Response to reviews of manuscript:

Is there warming in the pipeline? A multi-model analysis of the zero emission commitment from CO_2

We 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.

Reviewer 1:

Review of "Is there warming in the pipeline? A multi..." by A. H. MacDougall and coauthors. In this model intercomparison the global mean temperature response following a ceasure of CO2 emissions is investigated. This is a welcome addition to a literature mostly based on disparate evidence from single models. The study is mostly well conducted, and can in my opinion be published after the below mostly minor issues have been addressed.

Many thanks for the positive and encouraging review.

Suggestions:
14, I would add "and simple theory"

The change has been made.

150, I would delete ", often called ...". I personally have never heard the expression "Gregory ECS"

Gregory ECS has been changed to 'Effective Climate Sensitivity' throughout the manuscript.

153, Andrews et al. (2012) use years 1 to 150, not 20 to 140 as stated here

We have deleted the sentence "Usually the slope is computed from year 20 to year 140 of the 4XCO2 experiment (Andrews et al., 2012)"

171-172, if the method is unbiased, how come nearly all models have negative ZEC at year zero in Figure 2b?

Figure 2b displayed the 20 year moving average of ZEC. This window crosses over the time emissions cease and hence shows the very bias the method was intended to remove. We have revised Figure 2 to show the unsmoothed ZEC values. Please note that in response to another comment the figure was split into subplots for ESMs and EMICs.

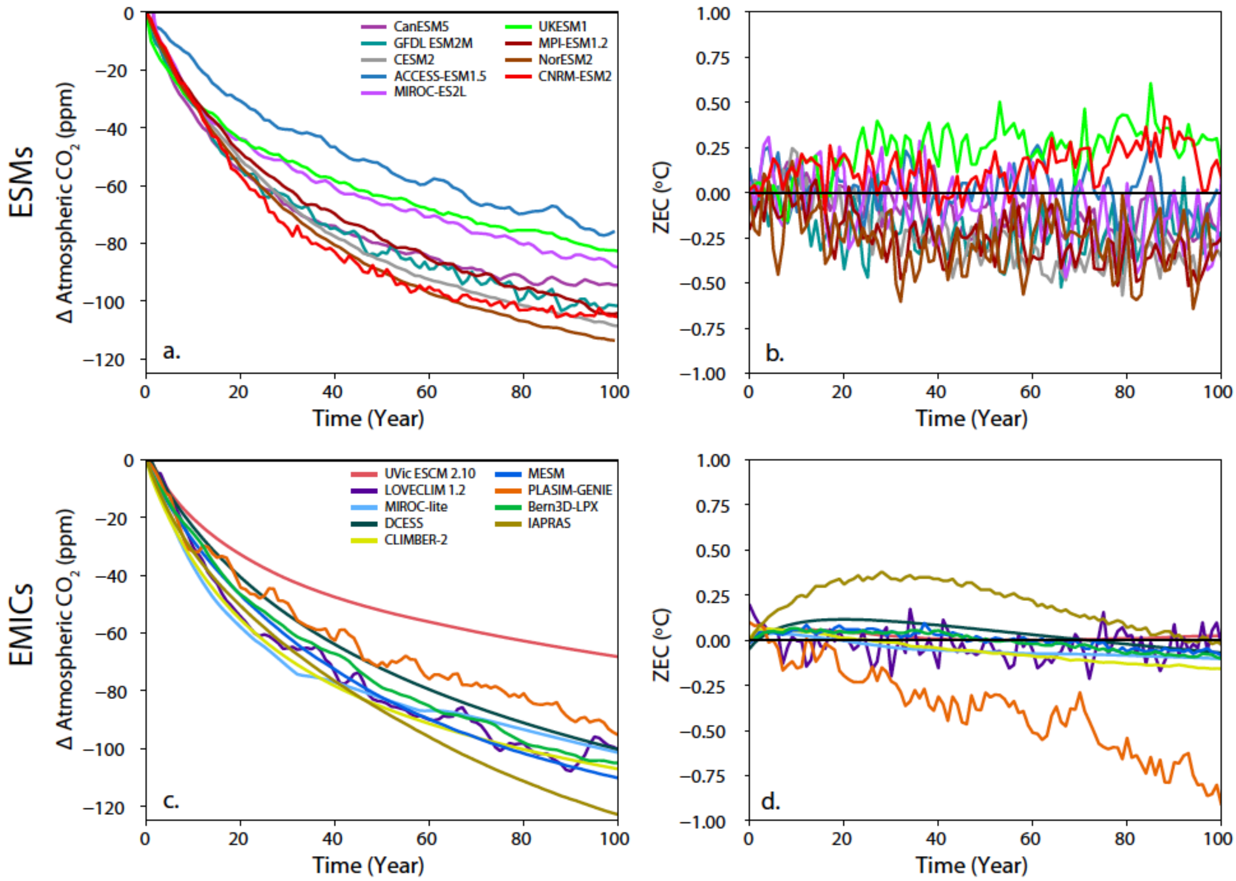

Figure 2. (a,c) Atmospheric CO2 concentration anomaly and (b,d) Zero Emissions Commitment following cessation of emissions under the experiment where 1000 PgC was emitted following the 1% experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation. Top row shows output for ESMs and bottom row for EMICs.

