps for a next generation we should more explicitly engage with EMICs and provide additional simulations which EMICs can lead on to supplement joint ESM/EMIC runs. In fact it was a requirement of CMIP6 that no MIPs added new experiments which had not been tried by at least some models. They (very reasonably) wanted to avoid too many brand new experiments being suggested and possibly wasting time of model groups. So it is really positive to see suggestions like this also being tested with a model.

I list below some comments which I hope will be useful both for the improvement of this manuscript and also in general as part of the evolving discussion. There are some areas of literature which can be helpful, and there are some issues which are relevant to ESMs more than EMICs (mainly around computational expense). But overall I very much like this paper and would recommend publication with only minor amendments.

My main question really is not just the choice of scenario - what do you recommend about an analysis technique. You do not mention performing coupled/uncoupled simulations with the logistic pathway - so how would you look at climate-carbon and CO2- carbon feedbacks? Would you still want to do COU, BGC and RAD versions of the logistic pathway? (which would increase computational cost of course). How do these metrics (beta/gamma) evolve in time?

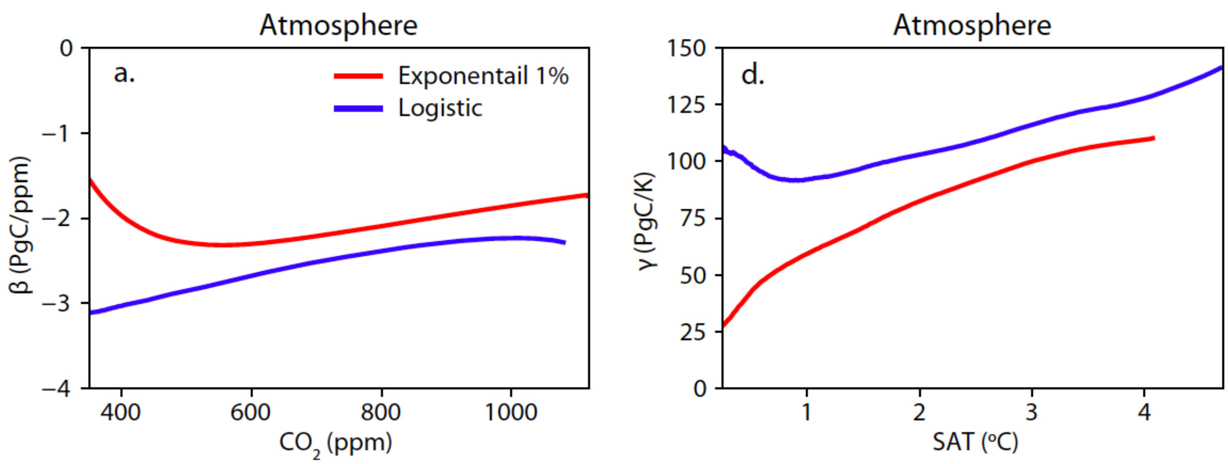
Or are you suggesting keeping the 1% run for the feedback separation and using the logistic run to look more at emissions/TCRE/AF?

It would be good to be clear on the intended USE as well as scenario that you are suggesting.

Otherwise, I list some comments below which I hope you find useful. It would be great to involve you in future discussions around C4MIP analysis and experimental design.

Chris Jones

I did conduct simulations with Radiative CO_2 and Biogeochemically coupled CO_2 under the logistic 4X CO_2 experiment to allow comparison of Beta and Gamma metrics.



What these simulations ended up showing was the Beta and Gamma metrics are scenario dependent and evolve in time, points that have been clearly articulated in existing literature (e.g. Arora et al. 2013). Since these experiments added so little to the conclusions of the paper I decided to not include the experiments in the submitted manuscript.

To clearly state the intended use of the logistic experiment a new subsection has been added to the discussion section of the paper. The subsection reads:

"4.2 Recommendations for incorporation of the logistic experiment into CMIP7

The key advantages of the logistic experiment over the 1% experiment are that the logistic experiment captures the phase of declining emissions, and allows for a smoother transition to zero emissions or negative emissions scenarios. The principle disadvantages of switching to the logistic experiment are the much higher computation cost of the experiment, and the loss of historical continuity in experiment design. Therefore several options are available for incorporation of the logistic experiment into the CMIP7 iteration of C^4MIP, ranging from full replacement of the 1% experiment, to incorporation of the logistic experiment into the Tier 2 experiment recommendations.

Given the high computation cost of feedback separation, which necessitates running fully coupled, radiatively coupled, and biogeochemically coupled simulations (Gregory et al., 2009; Arora et al., 2013), it is prohibitively expensive for the logistic experiment to be used for this purpose. Thus I recommend that the logistic experiment be added to the Tier 1 set of experiments, in addition to the 1% experiment. With the logistic experiment used for examining carbon fraction under declining emissions, and evaluating the strength of the permafrost carbon cycle feedback. Either the 2X CO_2 or 4X CO_2 versions of the logistic experiment could be incorporated into the Tier 1 experiments, with the 2X CO_2 version having the advantage of being 'policy relevant', and less computationally demanding."

1. In several places, including the abstract and conclusions the paper mixes up features of the models/results with features of the experiment itself. For example you say sink to- source transition is "absent from the 1% experiment". I think you should be a bit stricter in which phrasing you use - the sink-to-source transition is neither present nor absent in the 1% experiment - but it will depend on the results. It may or may not occur depending on the model. You might be able to say it is more likely in one set of model runs than another, but it is not a "feature of the experiment".

The abstract and conclusions have been re-written to clearly distinguish the experiment from the results of the experiment in the UVic ESCM. The abstract did read:

"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."

And has been re-written to:

“Idealized climate change simulations are used as benchmark experiments to facilitate the comparison of ensembles of climate models. In the Fifth phase of the Climate Model Intercomparison Project (CMIP5) 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 three key differences in model output when forcing the model with the Logistic experiment. (1) The model forced with the logistic experiment exhibits a transition of the land biosphere from a carbon sink to a carbon source, a feature absent when forcing the model with the 1% experiment. (2) The ocean uptake of carbon comes to dominate the carbon cycle as emissions decline, a feature that cannot be captured when forcing a model with the 1% experiment, as emissions always increase in that experiment. (3) The permafrost carbon feedback to climate change under the 1% experiment forcing is less than half the strength of the feedback seen under logistic experiment forcing. Using 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.”

The second paragraph of conclusions of the paper have been re-written from:

“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 4X CO_2 1% experiment relative to the 4X 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.”

To:

“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) simulations forced with the logistic experiment have a terrestrial sink to source transition, while simulations forced with 1% experiment do not. (2) Forced with the logistic experiment the simulated ocean uptake of carbon comes to dominate the global carbon cycle as emissions decline. (3) Permafrost soils release less than half the carbon at the point of CO_2 doubling when forced with the 4X CO_2 1% experiment relative to the 4X CO_2 logistic experiment simulations. (4) Following cessation of CO2 emissions, the zero emissions commitment is much larger in simulations following the 1% experiment than for simulations following a logistic experiment. (5) Simulations with the 1%–up 1%–down experiment exhibits a smaller warming tail than simulations with 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, I recommend adding a logistic-like experiment to the protocol of the CMIP7 iteration of C^4MIP.”

2. The paper gives a nice overview of the history of the 1% simulation. There has, though, been more discussion around the choice of this for C4MIP than acknowledged here (it’s not true to say, "a clear rationale for... 1% experiment... is absent". The best paper on this is Gregory et al (2009, J.Climate). They look in some detail at the Friedlingstein 2006 paper and discuss some of the limitations you mention. They conclude that the 1% should be used and cumulative airborne fraction is a good measure. This is closely related to subsequent papers which derived TCRE or similar metrics relating cumulative emissions to warming levels. Gregory et al also perform and acknowledge differences between scenarios due to rate of change - beta and gamma feedback metrics are seen to vary in 0.5%, 1% and 2% rates of rise.

Thanks for the citation. The sentence: “However, a clear rationale for using the 1% experiment for analysis of the carbon cycle is absent from the literature.” has been deleted.

A brief summary of the rational given in Gregory et al. 2009 has been incorporated into the history of the 1% experiment.

The lines: “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 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).”

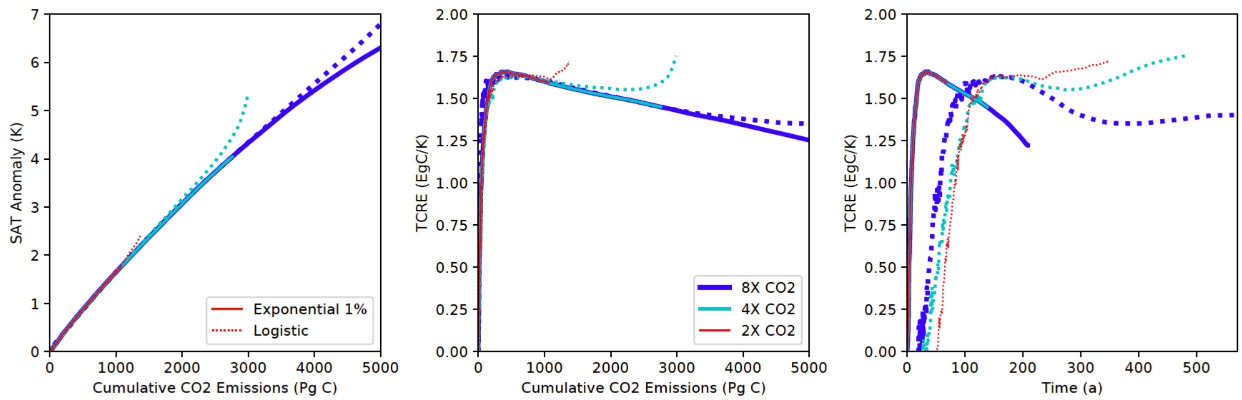
Have been changed to:

“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 (Gregory et al., 2009; Matthews et al., 2009). Gregory et al. (2009) recommended using the

1% experiment in place of a modified scenarios, due to the simplicity of the 1% experiment, the experiment's well established role in model intercomparison projects, and the magnitude of emissions implied by the 1% experiment being of similar magnitude to socioeconomic scenarios. 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)."

3. I like how you show various outputs change in time during the various simulations (airborne fraction etc). Can you also derive and show TCRE? You may find that this is actually better behaved in terms of being more constant in time and between scenarios. Which is a nice feature of it in fact.

In my experience TCRE is a mess when examining it in time-space instead of cumulative emission-space. The figure below shows cumulative emissions versus temperature change curves, and TCRE values in cumulative emissions-space and time-space.