210, the way efficacy, or epsilon, is calculated it folds in state-dependence of feedbacks into the epsilon. Probably not an essential issue in this paper, since this parameter isn't important for ZEC, though worth a few words of mention

210, on the same theme, the study would benefit from a more up-to-date treatment of efficacy. In newer studies this is referred to as time-dependent feedback or pattern effects.

A paragraph has been added after line 216 to give an extended description of efficacy.

"Efficacy has been shown to arise from spatial patterns in ocean heat uptake (Winton et al., 2010, 2013; Rose et al., 2014), with ocean heat uptake in the high latitudes being more effective at cooling the atmosphere than ocean heat uptake in low latitudes (Rose et al., 2014). This spatial structure in the effectiveness of ocean heat uptake in turn is suspected to originate from shortwave radiation 220 cloud feedbacks (Andrews et al., 2015). The method we have used to calculated efficacy folds state-dependent feedbacks and temporal change in the climate feedback parameter (Rugenstein et al., 2016) into the efficacy parameter."

218, delete 'of the models'

This has been done.

227-229, this sentence is confusing. Models may in addition exhibit cloud adjustments not taken into account in neither Myhre nor Etminan. Therefore models may well lay outside (and they do). I recommend deleting.

Deleted.

239-240, somewhat repetitive.

The sentence did read:

"Some models such as UKESM, CNRM, and UVic exhibit continued warming in the century following cessation of emissions."

There is a typo in the sentence changing its meaning. The sentence should have read:

"Some models such as UKESM, CNRM, and UVic exhibit continued warming in the centuries following cessation of emissions."

This error has been fixed in the revised manuscript.

241, I believe the authors have mistaken MPI-ESM for Loveclim.

This is correct. We have adjusted the colour selector to eliminate the second shade of light blue (while maintained a colour-blind friendly palette).

249-250, any reason we should pay attention to such awkward behaviour?

The sentence being referred to is:

"The renewed growth in atmospheric CO_2 in P. GENIE results from release of carbon from soils overwhelming the residual ocean carbon sink."

This explanation was included for completeness. We were anticipating readers seeing the anomalous behavior of P. Genie and wondering why such a behaviour occurs. In order to not overemphasize this anomaly we have re-written the two sentences into one. The sentence did read:
"One model (P. GENIE) shows a renewed growth in atmospheric CO_2 concentration beginning about 600 years after emissions cease. The renewed growth in atmospheric CO_2 in P. GENIE results from release of carbon from soils overwhelming the residual ocean carbon sink."

And has been re-written to:

"One model (P. GENIE) shows a renewed growth in atmospheric CO_2 concentration beginning about 600 years after emissions cease, resulting from release of carbon from soils overwhelming the residual ocean carbon sink."

299-344, here I didn't understand why the authors refer to a diagnostic framework (Equation 4), and then don't use it? In particular if ZEC is non-zero, then climate change feedbacks (lambda) will affect the balance, and likewise if there is ocean heat uptake efficacy (non-unitary epsilon).

The diagnostic framework summarized in Equation 4 was used to compute the components of Figure 7 and Figure 9. It was felt that showing the energy balance terms in graphic form would be easier for readers to interpret than a table of values. To clarify what was done the introduction of the section was re-written from:

"The framework introduced in section \ref{Frame} was applied to the ZECMIP output to partition the energy balance components of ZEC into contributions from the warming effect of the reduction in ocean heat uptake ($-\Delta N$), and the effect of the change in radiative forcing from the ocean and terrestrial carbon fluxes. Figure \ref{EB_bar} shows the results of this analysis for each model averaged over the period 40 to 59 years after emissions cease for the 1000 PgC 1\% (A1) experiment (the same time interval as ZEC$_{50}$)."

To:

"The framework introduced in Section 2.4 was applied to the ZECMIP output to partition the energy balance components of ZEC into contributions from the warming effect of the reduction in ocean heat uptake ($-\Delta N$), and the effect of the change in radiative forcing from the ocean (F_{ocean}) and terrestrial carbon fluxes (F_{land}). Figure 7 shows the results of this analysis for each model averaged over the period 40 to 59 years after emissions cease for the 1000 PgC 1% (A1) experiment (the same time interval as ZEC50). The components of the bars in Figure 7a are the terms of the right hand side of Equation 4."

319, delete last instance of 'and'

Done

Figure 8, I recommend using a different colour than blue for the outlier, in print it was hard to distinguish.

The outlier is now shown as a magenta square.