The figure shows that TCRE is exhibits strong path-independence, with simulations forced with the exponential and logistic experiments exhibiting similar TCRE values, until the emission rate slows in the logistic experiment near the end of the simulations. The strong path-independence is not obvious when plotting TCRE in time-space.

TCRE has been incorporated into the manuscript with a new figure and a paragraph and the end of section 3.1. The figure is:

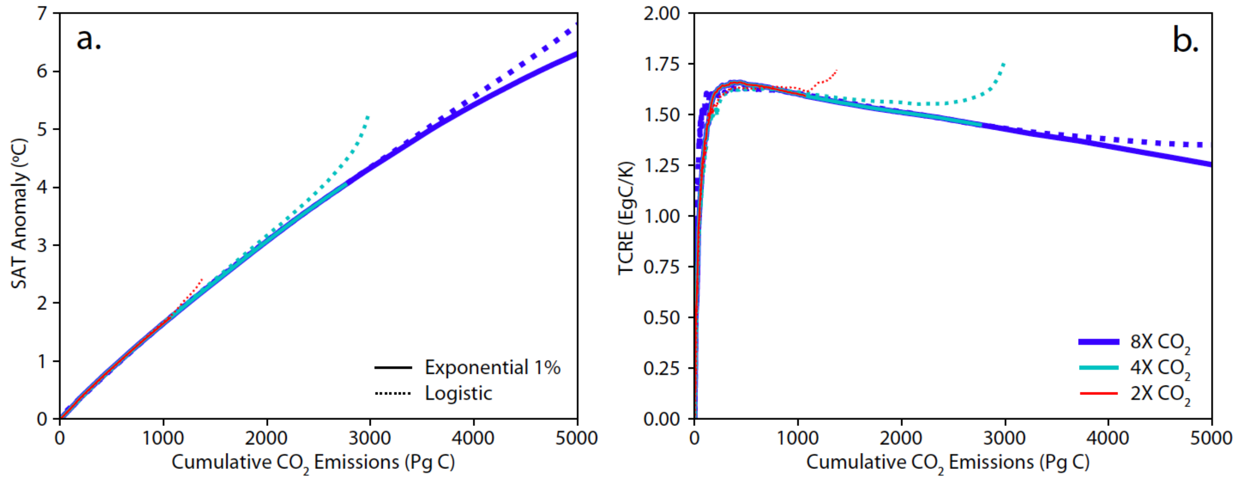


Figure 9: (a) Temperature change verses cumulative emissions curve, and (b) TCRE values for all logistic and 1% experiments. Logistic experiments given in dotted lines, 1% experiments given in solid lines. TCRE exhibits strong path-independence except near the end of the logistic experiments when the implied rate of emissions slow.

The paragraph is:

"Cumulative emissions versus temperature change curves and TCRE values for the 2X, 4X, and 8X, 1% and logistic experiment simulations are shown in Figure 9. The TCRE relationship in general shows strong independence from forcing scenario, (e.g. MacDougall et al., 2017), a feature which is evident in Figure 9. Near the end of the logistic experiments when the rate of implied CO2 emissions slows, the TCRE values deviate from scenario independence. Theoretical work on the TCRE relationship suggests that path independence should break-down at very high and very low emission rates (MacDougall, 2017). The results shown in Figure 9 and consistent with this understanding. At the time of CO2 doubling the simulated TCRE value is 1.6 EgC K^{-1} under all experiments except the 2X logistic experiment where that value is 1.7 EgC K^{-1}. "

4. Top of page 5 lists a nice sequence of phases (accelerating/decelerating emissions etc). I agree it is good to make sure these are assessed. In fact RCP2.6 makes a nice example of this succession and my 2016 ERL paper (http://iopscience.iop.org/article/10.1088/1748-9326/11/9/095012). In there we show explicitly a sequence of how human and nature sinks/sources gradually transition from positives to negatives and the interesting dynamics of the earth system. To some extent therefore this scenario can achieve (but not in a clean idealised way) they same sequence that you get via your logistic pathway.

Thank you for the link. That paper illustrates well the different stages of emission pathways. A sentence has been added to line 6 of page 5 to acknowledge the prior work done separating the stages of emissions pathway stages. The sentence reads:

"Previous studies have used the multi-gas RCP 2.6 scenario to examine increasing, decreasing, and negative emission stages (Jones et al, 2016b)."

A minor aside here (not that I should be one to complain since my papers are often riddled of minor spelling errors) but my name is misspelled in the citations of Jones et al. 2016b. ‘MacDougall’ not ‘MacDougal’ .

5. I don’t disagree with your choice of a pathway - it would indeed be useful. There are also many other possible choices which would be useful. Various ones were discussed during our selection of the latest generation of C4MIP experiments, and include:

- 4xCO2 run, BGC mode, extended beyond 150 years - this gives a large signal to noise and the step change helps avoid conflating various timescales of response

- ZEC - as you suggest a sudden stop in emissions and let the model run free – ideally from a "policy relevant" level of CO2 (such as 2xCO2, rather than 4xCO2)

- CO2 pulse (as per Joos et al 2013, ACP)

- 1% ramp-down

- other (faster/slower than 1%) idealised % runs

there were also desires to run other scenarios as well as the idealised cases (e.g. an emissions-driven RCP2.6). We also tried to align with other MIPs - such as LUMIP.

In conclusion therefore - in order to not end up with way too many model years required from model groups, we selected a small and succinct set. It is highly likely, as you suggest, that this is not perfect and there will be value in other simulations too. For CMIP7 we can certainly open this discussion again and evolve our thinking once more.

On reflection I feel the ZEC run in particular would be very valuable. And in fact the 1% ramp-down has now entered into CMIP6 via CDR-MIP. CDRMIP is explicitly focussed on negative emissions, as the name suggests. Please can youmention this and the negative-pulse experiment discussed in Keller et al (2018, GMD)

A citation to Keller et al. (2018) has been added to the description of the negative emission experiments. In line 8 of Section 2.3 the following sentence has been added:

“The 1%–up 1%–down experiment has been incorporated as a standard model experiment for CMIP6 as part of the Carbon Dioxide Removal (CDR) MIP (Keller et al., 2018).”

So in summary - the main concern over your suggestions is simply computational expense. Your logistic experiment is many hundreds of years - I can value in this, but it needs to be accessible by ESM groups. If we were to require BGC coupled version to then this doubles.

The issue on computational expense is now discussed in section 4.2. See above response for the text of the new subsection.

6. Your point about needing to explore low stabilisation and/or peak-and-decline scenarios is well made, and I fully agree. In fact I'd like to point you to my recent PhD thesis available here: https://ore.exeter.ac.uk/repository/handle/10871/27943 - this has (I hope!) some useful background on the feedback framework (section 3.1) including discussion of Gregory et al 2009 - then I make some very similar points to you in section

Congratulations of the PhD, and thanks for the link. A citation to the thesis has been added following the sentence: "Thus examining the behaviour of the carbon cycle under conditions of decelerating emissions is a area of imminent importance (e.g. Jones, 2017)."

minor points:

1. Intro. don't confuse CMIP and IPCC - they have very different remits (even if in reality there is overlap of who takes part). CMIP is the modelling community. They design and run the simulations. IPCC assembles experts to assess the literature - these often draw on, but are not limited to, CMIP simulations. IPCC itself neither does, nor recommends science - it does not choose which scenarios for example CMIP should run.

The sentence:

"In the Fifth Assessment Report of the IPCC"

Has been changed to:

"In the Fifth phase of the Climate Model Intercomparison Project (CMIP5)"

The sentence: "Two of the idealized experiments outlined by the Climate Model Intercomparison Project (CMIP) and the Intergovernmental Panel on Climate Change (IPCC)", has been changed to:

"Two of the idealized experiments outlined by the Climate Model Intercomparison Project (CMIP)"

The sentence:

"In preparation for the sixth assessment report of the IPCC (AR6) …"

Has been changed to:

"In preparation for CMIP6 …"

2. 8xCO2 might be interesting, but (hopefully!) is not policy relevant. I think this would stretch any linearity of the system and not be useful for policy targets. I would expect most ESM groups therefore not to do this one, although EMIC groups, less limited by CPU, may well do.

The atmospheric CO_2 concentration at the end of the 8x CO_2 experiments is 2240ppm. The UVic ESCM forced with the 8x logistic experiment diagnoses emissions of 5580 PgC. A total less than half of the 12500 PgC estimated to be in the Total Recoverable Base of fossil fuel reserves (e.g. Swart & Weaver, 2012). The RCP 8.5 extension to 2300 has final CO_2 concentrations of 1980 ppm (Meinshausen et al 2011). Thus, while I agree that the 8x CO_2

experiment should not be the primary idealized experiment used for model intercomparison, I do not share your optimism about the implausibility of the pathway

3. I'm not sure of the value of plotting the compatible fossil fuel emissions for either the 1% or logistic scenarios. To me this is not a relevant quantity. I think experiments should EITHER be "realistic" - i.e. follow a plausible scenario to try to derive useful information about how the real world may unfold, OR be "idealised" - i.e. stripped down or simplified in some way to aide understanding of the system. Both have great value, but shouldn't be mixed. The fossil fuel emissions that would be required to follow a scenariomare only really an interesting quantity in the first case. In the second case I don't think they have either scientific nor policy interest. So I would stick to showing more process-based quantities, such as the land/ocean components, the airborne fraction etc. But not the fossil emissions.

Reviewer 2 disagreed with this point and requested that the diagnosed emission be left in the figures. I have thus left the diagnosed emission in the figures.

4. in figure 6 - as well as a split into soil/veg carbon. Have you also looked at regional splits? e.g. tropics vs high-latitudes? I could imagine these behave differently and might be interesting to see them separated.

A new figure has been created to complement Figure 6. The figure examines the regional changes in the vegetation and soil carbon pools between pre-industrial conditions and 2X CO_2 conditions.