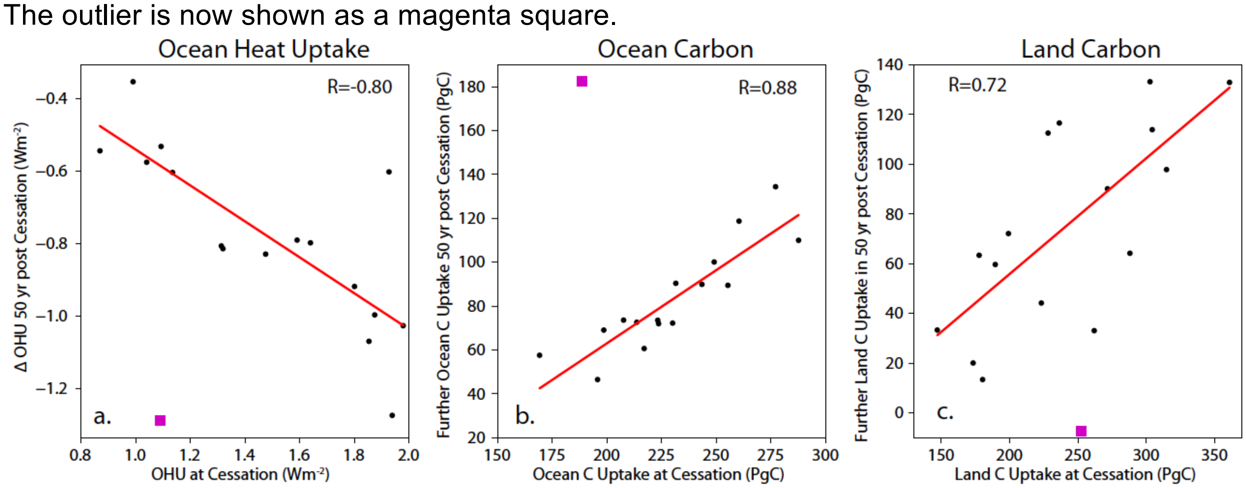

Figure 9. Relationship between variables before emissions cease and 50 years after emissions cease. (a) Ocean Heat Uptake (OHU) is computed for 20 year windows with the value at cessation taken from the 1pctCO2 experiment analogous to the how temperature of cessation is computed. (b) Cumulative ocean carbon uptake, (c) Cumulative land carbon uptake. Each marker represents value from a single model. Line of best fit excludes the outlier model IAPRAS which is marked with a magenta square.

346-355, here I would like to see a statistical test that the slopes are actually nonzero. To me it seems rather random, for instance the slope in panel c would probably disappear if omitting the single high TCRE model.

We are hesitant here to include a statistical test of slope due to the lack of independence between Earth System Models. ESM have been shown to exhibit an almost phylogenetic relationship with one-another (Knutti et al. 2013). To better explain this we have replaced the sentence:

“However the relationship is weak and several models with high TCRE values have low ZEC values.”

With:

“However, these relationships may not be robust due to small number of non-independent models”

361, use another word than ’Gregory ECS’

Changed to ‘effective climate sensitivity’

368, any reason to think that ZEC should be related to these quantities? In fact, I think it is great that it is not, since basic theory suggests it shouldn’t.

Upon examining the question in detail it is clear basic theory suggests there should be no relationship. However, before examining the question many of the investigators suspected there might be relationships between ZEC and other metrics. We anticipate that many readers would also intuitively make the same error and hence included the analysis.

400, the phrasing ’will be required’, seems to suggest that sustaining a constant global temperature somehow is desirable. I suggest leaving it to others to decide this.

We have changed “will” to “would” to make clear that this is a choice.

418-419, I didn’t understand this sentence.

The sentence has been re-written from:

“However, in experiments with a gradual reduction in emissions the temperature adjustment from the values expected from TCRE (i.e. ZEC) begin to manifest while emissions are ramping-down.”

To:

“However, in experiments with a gradual reduction in emissions a mixture of TCRE and ZEC effects occur as the rate of emissions declines.”

425, since we don’t expect ZEC to be related to ECS, TCR and TCRE, why start the sentence like this?

The first part of the sentence “ZEC is poorly correlated to other Earth system metrics, however”, has been deleted

430, I recommend amending: ’... cannot be ruled out purely on the basis of models.’

Done

Reviewer 2:

The study is addressing an important unknown in the climate system as to whether there is continued warming or cooling on a decadal timescale after carbon emissions cease. There is a comprehensive analysis of 18 Earth system models (of either full or intermediate complexity) following a common default experiment of CO2 increasing until 1000 PgC has been emitted and then freely varying.

I am very positive towards the ambition, scope and rigour of the manuscript. A key outcome is the message is that ocean and terrestrial carbon uptake is particularly important in determining the Zero Emissions Commitment (ZEC). I have 2 concerns with regards the strength of this conclusion.

1. The analysis of the thermal response on a decadal timescale focuses on changes in planetary heat uptake and the efficacy, representing a non-dimensional weighting of planetary heat uptake. The study ignores any explicit discussion of temporal changes in climate feedback parameter (due to their method to diagnose the effective climate sensitivity), particularly associated with clouds. Since the study is focussing on decadal timescales, this omission is likely to be important and should be more fully discussed.
Clouds represent one of the biggest uncertainties in climate sensitivity and are known to evolve in time. This potentially important contribution of physical climate feedbacks merits a fuller discussion.

We have included additional explanation for the efficacy parameter and how we treat it in the analysis, including that any temporal changes in the climate feedback parameter would be folded into our efficacy parameter. After line 216 the following paragraph has been added:

“Efficacy has been shown to arise from spatial patterns in ocean heat uptake (Winton et al., 2010, 2013; Rose et al., 2014), with ocean heat uptake in the high latitudes being more effective at cooling the atmosphere than ocean heat uptake in low latitudes (Rose et al., 2014). This spatial structure in the effectiveness of ocean heat uptake in turn is suspected to originate from shortwave radiation 220 cloud feedbacks (Andrews et al., 2015). The method we have used to calculated efficacy folds state-dependent feedbacks and temporal change in the climate feedback parameter (Rugenstein et al., 2016) into the efficacy parameter."

I fully realise that time-variations of the climate feedback parameter may be related to temporal variability in the efficacy. Indeed the authors include a 30% uncertainty in the planetary heat uptake term to take account of this effect, but do not extensively discuss the implications of this uncertainty. In their crucial figure 7, the sign of the ZEC in most model cases is uncertain given the uncertainty arising from the efficacy weighting of the change in the planetary heat uptake. Thus, there needs to be more acknowledgement of the uncertainty in the ZEC due to physical climate feedbacks (or an explanation of why these physical climate feedbacks are less uncertain at the time of zero emission).
Whether this uncertainty represents random variability or a systematic trend needs to be addressed.

Our analysis does show that the time evolution of ZEC is sensitive to physical climate feedbacks. Within our framework, this is captured by the efficacy parameter. To better acknowledge this we have added a paragraph to the discussion about physical climate feedbacks and ZEC. The paragraph has been added to the subsection 'Drivers of ZEC', and reads:

"Our analysis has suggested that the efficacy of ocean heat uptake is crucial for determining the temperature effect from ocean heat uptake following cessation of emissions. Efficacy itself is generated by spatial patterns in ocean heat uptake and shortwave cloud feedback processes (Rose et al., 2014; Andrews et al., 2015). Thus, evaluating how these processes and feedbacks evolve after emissions cease is crucial for better understanding ZEC. As the spatially resolved outputs for ZECMIP are now available (see Section 5), evaluating such feedbacks presents a promising avenue for future research."

2. There is a larger inter-model spread in the response of the terrestrial carbon feedback. A key conclusion is that the terrestrial carbon response is of central importance in dictating whether surface temperature continues to rise or fall after emissions ceases.

However, this conclusion needs to be seriously caveated by the choice of terrestrial carbon cycle and whether nutrient limitation is included. It might be the case that the terrestrial carbon cycle is becoming over strong if there are no constraining limitations applied. It would be useful to group the analysis of the terrestrial response into those model responses with and without nutrient limitation, and then more clearly contrast their behaviour.

We have conducted an analysis of the terrestrial carbon cycle for models with and without a representation of the nitrogen cycle. The existing section that discussed the nitrogen cycle has been re-written from:

"The remaining models have substantial contributions from both carbon sinks. In all models the reduction in forcing from ocean carbon uptake is smaller than the reduction in ocean heat uptake, suggesting that the post-cessation net land carbon sink is critical to determining ZEC values. Given that the behaviour of the terrestrial carbon cycle varies strongly between models \citep{FriedlingsteinEtAl2006,AroraEtAl2013,AroraEtAl2019} and that many models lack feedbacks such as nutrient limitation and permafrost carbon pools, the strong dependence of ZEC$_{50}$ on terrestrial uptake is concerning. Notably the three ESMs with the weakest modelled terrestrial carbon sink response (ACCESS, MIROC-ES2L, and UKESM) are three which include terrestrial nutrient limitations (Table \ref{MD_ESM_A}, \ref{MD_ESM_B}). The

UVic model includes permafrost carbon and has a relatively weak terrestrial carbon uptake (Table \ref{MD_EMIC_B}). However, Bern and MPI-ESM also have nutrient limitations and have a terrestrial carbon uptake in the middle (Bern) and upper (MPI-ESM) parts of the inter-model range. IAPRAS does not account for either nutrient limitations or permafrost carbon and has the weakest terrestrial carbon uptake of all (Table \ref{MD_EMIC_A}). Ocean carbon uptake also varies substantially between models, with some of the EMICs (P. GENIE, MESM, and IAPRAS) having very high ocean carbon uptake, and two of the ESMs (CanESM5 and CNRM) and having very low ocean carbon uptake."