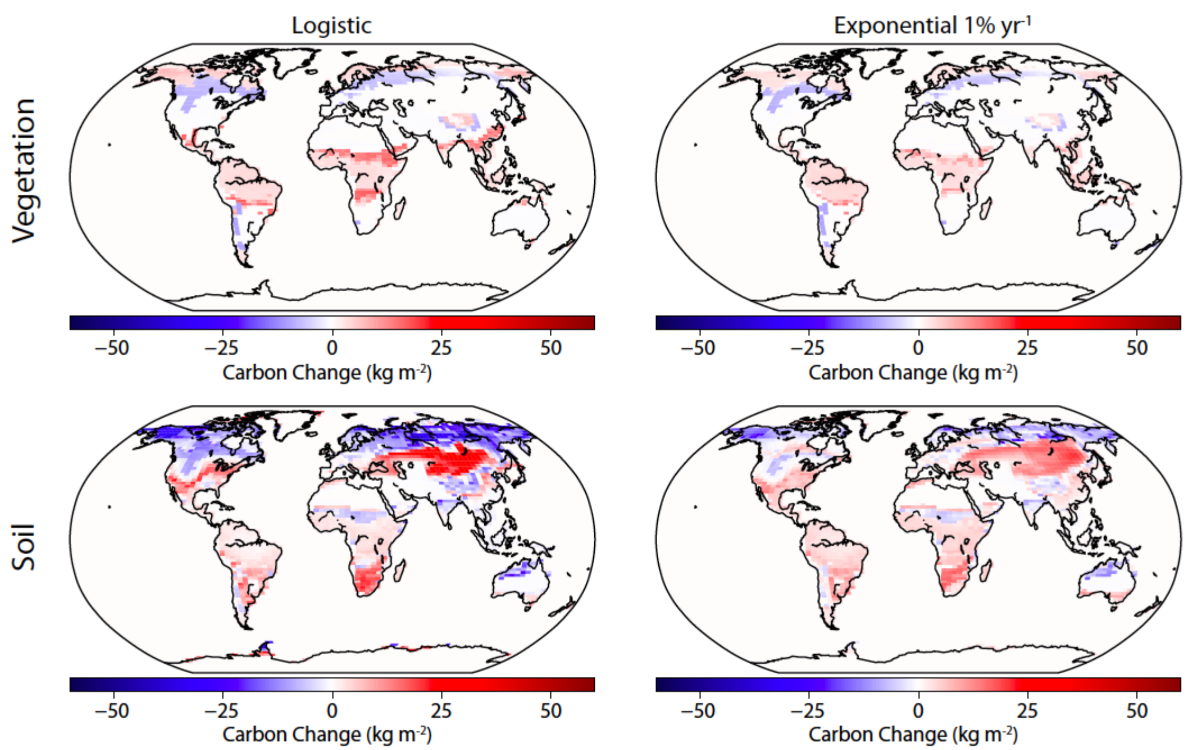


Figure 5. Change in carbon content (per unit area) between pre-industrial conditions and 2X CO2 concentration for UVic ESCM simulations forced with the logistic and 1% experiments. Top row shows changes in vegetation carbon, bottom row shows changes in soil carbon.

A paragraph describing the figure has been added to the manuscript below line 12 of page 7 to describe the figure:

"Figure 5 displays the change in vegetation and soil carbon between pre-industrial conditions and the time of doubled atmospheric CO_2 under the 4X CO_2 1% and logistic experiments. The spatial patterns of change are similar under both experiments, but of greater magnitude under the logistic experiment. Vegetation experiences a loss of carbon in the Andes and in mid-latitude northern extra-tropics, while gains in vegetation carbon are seen in the topics, subtropics, sub-arctic and arctic regions. Soils show a reduction in carbon in the permafrost region, boreal forests, and Sahel. Increases in soil carbon in seen in central North America, central Eurasia, and southern Africa, regions generally corresponding to grasslands. Overall the figure shows complex biome-specific responses of the terrestrial biosphere to increasing atmospheric CO_2 concentration."

5. on p.7 you say that the increasing ocean-fraction has never been pointed out. While this is true of AR5 (perhaps an omission there), the analysis in Jones et al (2013, J. Climate) does cover this - see the bottom right of our figure 7.

The phrase: "but to our knowledge increasing ocean-borne fraction under decelerating emissions has not been explicitly pointed out in literature."

has been deleted and has been replaced by:

",and is evident for model simulations under the peak-and-decline RCP 2.6 scenario in CMIP5 ESM output (Jones et al., 2013). "

6. a couple of other papers you might want to see: Randerson et al 2015, GCB on the long timescales and how the ocean becomes more important; Schwinger et al 2018, GRL, on ocean carbon reversibility.

Citations to both papers have been incorporated into the manuscript.

Response to Reviewer 2:

First, I want to disclose that I received a draft of the manuscript before it was published in GMDD and my summer intern used the provided scenarios in our research that is hopefully published at some later time. Although this can be perceived as a minor conflict of interest, I have currently no plans to collaborate with Dr. MacDougall and believe I can deliver an impartial review of the manuscript.

The manuscript describes a new idealized scenario that could be used in C4MIP carbon cycle model intercomparison and potentially replace the standard 1% scenario. The author has also conducted model simulations with the UVic ESCM, an Earth system model of intermediate complexity, to study how the proposed scenarios compare with the 1% scenario. He presents convincing arguments of the limitations of the 1% scenario and how the proposed scenarios could address these. Thus the scenarios presented are potentially an important contribution to model intercomparisons. In addition, they can be valuable in single-model studies as well when idealized scenarios are needed. In our case, we needed a CO2-only scenario that would be of similar length as a historical (1750-2005) + RCP run until 2100. 1% scenario was impractical because the CO2 concentration increase is so much faster compared to the historical scenario. The manuscript is clearly structured and mostly clearly written, although I would prefer more punctuation, as some sentences are hard to read.

I have edited the manuscript to try to improve punctuation and readability.

I recommend the manuscript to be published with some minor improvements.

The other reviewer had many good comments and suggestions, and I agree on almost all of them. One exception is that I think that diagnosed emissions should be shown as they are now. They are used in the discussion of the results and are an important part of understanding the source-sink transitions for example.

The diagnosed emission have been retained in the revised version of the manuscript.

Minor comments:

I do not know the conventions, but I would consider using increasing and decreasing emissions instead of accelerating and decelerating emissions. I think that would be more clear. "Accelerating" could be potentially interpreted (or at least misinterpreted) that the rate of change of emissions is increasing, but you seem to imply only that emissions are higher on year n than on year n-1.

Throughout the manuscript 'accelerating' has been changed to 'increasing', and 'decelerating' to 'declining'.

Page 1, Line 6: I agree with the first reviewer that it should be made more clear when you are talking about the experiment design and when about the results of the simulations.

See response to Reviewer 1. The abstract and conclusions have been re-written to make clear the distinction between the experiment design, and the results of the simulations with the UVic ESCM.

Page 1, Line 20: I'm aware that there are several ways to spell out what TCRE stands for. Gillet et al. (2013) used "Transient climate response to cumulative carbon emissions". H. D. Matthews recommended to use "Transient climate response to cumulative CO2 emissions" (personal communication, 2016). Although the form used here is consistent with the abbreviation (even more than most other versions), I think that including the word carbon or CO2 would be informative here.

Leaving out 'CO_2' was an unintentional error. I have in the past used the "Transient Climate Response to CO_2 Emissions" definition (e.g. MacDougall, 2015). This error has been corrected in the revised manuscript.

Page 4, Line 29: I think these stages are not fully exhaustive. Constant emissions would be at least one easily conceived idealised state of emissions.

Yes, some studies have used idealized constant rate of emission experiments (e.g. Krasting et al. 2014). This is now acknowledged in the manuscript. A sentences has been added to Page 5 line 6 reading:

"Some studies have used a fifth stage of the emissions pathway where the emission rate is constant (e.g. Krasting et al., 2014). Although useful for some examining some problems, such a state not necessary to capture the likely evolution of CO_2 emissions."

Page 5, second lines 3-5 (in 2.3, the line numbering is confusing here): I have been doing some tests with the UVic ESCM by taking restart files from the preindustrial state with prescribed constant CO2 concentration and used them in a zero-emission driven simulation. The sudden transition from concentration driven to emission driven has caused some imbalances in the model's carbon cycle, and the model was not in equilibrium anymore in contrast with my expectations. Therefore, I would guess there might be something similar happening in your case as well when you do the switch to zero emissions. Did you notice anything like that?

I re-ran the 2X CO_2 1% transition to zero emissions experiment with Global Sums turned on to check mass conservation. Just before the transition to zero emissions totals are (3rd column is carbon):

```
Total heat (in Joules referenced to 0 C and no ice or snow) and fresh water (in kg)
Total ocean fresh water is the equivalent difference from the ocean volume referenced to socn
 t atm     0.11719870007928E+24 J   0.13077251701155E+17 kg   0.11853186632084E+16 kg
 t snow   -0.16578942267172E+23 J   0.49637551698120E+17 kg   0.00000000000000E+00 kg
 t ice    -0.17937075287971E+22 J   0.53703818227460E+16 kg   0.00000000000000E+00 kg
 t lnd     0.26393241131399E+26 J   0.28829451542494E+18 kg   0.32967334597316E+16 kg
 t ocn     0.24463092309902E+26 J   0.10685384656284E+20 kg   0.37424132403260E+17 kg
 t total   0.50955159491584E+26 J   0.11041764356931E+20 kg   0.41906184526200E+17 kg
```

Immediately after the transition to zero emissions the sums are (after the model has been restarted with different flags in the mk.in file):

```
Total heat (in Joules referenced to 0 C and no ice or snow) and fresh water (in kg)
```

Total ocean fresh water is the equivalent difference from the ocean volume referenced to socn

t atm	0.11719870007928E+24 J	0.13077251701155E+17 kg	0.11853186632084E+16 kg
t snow	-0.16578942267172E+23 J	0.49637551698120E+17 kg	0.00000000000000E+00 kg
t ice	-0.17937075287971E+22 J	0.53703818227460E+16 kg	0.00000000000000E+00 kg
t lnd	0.26393241131399E+26 J	0.28829451542494E+18 kg	0.32967334597316E+16 kg
t ocn	0.24463092309902E+26 J	0.10685384656284E+20 kg	0.37424132403260E+17 kg
t total	0.50955159491584E+26 J	0.11041764356931E+20 kg	0.41906184526200E+17 kg

Note that the carbon totals are identical on either side of the transition, indicating no error in mass conservation. The model conservers mass to machine precision, as it was designed to do.

I have encounter similar problems with model drift following releases from model spin-up. These are usually either caused by a spin-up that is insufficiently long (10,000 years for the ocean to come to equilibrium is recommended), or slight differences in forcing between the spin-up configuration and the run configuration.

Page 5, second lines 6-7: The wording is a bit imprecise here. The negative emission scenario is only the negative emission part of 1% up, 1% down scenario. Maybe there is a way to be precise and keep the sentence still readable?

The referenced sentence did read:

"For the 1% experiment the negative emissions scenario is the 1% up, 1% down experiment used by several previous studies"

And has been changed to:

"The mirrored return negative-emissions-scenario derived from the 1% experiment is the 1%–up 1%–down experiment used by several previous studies"

Page 6, line 16-17: Are the emissions raw model (annual) output or have you applied some running-mean averaging or something similar?