To:

"The remaining models have substantial contributions from both carbon sinks. In all models the reduction in forcing from ocean carbon uptake is smaller than the reduction in ocean heat uptake, suggesting that the post-cessation net land carbon sink is critical to determining ZEC values. The ocean carbon uptake itself varies substantially between models, with some of the EMICs (P. GENIE, MESM, and IAPRAS) having very high ocean carbon uptake, and two of the ESMs (CanESM5 and CNRM) having very low ocean carbon uptake. Given that the behaviour of the terrestrial carbon cycle varies strongly between models (Friedlingstein et al., 2006; Arora et al., 2013, 2019) and that many models lack feedbacks related to nutrient limitation and permafrost carbon pools, the strong dependence of ZEC_{50} on terrestrial carbon uptake is concerning for the robustness of ZEC_{50} estimates. Notably, the three ESMs, with the weakest terrestrial carbon sink response (ACCESS, MIROC-ES2L, and UKESM), include terrestrial nutrient limitations (Table A1, A2). However, despite including terrestrial nutrient limitation Bern and MPI-ESM simulate a terrestrial carbon uptake in the middle and upper parts of the inter-model range, respectively. The UVic model includes permafrost carbon and has a relatively weak terrestrial carbon uptake (Table A4). IAPRAS does not account for either nutrient limitations or permafrost carbon and has the weakest terrestrial carbon uptake among all models studied here (Table A3)."

A new paragraph has been added to describe our additional analysis of model with and without a terrestrial nitrogen cycle. The paragraph reads:

"To further investigate the effect of nutrient limitation on ZEC we have compared models with and without terrestrial nutrient limitations. Eight of the models that participated in ZECMIP included a representation of the terrestrial nitrogen cycle, ACCESS, CESM2, MIROC-ES2L, MPI-ESM, NorESM, UKESM, Bern and MESM. One model (ACCESS) includes a representation of the terrestrial phosphorous cycle. Figure 8 shows behaviour of the terrestrial carbon cycle before and after emissions cease for models with and without terrestrial nutrient limitations. Figure 8a shows that consistent with Arora et al. (2019) models with a terrestrial nitrogen cycle have on average a lower carbon uptake than those without. However, after emissions cease there is little difference in the terrestrial uptake of carbon between models with and without nutrient limitations. For both sets of model the median uptake is almost the same at 68 PgC and 63 PgC respectively, and the range for models without nutrient limitation fully envelops the range for those with nutrient limitations. Thus, while nutrient limitations do not appear to have a controlling influence on the magnitude of the post cessation terrestrial carbon uptake they have a marked impact on its uncertainty. As with carbon cycle feedbacks (Arora et al., 2019) those models including terrestrial nitrogen limitation exhibit substantially smaller spread than those which do not. This offers hope for future reductions in ZEC uncertainty as more models begin to include nitrogen - and thereafter phosphorus - limitations on the land carbon sink."

The new figure is below:

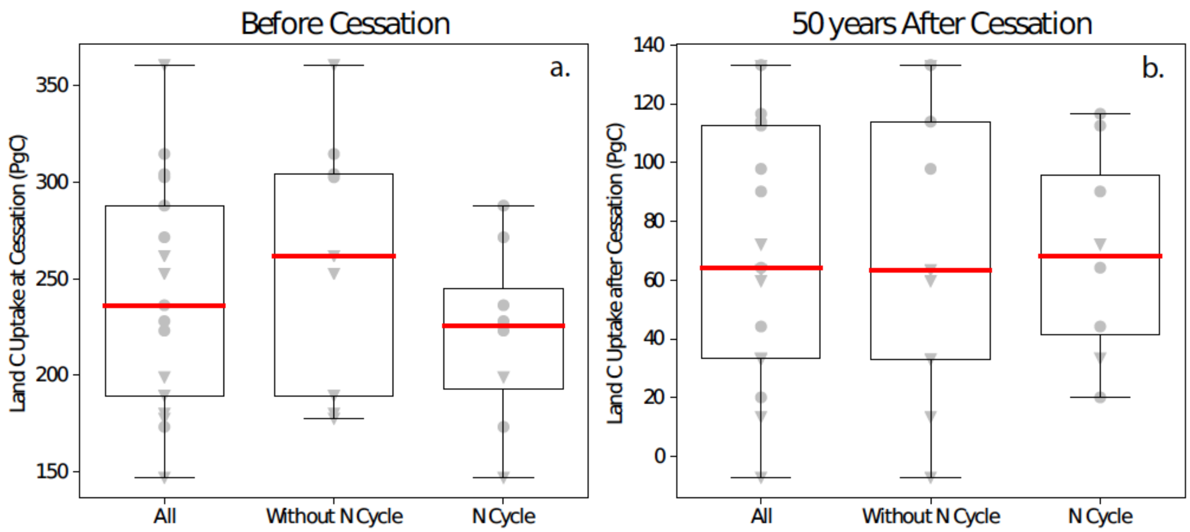

Figure 8. Terrestrial carbon uptake for models with and without a nitrogen cycle, before emissions cease and after emissions cease. Eight models have a representation of nutrient limitations and ten do not. Circles indicate data points for ESMs and triangle indicate data points for EMICs.

A further recommendation is in the final conclusion is to recap as to how this work compares with prior studies, particularly for the multi-centennial timescale. This context is set out earlier in the motivation, but it is unclear as to the extent of agreement or not with the inferences in the prior work.

We have added a paragraph after line 427 to discuss how our results compare to prior works. The paragraph reads:

"The results of the ZECMIP experiments are broadly consistent with previous work on ZEC, with a most likely value of ZEC close to zero and a range of possible model behaviours after emissions cease. In our analysis of ZEC we have shown that terrestrial uptake of carbon plays a more important role in determining that value of ZEC on decadal timescales than has been previously suggested. However our analysis is consistent with previous results from Ehlert and Zickfeld (2017) and Williams et al. (2017) in terms of ZEC arising from balance of physical and biogeochemical factors."

In summary, I think that the study is important and recommend minor edits, particularly to discuss the outcomes of the study in terms of the effect of physical climate feedbacks (via the efficacy) and the controls of nutrient limitation in the terrestrial system, and placing the study in the context of prior work.

Many thanks for this positive and encouraging review.

Detailed points:

L12 Mention the large uncertainty in the sign of the ZEC from the 30% uncertainty in the efficacy.

The large uncertainty in efficacy affects our ability to decompose ZEC into energy balance terms for each model, it does not affect the values of ZEC from the models global temperature outputs.

To include the efficacy uncertainty in the abstract we have modified the sentence the describes the analysis from:

"Analysis shows that both ocean carbon uptake and carbon uptake by the terrestrial biosphere are important for counteracting the warming effect from reduction in ocean heat uptake in the decades after emissions cease."

To:

"Analysis shows that both the carbon uptake by the ocean and the terrestrial biosphere are important for counteracting the warming effect from the reduction in ocean heat uptake in the decades after emissions cease. This warming effect is difficult to constrain due to high uncertainty in the efficacy of ocean heat uptake."

L71/72. Both prior studies are addressing the multi-centennial timescale, rather than the previous discussion of a millennial timescale (L30-41). Your study should relate back to these two prior studies and identify what is different to the arguments outlined by Ehlert and Zickfeld (2017) and Williams et al. (2017).

To clarify Line 31 has been changed from:
"such that the atmospheric CO_2 concentration continues to evolve over several millennia"

To

"such that the atmospheric CO_2 concentration continues to evolve over centuries to millennia"

A call-back to Ehlert and Zickfeld (2017) and Williams et al. (2017) has been added to the discussion (see comment above)

"However our analysis is consistent with previous results from Ehlert and Zickfeld (2017) and Williams et al. (2017) in terms of ZEC arising from balance of physical and biogeochemical factors."

L77 Recommend rephrase to avoid ambiguity so as to make clear to the reader what part of the sentence "only" refers to.

The sentence did read:
"The ZEC from all emissions over multiple centuries is generally consistent with ZEC from CO_2 emissions only for moderate future scenarios (Matthews and Zickfeld, 2012)."

And had been re-written to:

“The ZEC from all emissions over multiple centuries is generally consistent with ZEC from only CO2 emissions, for moderate future scenarios (Matthews and Zickfeld, 2012).”

P8-11 Recommend placing the model descriptions in Tables 2 to 5 in the Appendix.

The tables have been moved to appendix A, and are now Tables A1, A2, and A3.

L175. Add Williams et al. (2017) for the multi-centennial case as that study has addressed the different thermal and carbon controls for delayed warming.

Done

P13. In contrast to the model descriptions, I think that the theory in Appendix A could have been placed in the main text, but up to the authors discretion.

In an effort to make the paper as accessible as possible it was felt that it was better to have the detailed mathematics in an appendix.

L198 include that the change in ocean heat uptake includes a time-dependent weighting from the efficacy.

The statement:
“3) the change in ocean heat uptake”

Has been changed to:

“3) the change in effective ocean heat uptake”

L209. Include that the Gregory ECS is a time average fit over the time period of interest, while the efficacy is time dependent.

A sentence has been added to line 214:

“Effective climate sensitivity is here calculated as a time average fit and hence is assumed to be a constant, while efficacy values are expected to change in time.”

Note ‘Gregory ECS’ was changed to ‘effective climate sensitivity’ in response to a comment from Reviewer 1.

L217 The efficacy values may not simply be representative of internal variability, but may also be associated with systematic shifts in climate feedback, such as systematic changes in cloud types with changing surface temperature.

We have added a paragraph at this location in the paper to better explain efficacy. See response to general comment.

“Efficacy has been shown to arise from spatial patterns in ocean heat uptake (Winton et al., 2010, 2013; Rose et al., 2014), with ocean heat uptake in the high latitudes being more effective at cooling the atmosphere than ocean heat uptake in low latitudes (Rose et al., 2014). This spatial structure in the effectiveness of ocean heat uptake in turn is suspected to originate from shortwave radiation 220 cloud feedbacks (Andrews et al., 2015). The method we have used to calculated efficacy folds state-dependent feedbacks and temporal change in the climate feedback parameter (Rugenstein et al., 2016) into the efficacy parameter."

L223 The authors have acknowledged the importance of the efficacy by including a 30% uncertainty. However, is there a systematic trend to the efficacy or are there random variations in the different models? In diagnostics of ESM2M, there is a progressive increase in the efficacy from close to 1.5 to over 2 in 100 years after emissions cease, which may be equivalently interpreted as a systematic decrease in climate feedback parameter that continues for several centuries; see Williams et al. (2017). If there is a systematic trend, then the implications for the ZEC are different to if there is simply uncertainty in how the efficacy evolves.