These are the raw output, no moving average or filtering has been applied. In my experience with the UVic ESCM inter-annual variability in diagnosed emissions comes from the model overcompensating for non-CO_2 forcing such as volcanic eruptions.

Page 6, line 27: I think the word "near-surface" is somewhat misleading here. It lead me to think whether only surface-ocean is included. I think that deep ocean carbon is farther away from surface than many fossil carbon reservoirs.

"Near surface" was meant to exclude fossil fuel reserves and ocean sediments. The phrase:

"stored in each of the main near-surface carbon reservoirs"

Has been changed to:

"stored in each of the main fast-cycling carbon reservoirs"

Page 6, Line 36 (or 2?): I would use "decrease" instead of slow. This sentence is also an example that would be more readable with a comma (As emissions slow, the land system: : :). Without comma, the beginning of the sentence could be misunderstood so that emissions slow the land system.

The sentence has been re-written from:

"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."

To:

"As emissions decline, the land system transitions from a carbon sink to a carbon source. The ocean sink comes to dominate the system absorbing more carbon than the anthropogenic CO_2 emissions to the atmosphere."

Page 6, Line 37 (or 3): What do you mean with "net emissions" here? Diagnosed fossil fuel emissions or are you taking into account the carbon released from land? If the former, the sentence might be more clear without the word "net". If the latter (which I doubt), it should be written explicitly.

As shown above this has been changed to "anthropogenic CO_2 emissions" for clarity.

Page 7, Line 12: I would recommend replacing "not captured" with "not visible" or "not present" or something similar. To me, "not captured" sounds like a phrase you would use when a model cannot capture some process due to lack of relevant physical description.

"not captured well" has been changed to "not present"

Page 7, line 14: I would refer to Fig. 5c here.

A citation to Figure 5c has been added to the end of the sentence.

Page 7, line 27: It's probably clear to most readers, but I think it would be better to avoid the potential interpretation that slower warming itself is the cause when the cause is approximately that for a given warming, the longer simulation releases more carbon. Thus, I would rephrase the sentence.

The sentence has been re-written from:

"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."

To:

"Figure 8 demonstrates the importance of elapsed time in destabilizing permafrost carbon. The logistic experiment implies lower CO_2 emission rate and hence a lower rate of warming, results in a higher release of carbon from permafrost regions at any given CO_2 concentration. The result is consistent with previous work on the permafrost carbon feedback, which demonstrates a long lag time between forcing and response due to the time taken to thaw soil and decay soil carbon (e.g. Schuur et al., 2015)."

Page 7, second Line 8: I think the "when emissions cease" could be interpreted also to mean "after emissions cease". Could you make it clearer that you are referring to the very moment of transition (e.g. at the turning point).

"when emissions cease" has been replaced by: "at the time emission stop"

Page 8, Line 15: Can you explain the difference in ZEC between the experiments? Ehlert and Zickfeld (2017) would probably be a good reference here.

An addition panel has been added to old Figure 10 (now Figure X), showing the radiative forcing and ocean heat uptake under both experiments, to explain the difference in ZEC:

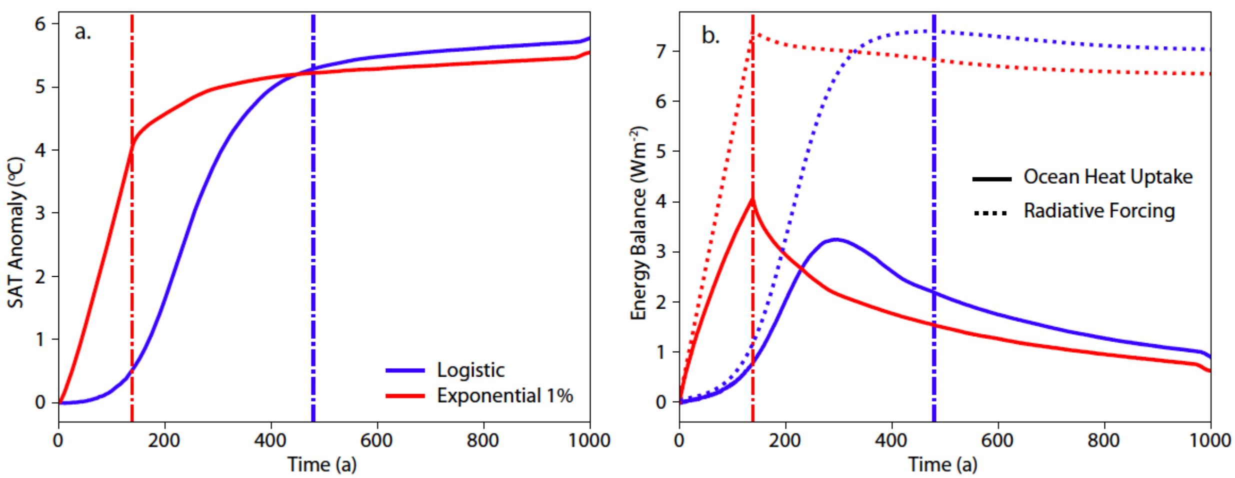


Figure 11. (a) Evolution of global Surface Air Temperature (SAT) anomaly during transient run and zero emissions phase of logistic and 1% 4X CO_2 experiment. (b) Ocean heat uptake (solid lines) and radiative forcing (dashed lines) for each experiment. Vertical dash-dot lines mark transition from prescribed atmospheric CO_2 concentration to zero emissions with free-evolving atmospheric CO_2 concentrations. Note ocean heat uptake peaks before emissions cease under the logistic experiment.

A short paragraph explaining the difference in ZEC has been included after line 15 of page 8:

"Figure 11b shows the radiative forcing and ocean heat uptake under both the 1% and logistic ZEC experiments. The figure shows that under the 1% experiment radiative forcing and ocean heat uptake peak the moment emissions cease. While under the logistic experiment ocean heat uptake peaks over a century before emission cease. The declining ocean heat uptake under that logistic experiment explains the smaller ZEC under that experiment. When emissions cease under the logistic experiment the Earth system is closer thermal equilibrium resulting in a smaller radiative imbalance and unrealized warming. These results are consistent with previous experiments examining the pathway dependence of ZEC (Ehlert and Zickfeld, 2017)."

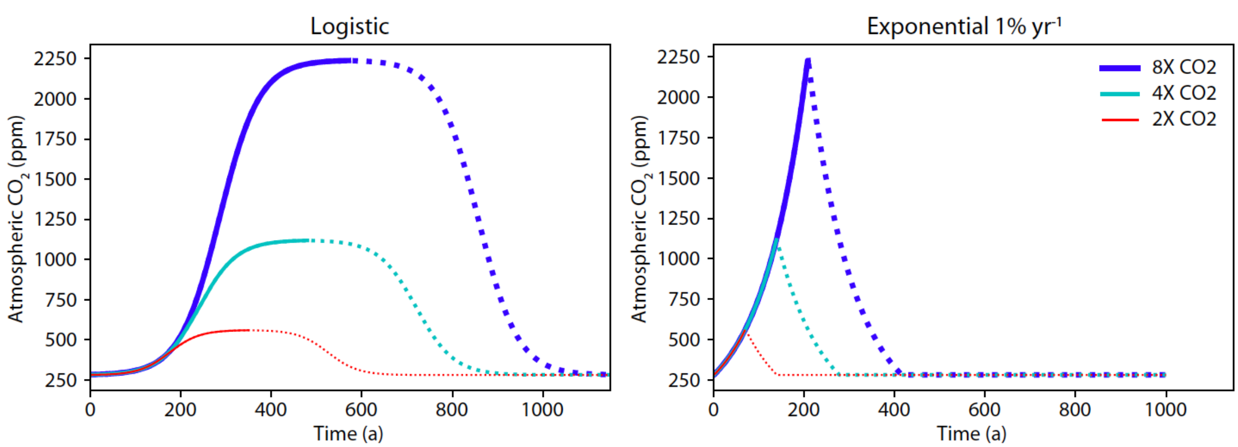
Page 10, Lines 21 and second 8: I would recommend using "I" instead of "we" in single-author paper.

I have changed "we" to "I" in the context of recommendations. "we" is retained when the reader is included in the we.

Figure 2. This figure is basically replicating part of Figure 4, right? Is it necessary redundancy? Also, the lines are quite hard to read due to overlapping. Could you at least on the 1% side divide the line to 2X,4x,and 8x parts and say that 8x includes also the other two. I know that correcting this and keeping all the figures looking consistent is hard, but especially in Fig. 2b and d it's hard to tell the lines apart.

Figure 4 does replicate Figure 2. This was done to avoid placing too much emphasis on the negative emission scenarios, which make up only a small part of the paper. However, the paper is now very figure heavy thus Figure 2 has been removed and replaced by Figure 4.

Figure 4 has been re-drafted with a new colour scheme, which makes the lines much easier to distinguish:



Figures in general: The style is not entirely consistent. In some figures, the time axis is only to the end of the simulations while in others there is some empty space which I see no reason for (especially in Fig. 5bdf.)

The figures have been re-drafted such that the length of the X-axis is defined by the longest simulation.

Technical corrections:

Page 4, Line 18: UVic ESCM

Fixed

Page 5, Line 20 and elsewhere: I'm not sure of journal style, but I think normally you should capitalize "Figure" when coupled with a number.

Figure is now capitalized when coupled with a number.

Page 7, Line 32: Remove either "will" or "s"'s in increases, deceases: : :

Fixed

Figure 1 caption: add missing % after 0.46

Fixed.

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MacDougall, A. H., 2015: The transient response to cumulative CO_2 emissions: A review. Current Climate Change Reports, 2, 39–47, doi:10.1007/s40641-015-0030-6.