Three of the four EMICs without internal variability all show a declining trend in efficacy, while UVic ESCM shows no change in time (see Figure A1).

We have added a sentence here to note this. The sentence reads:

"Notably efficacy declines in three of the four models, consistent with previous work showing strong trends in efficacy over time (Williams et al., 2017)"

L254. Clarify the timescale.

The sentence has been re-written from:

"Of the eight models that extended simulations beyond 150 years, five show temperature peaking then declining (Bern, MESM, DCESS, LOVECLIM and MIROC-ES2L), GFDL shows temperature declining and then increasing but ultimately remaining close to the temperature at cessation, and the UVic model shows continuous, if slow, warming."

To:

"Of the nine models that extended simulations beyond 150 years, seven show temperature on a long-term decline (Bern, MESM, DCESS, IAPRAS, LOVECLIM, P. GENIE, and MIROC-ES2L), GFDL shows temperature declining and then increasing within 200 years after cessation but ultimately remaining close to the temperature at cessation, and the UVic model shows slow, warming."

Figure 2. It is difficult to pick out individual model types, particularly those coloured blue and green. Recommend split the panels and show the responses for different types of models to gain more insight.

The figure has been split between ESMs and EMICs. The colour pallet has also been adjusted to remove colours that are too similar.

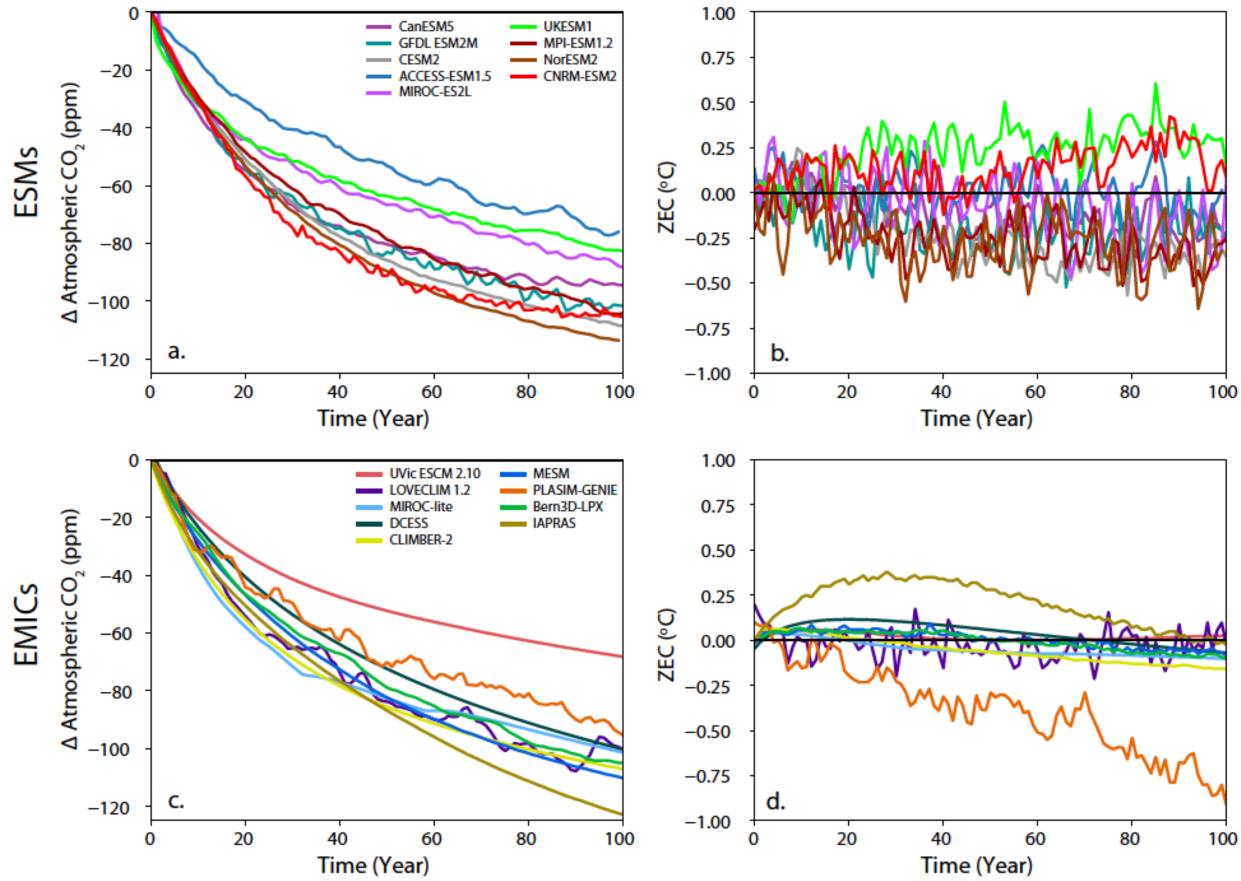

Figure 2. (a,c) Atmospheric CO2 concentration anomaly and (b,d) Zero Emissions Commitment following cessation of emissions under the experiment where 1000 PgC was emitted following the 1% experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation. Top row shows output for ESMs and bottom row for EMICs.