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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.~~

Idealized climate change simulations are used as benchmark experiments to facilitate the comparison of ensembles of climate models. In the Fifth phase of the Climate Model Intercomparison Project (CMIP5) 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 three key differences in model output when forcing the model with the Logistic experiment. (1) The model forced with the logistic experiment exhibits a transition of the land biosphere from a carbon sink to a carbon source, a feature absent when forcing the model with the 1% experiment. (2) The ocean uptake of carbon comes to dominate the carbon cycle as emissions decline, a feature that cannot be captured when forcing a model with the 1% experiment, as emissions always increase in that experiment. (3) The permafrost carbon feedback to climate change under the 1% experiment forcing is less

than half the strength of the feedback seen under logistic experiment forcing. Using 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 CO_2 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)~~ Two of the idealized experiments outlined by the Climate Model Intercomparison Project (CMIP) 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 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., 2016b). ~~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. It was well understood that CO_2 concentration rose much faster in the 1% experiment than CO_2 concentration was expected to rise in the natural world (Stouffer et al., 1989). 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)~~ In preparation for CMIP6 the 1% experiment has been incorporated into the CMIP Diagnostic, Evaluation and Characterization of Klima (DECK) protocol, 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 were 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 scenario~~ (Matthews et al., 2009). 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 (Gregory et al., 2009; Matthews et al., 2009). Gregory et al. (2009) recommended using the 1% experiment in place of a modified scenarios, due to the simplicity of the 1% experiment, the experiment's well established role in model intercomparison projects, and the magnitude of emissions implied by the 1% experiment being of similar magnitude to socioeconomic scenarios. 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., 2016b).

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 domain 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., 2016b).

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). Therefore, 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 of 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^4MIP and the CMIP5 iteration of C^4MIP (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 potential stages: (1) increasing emissions, that are captured by the 1% experiment and also by the modified A2 scenario used by the original C^4MIP (Friedlingstein et al., 2006). (2) Decreasing 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. 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). Previous studies have used the multi-gas RCP 2.6 scenario to examine increasing, decreasing, and negative emission stages (Jones et al., 2016a). Some studies have used a fifth stage of the emissions pathway where the emission rate is constant (e.g. Krasting et al., 2014). Although useful for some examining some problems, such a state not necessary to capture the likely evolution of CO_2 emissions. Thus an ideal idealized scenario should include both an increasing and decreasing 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:

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

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 2). ~~For the 1% experiment the negative emissions scenario is the 1% up, 1% down experiment used by several previous studies~~ The mirrored return negative-emissions-scenario derived from the 1% experiment is the 1%–up 1%–down experiment used by several previous studies (Samanta et al., 2010; Boucher et al., 2012; Zickfeld et al., 2013, 2016; Schwinger and Tjiputra, 2018). The 1%–up 1%–down experiment has been incorporated as a standard model experiment for CMIP6 as part of the Carbon Dioxide Removal (CDR) MIP (Keller et al., 2018). 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 increase before reaching peak emissions and going into a decreasing phase. After the peak, emissions decline 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 increasing 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~~ stored in each of the main fast-cycling 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 4 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 increasing 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 increasing phase. In the declining emission 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.~~ As emissions decline, the land system transitions from a carbon sink to a carbon source. The ocean sink comes to dominate the system absorbing more carbon than the anthropogenic CO_2 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 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 not present in the 1% experiment.

Figure 5 displays the change in vegetation and soil carbon between pre-industrial conditions and the time of doubled atmospheric CO_2 under the $4\times$ CO_2 1% and logistic experiments. The spatial patterns of change are similar under both experiments, but of greater magnitude under the logistic experiment. Vegetation experiences a loss of carbon in the Andes and in mid-latitude northern extra-tropics, while gains in vegetation carbon are seen in the topics, subtropics, sub-arctic and arctic regions. Soils show a reduction in carbon in the permafrost region, boreal forests, and Sahel. Increases in soil carbon in seen in central North America, central Eurasia, and southern Africa, regions generally corresponding to grasslands. Overall the figure shows complex biome-specific responses of the terrestrial biosphere to increasing atmospheric CO_2 concentration.

The second key feature of the carbon cycle under declining emissions is the increase in the instantaneous ocean-borne fraction of carbon (Figure 4b). 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 declines, however the ocean remains a sink and by the end of the simulation is absorbing carbon at 1.3 $\mathrm{Pg\,C\,a^{-1}}$. 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; Randerson et al., 2015) this feature is not unexpected, but to our knowledge increasing ocean-borne fraction under decelerating emissions has not been explicitly pointed out in literature. , and is evident for model simulations under the peak-and-decline RCP 2.6 scenario in CMIP5 ESM output (Jones et al., 2013).

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. Figure 8 demonstrates the importance of elapsed time in destabilizing permafrost carbon. The logistic experiment implies lower CO_2 emission rate and hence a lower rate of warming, results in a higher release of carbon from permafrost regions at any given CO_2 concentration. The result is consistent with previous work on the permafrost carbon feedback, which demonstrates a long lag time between forcing and response due to the time taken to thaw soil and decay soil carbon (e.g. Schuur et al., 2015).

Cumulative emissions versus temperature change curves and TCRE values for the $2\times$, $4\times$, and $8\times$, 1% and logistic experiment simulations are shown in Figure 9. The TCRE relationship in general shows strong independence from forcing scenario, (e.g. MacDougall et al., 2017), a feature which is evident in Figure 9. Near the end of the logistic experiments when the rate of implied CO_2 emissions slows, the TCRE values deviate from scenario independence. Theoretical work on the TCRE relationship suggests that path independence should break-down at very high and very low emission rates (MacDougall, 2017). The results shown in Figure 9 and consistent with this understanding. At the time of CO_2 doubling the simulated TCRE value is 1.6 EgC K^{-1} under all experiments except the 2× logistic experiment where that value is 1.7 EgC K^{-1}.

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 increase, decrease, 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 10. 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 at the time emission stop. The logistic experiment has a continuous behaviour as emissions ~~when emissions cease~~ increase, decrease then reach zero, while the 1% experiment exhibits a sharp discontinuity in behaviour when emissions cease (Figure 10). 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 11 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.

Figure 11b shows the radiative forcing and ocean heat uptake under both the 1% and logistic ZEC experiments. The figure shows that under the 1% experiment radiative forcing and ocean heat uptake peak the moment emissions cease. While under the logistic experiment ocean heat uptake peaks over a century before emission cease. The declining ocean heat uptake under that logistic experiment explains the smaller ZEC under that experiment. When emissions cease under the logistic experiment the Earth system is closer thermal equilibrium resulting in a smaller radiative imbalance and unrealized warming. These results are consistent with previous experiments examining the pathway dependence of ZEC (Ehlert and Zickfeld, 2017).

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; Schwinger and Tjiputra, 2018). 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 2. 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 12. 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 declining emissions is a area of imminent importance (e.g. Jones, 2017). Here we have shown that the ocean comes to dominate the global carbon cycle as emissions decline. 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, 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 declining emission rates Ciais et al. (2013). Thus examining the ocean carbon cycle as emissions decline 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., 2016b), 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., 2016b), 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 declining emissions. That the choice of which idealized experiment to use can drastically change results of ZEC or negative emissions experiments 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., 2016b). 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 declining emission phase. However, two of the Tier two experiments, SSP5-8.5-BGC to 2300 and SSP5-3.4-Overshoot-BGC have declining phases and SSP5-3.4-Overshoot-BGC implies negative emissions (Jones et al., 2016b). 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~~ I 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 decreasing phases of SSP5-8.5-BGC to 2300 and SSP5-3.4-Overshoot-BGC

4.2 Recommendations for incorporation of the logistic experiment into CMIP7

The key advantages of the logistic experiment over the 1% experiment are that the logistic experiment captures the phase of declining emissions, and allows for a smoother transition to zero emissions or negative emissions scenarios. The principle disadvantages of switching to the logistic experiment are the much higher computation cost of the experiment, and the loss of historical continuity in experiment design. Therefore several options are available for incorporation of the logistic experiment into the CMIP7 iteration of C^4MIP, ranging from full replacement of the 1% experiment, to incorporation of the logistic experiment into the Tier 2 experiment recommendations.

Given the high computation cost of feedback separation, which necessitates running fully coupled, radiatively coupled, and biogeochemically coupled simulations (Gregory et al., 2009; Arora et al., 2013), it is prohibitively expensive for the logistic experiment to be used for this purpose. Thus I recommend that the logistic experiment be added to the Tier 1 set of experiments, in addition to the 1% experiment. With the logistic experiment used for examining carbon fraction under declining emissions, and evaluating the strength of the permafrost carbon cycle feedback. Either the $2\times$ CO_2 or $4\times$ CO_2 versions of the logistic experiment could be incorporated into the Tier 1 experiments, with the $2\times$ CO_2 version having the advantage of being 'policy relevant', and less computationally demanding.

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., 2016b). 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 declining 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 increasing, decreasing, 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 $4\times CO_2$ 1% experiment relative to the $4\times CO_2$ 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.

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) simulations forced with the logistic experiment have a terrestrial sink to source transition, while simulations forced with 1% experiment do not. (2) Forced with the logistic experiment the simulated ocean uptake of carbon comes to dominate the global carbon cycle as emissions decline. (3) Permafrost soils release less than half the carbon at the point of CO_2 doubling when forced with the $4\times CO_2$ 1% experiment relative to the $4\times CO_2$ logistic experiment simulations. (4) Following cessation of CO_2 emissions, the zero emissions commitment is much larger in simulations following the 1% experiment than for simulations following a logistic experiment. (5) Simulations with the 1%–up 1%–down experiment exhibits a smaller warming tail than simulations with 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, I recommend adding a logistic-like experiment to the protocol of the CMIP7 iteration of C^4MIP.

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. (2016b) for detailed description.

Competing interests. Author declares no competing interests.

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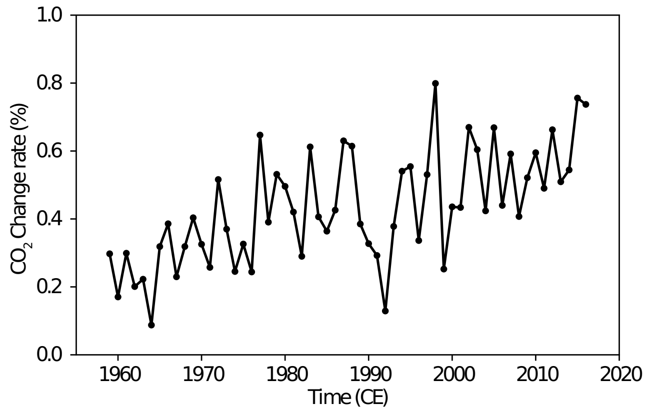

Figure 1. Historical yearly rate of atmospheric CO_2 change derived from the Mauna Loa record Trans and Keeling (2017). Note that the annual rate of increase has never breached 1% a year, and has averaged 0.46 % a^{-1} over the historical record.

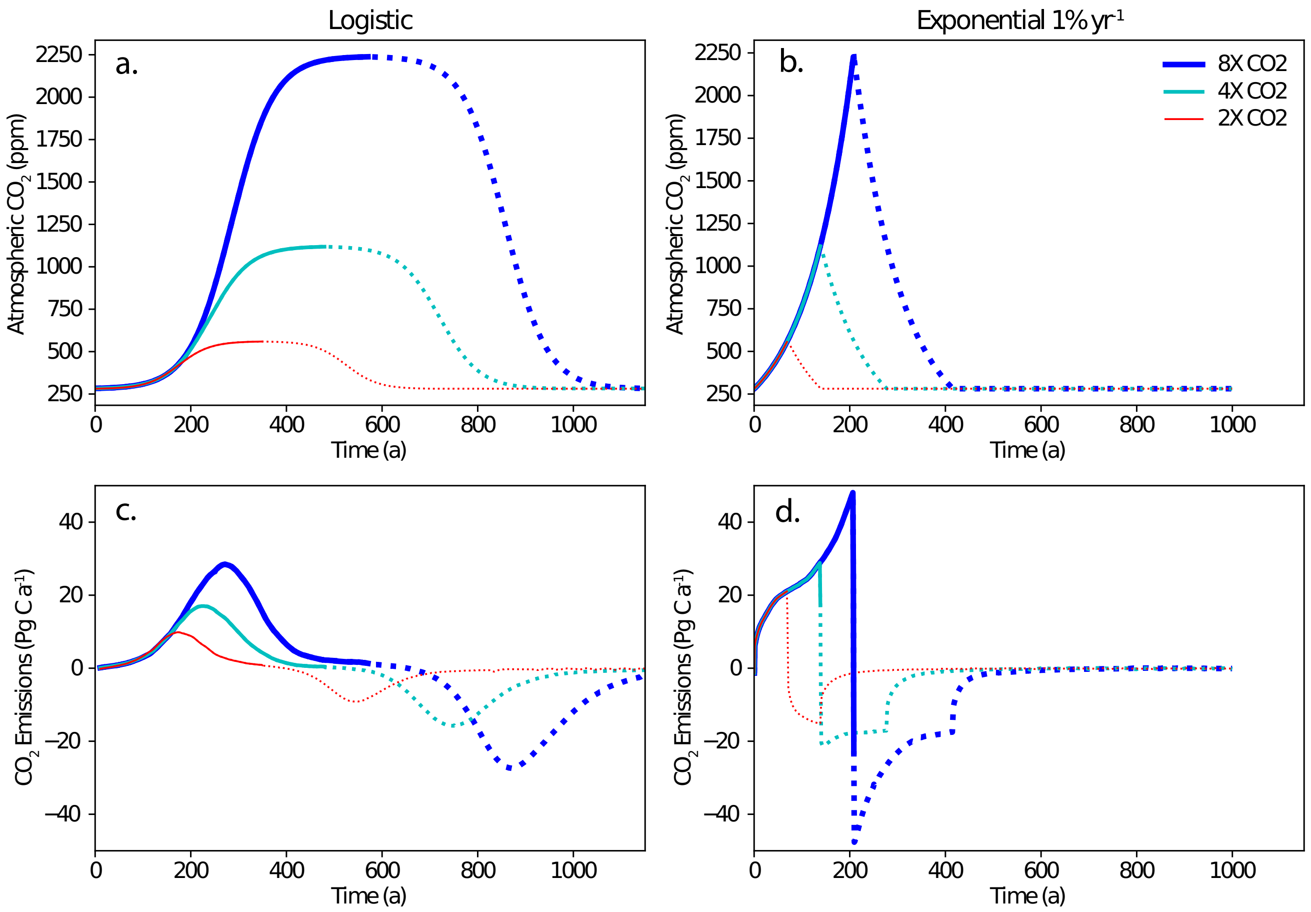

Figure 2. CO_2 pathways and diagnosed emissions for logistic and 1% experiment $2\times$, $4\times$, and $8\times$ CO_2 mirrored pathways. Solid lines are the increasing CO_2 phase of the simulation and dotted lines are the atmospheric CO_2 removal phase of the pathways. Note that the logistic CO_2 pathways 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.

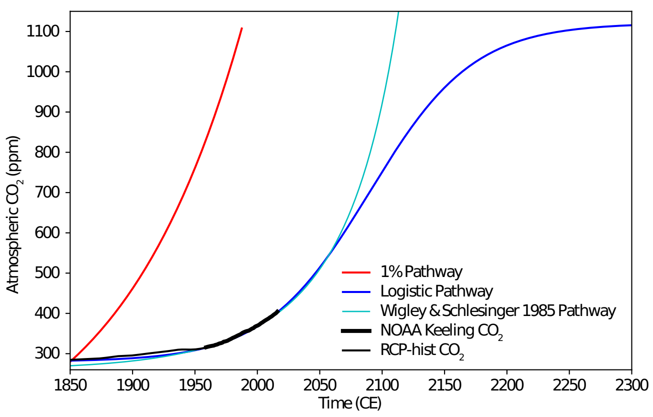

Figure 3. Historical atmospheric CO_2 trajectory and three idealized CO_2 pathways. Historical trajectories are from CMIP5 RCP-Historical archive for 1850 to 1958 (Moss et al., 2010) and from the National Oceanic & Atmospheric Administration (NOAA) record from Mauna Loa for 1959 to 2017 (Trans and Keeling, 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.

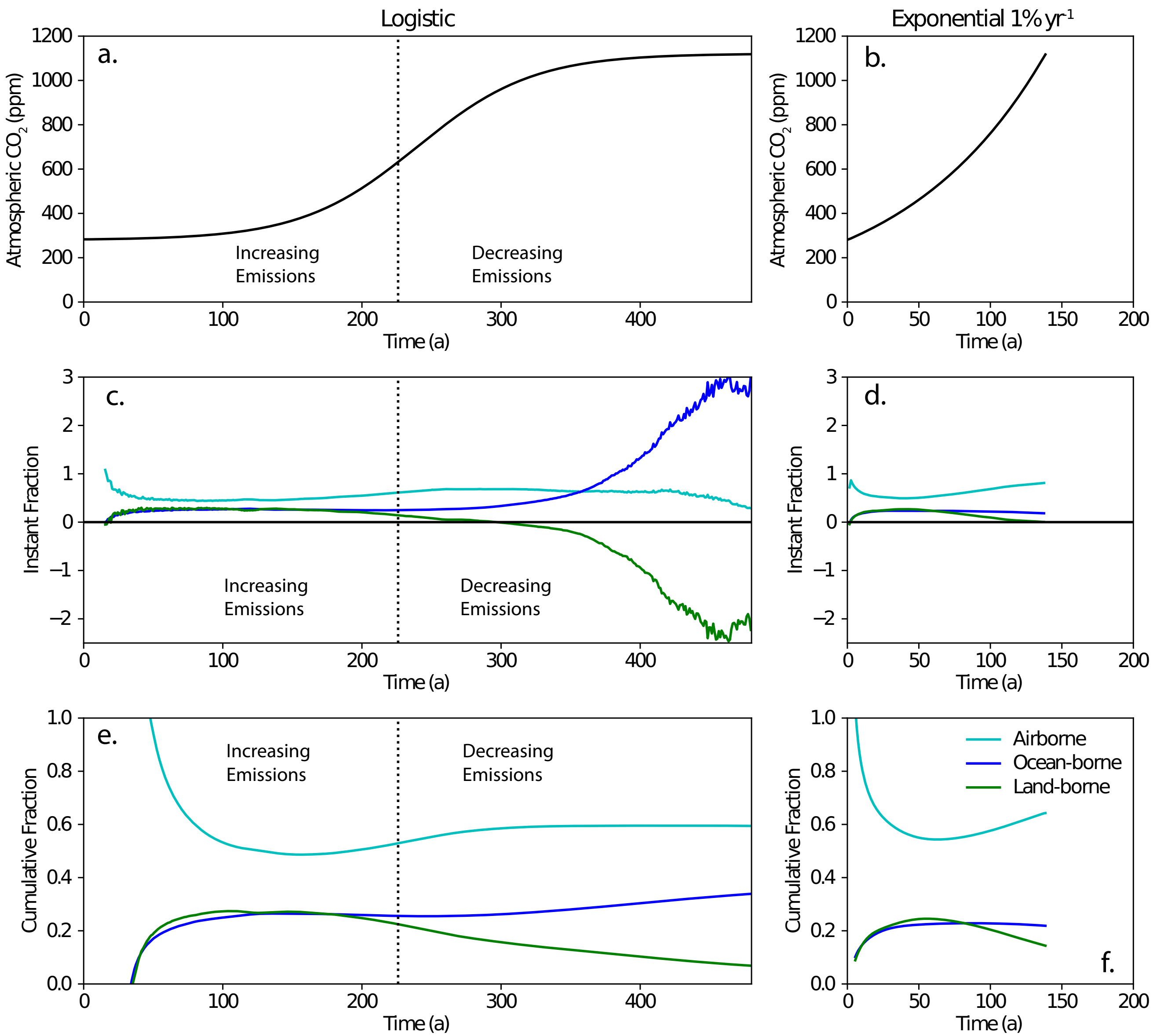

Figure 4. CO_2 concentration (a & b), instantaneous carbon fractions (c & d), and cumulative carbon fractions (e & f) for the $4\times$ CO_2 logistic and 1% experiments.

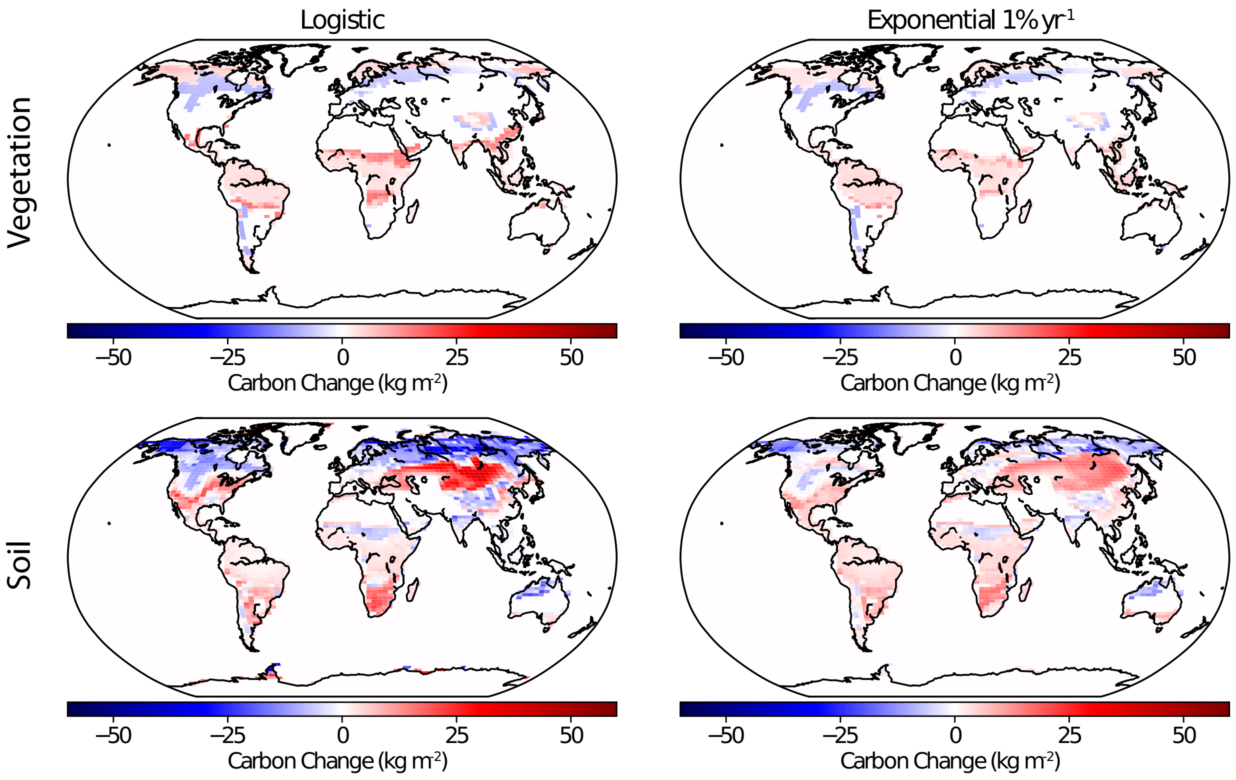

Figure 5. Change in carbon content (per unit area) between pre-industrial conditions and 2× CO_2 concentration for UVic ESCM simulations forced with the logistic and 1% experiments. Top row shows changes in vegetation carbon, bottom row shows changes in soil carbon.

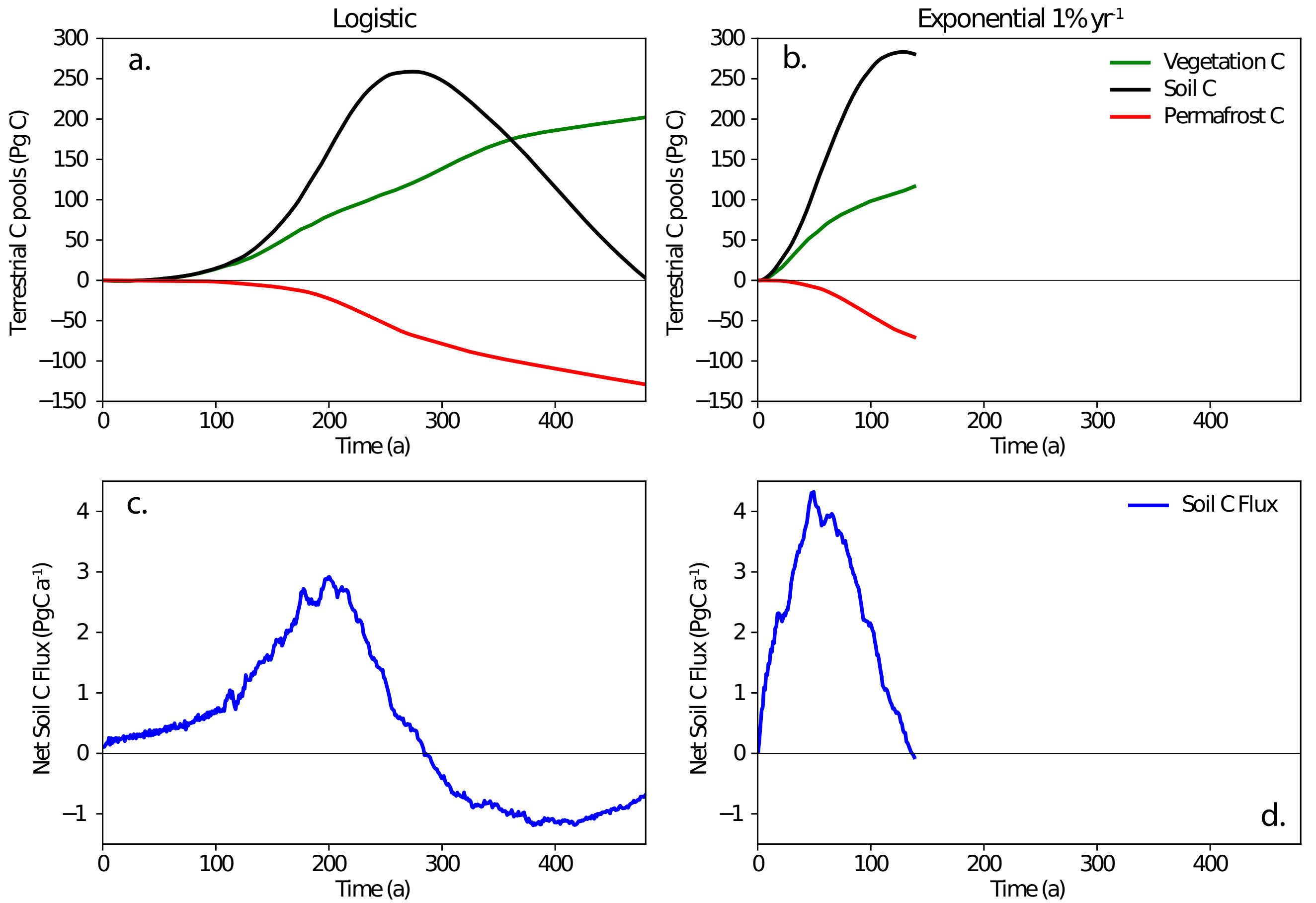

Figure 6. a,b – Evolution of terrestrial carbon pool anomalies in the logistic and 1% experiments. c,d – Flux of carbon into the soils computed from litter-fall minus heterotrophic soil respiration (excluding the permafrost carbon pool). Note that in the logistic experiment the enhanced soil respiration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

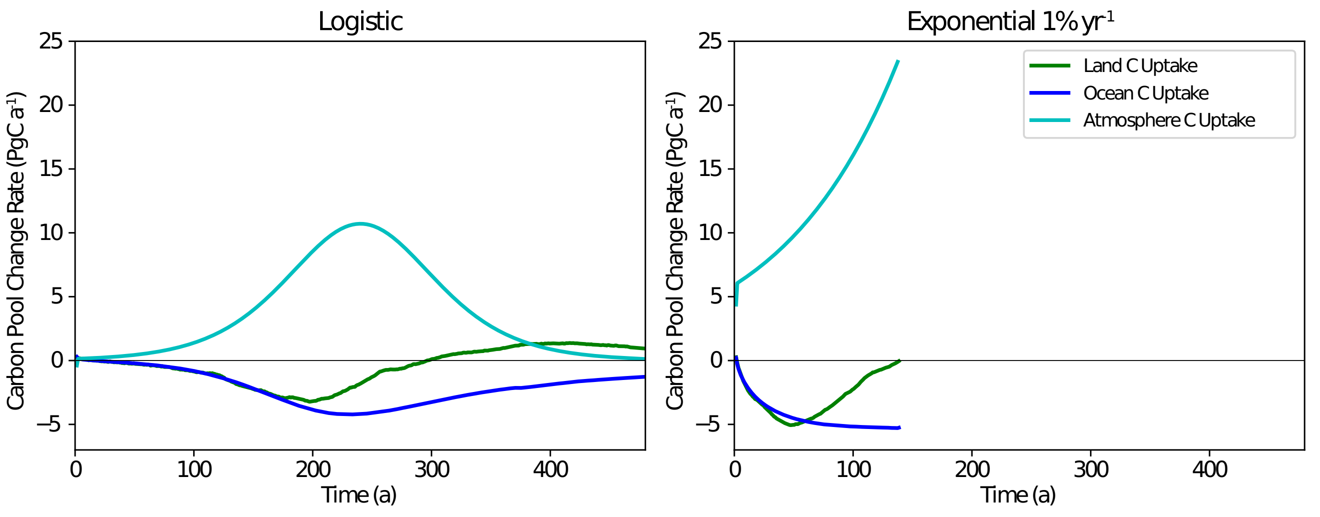

Figure 7. Uptake of carbon by the atmosphere, oceans and land systems in the logistic and 1% experiments.

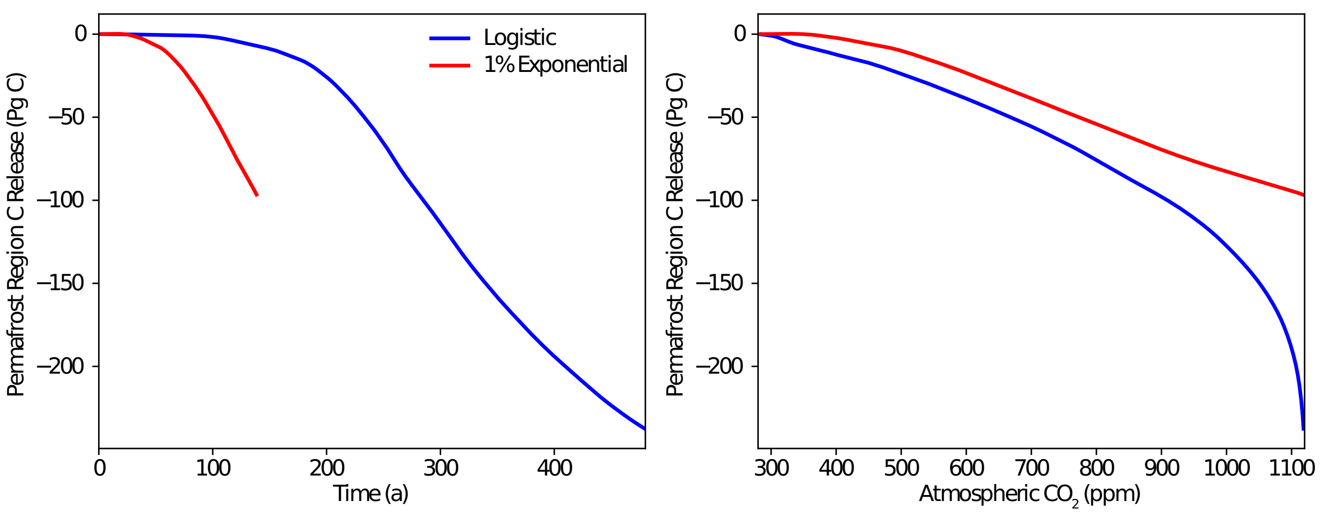

Figure 8. Release of carbon from permafrost region under logistic and 1% experiments. Release include both carbon from the permafrost carbon pool and soil carbon from the overlying active layer. Panel **a** compares the simulations with respect to time, and panel **b** with respect to atmospheric CO_2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

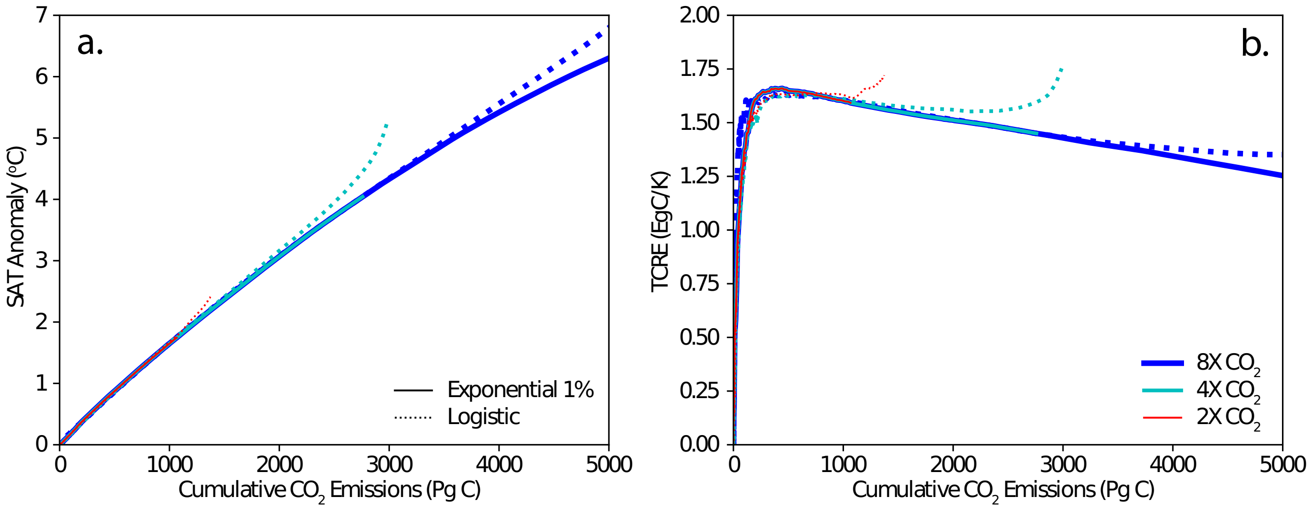

Figure 9. (a) Temperature change verses cumulative emissions curve, and (b) TCRE values for all logistic and 1% experiments. Logistic experiments given in dotted lines, 1% experiments given in solid lines. TCRE exhibits strong path-independence except near the end of the logistic experiments when the implied rate of emissions slow.

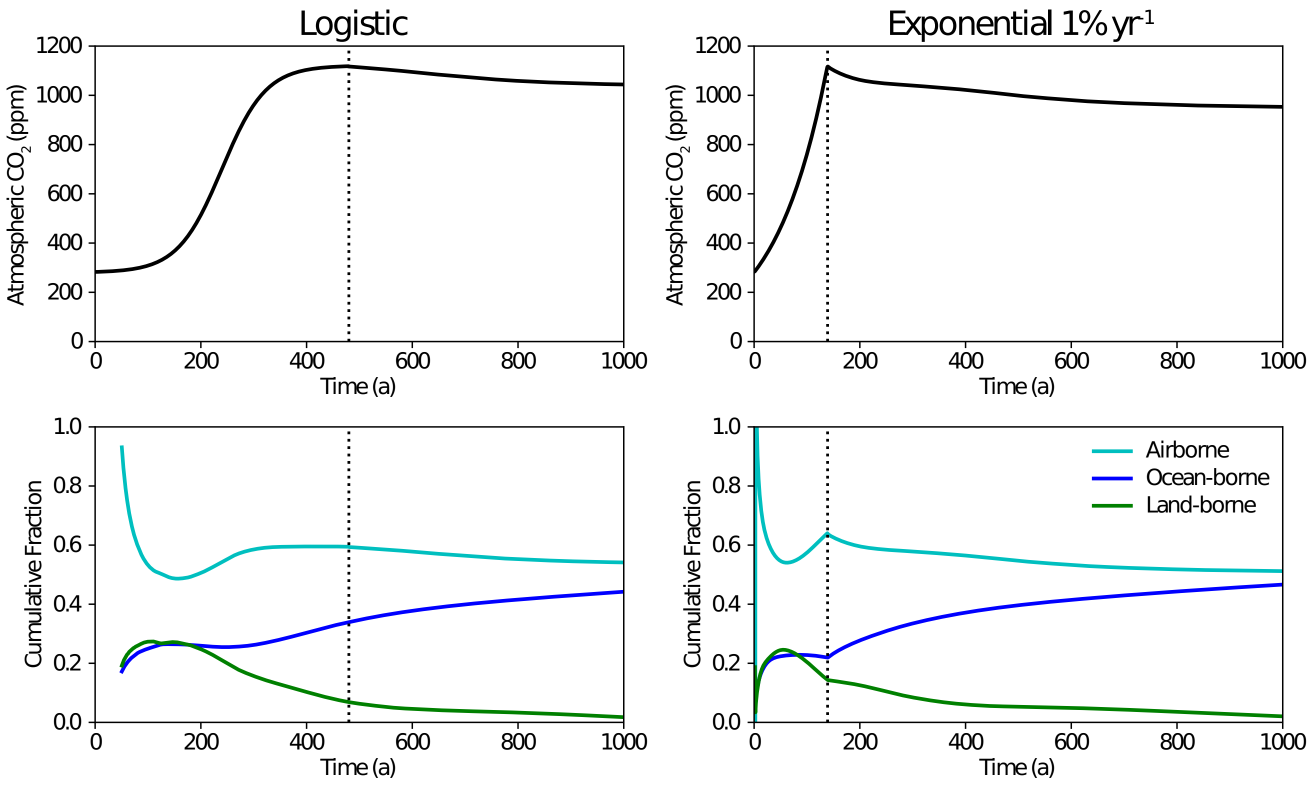

Figure 10. Evolution of atmospheric CO_2 concentration and cumulative carbon fractions for logistic and 1% experiments followed by net zero CO_2 emissions. Vertical dotted lines mark transition from prescribed atmospheric CO_2 concentration to zero emissions with free-evolving atmospheric CO_2 concentrations. Recall that instantaneous carbon fractions are not defined when emissions are zero (i.e. division by 0).

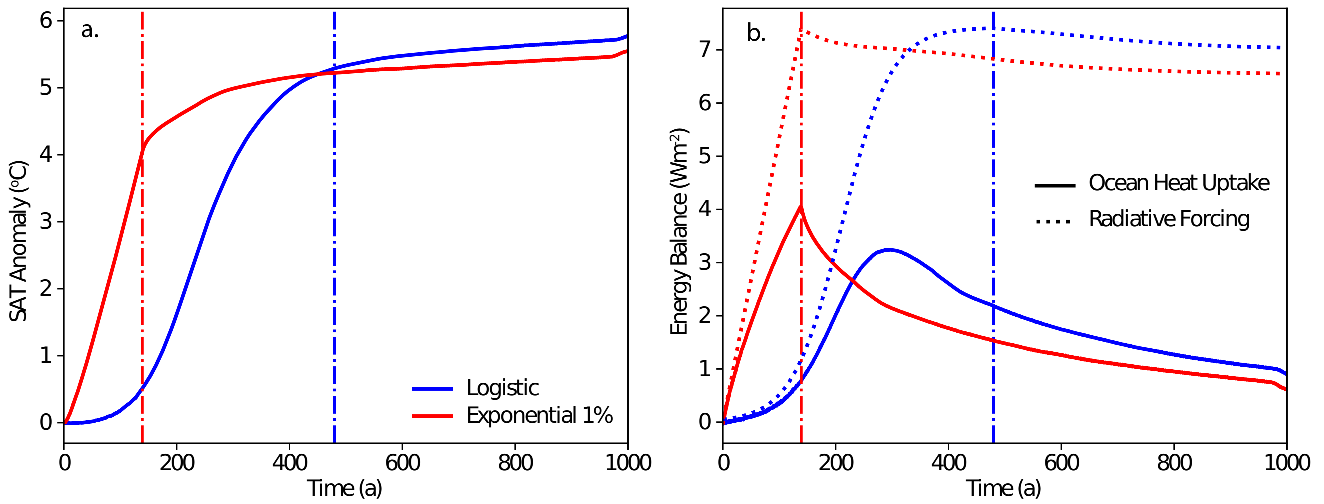

Figure 11. (a) Evolution of global Surface Air Temperature (SAT) anomaly during transient run and zero emissions phase of logistic and 1% 4×CO_2 experiment. (b) Ocean heat uptake (solid lines) and radiative forcing (dashed lines) for each experiment. Vertical dash-dot lines mark transition from prescribed atmospheric CO_2 concentration to zero emissions with free-evolving atmospheric CO_2 concentrations. Note ocean heat uptake peaks before emissions cease under the logistic experiment.

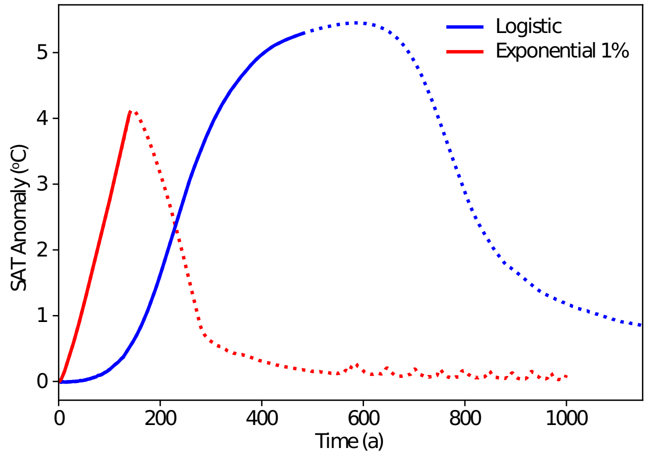

Figure 12. Evolution of global Surface Air Temperature (SAT) anomaly during 4×CO_2 1%–up 1%–down and mirrored logistic experiments. Solid lines are the increasing CO_2 phase of the simulation and dotted lines are the atmospheric CO_2 removal phase of the pathways.

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