L333 The response is interpreted in terms of changes in the "deep ocean circulation". However, the anthropogenic invasion of heat and carbon is being dominated by ventilation of the thermocline, see Sabine et al. (2004) Science or Zanna et al. (2019) PNAS. Schematic figure of Goodwin et al. (2015) Nature Geosciences or model diagnostics in Williams et al. (2017) J. Climate set out this thermocline ventilation view.

We thank the review for spotting this error and also for pointing us to this additional reference. We agree that the anthropogenic invasion of heat and carbon is mainly dominated by ventilation of the thermocline. We therefore changed the sentence from:

"It has long been suggested that the reason that long-term ZEC was close to zero is compensation between ocean heat and ocean carbon uptake (Matthews and Caldeira, 2008; Solomon et al., 2009; Frölicher and Paynter, 2015), which are both partially controlled by deep ocean circulation (Banks and Gregory, 2006; Xie and Vallis, 2012; Frölicher et al., 2015)."

To:

“It has long been suggested that the reason that long-term ZEC was close to zero is compensation between ocean heat and ocean carbon uptake (Matthews and Caldeira, 2008; Solomon et al., 2009; Frölicher and Paynter, 2015), which are both dominated by the ventilation of the thermocline (Sabine et al., 2004; Banks and Gregory, 2006; Xie and Vallis, 2012; Frölicher et al., 2015; Goodwin et al., 2015; Zanna et al., 2019). "

L335. The large uncertainty in the efficacy weighting of ocean heat uptake in Figure 7 can change the sign of the ZEC and so this aspect is certainly of comparable importance to the terrestrial carbon sink.

We have noted this with a few addition sentence added to the end of the paragraph. The sentences read:

“Also notable is the large uncertainty in effective ocean heat uptake, which originates from the uncertainty in efficacy. As efficacy is related to spatial patterns in ocean heat uptake and coupled shortwave cloud feedbacks (Rose et al., 2014; Andrews et al., 2015), shifts in these patterns in time thus likely affect the values of ZEC and hence represents an important avenue for further investigation.”

Figure 10. It is striking how low a proportion of the intermodel variability in the ZEC is explained by any of these metrics. Do these fits improve or alter if different subsets of models are included? The relatively weak fits suggests that the ZEC is being determined by a competition of processes and examining one process in isolation only provides limited insight.

We did examine fits with ESMs and EMICs alone but the fits were equally bad. As noted by **Reviewer 1** and described in lines 352 to 355 there is no mathematical basis to expect good fits between ZEC and other metrics. However, we have chosen to include the analysis as a priori many readers may suspect such relationships may exist.

Figure 11 is more encouraging in showing that for the same model type, there is a relationship between the ZEC and the TCRE, with an increasing ZEC with a higher ECS.

L368 There is a poor relationship between the ZEC and the TCR and ECS when looking across a range of models, but there is a stronger relationship when looking at the same model.

The sentence has been re-written from:
“The analysis here has shown that ZEC is poorly correlated to other metrics of climate warming, such as TCR and ECS.”

To:

“The analysis here has shown that across models decadal-scale ZEC is poorly correlated to other metrics of climate warming, such as TCR and ECS, though relationships 395 may exist within model frameworks (Figure 12).”

L399 Mentions that over multiple centuries that warming might further increase or decline. Useful to expand upon that statement and compare further with the prior studies examining the multi-centennial response.

We have added a paragraph after line 427 to discuss how our results compare to prior works. The paragraph reads:

"The results of the ZECMIP experiments are broadly consistent with previous work on ZEC, with a most likely value of ZEC close to zero and a range of possible model behaviours after emissions cease. In our analysis of ZEC we have shown that terrestrial uptake of carbon plays a more important role in determining that value of ZEC on decadal timescales than has been previously suggested. However our analysis is consistent with previous results from Ehlert and Zickfeld (2017) and Williams et al. (2017) in terms of ZEC arising from balance of physical and biogeochemical factors."

Addition modification to manuscript:

In addition to the changes suggested by the reviewers two further modifications have been made to the manuscript.

1) We have now computed TCRE values from the model output provided by each modelling group instead of self-reported values. This change was done due to our reported TCRE values differing from those reported in Arora et al. 2019. This changes Table 7, Figure 10.

2) UVic ESCM results have been updated to results from version 2.9pf to version 2.10 of the model. The results for the two model variants are very similar. All relevant figures, tables and text have been updated.

Is there warming in the pipeline? A multi-model analysis of the zero emission commitment from CO_2

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Abstract. The Zero Emissions Commitment (ZEC) is the change in global mean temperature expected to occur following the cessation of net CO_2 emissions, and as such is a critical parameter for calculating the remaining carbon budget. The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) was established to gain a better understanding of the potential magnitude and sign of ZEC, in addition to the processes that underlie this metric. Eighteen Earth system models of both full and intermediate complexity participated in ZECMIP. All models conducted an experiment where atmospheric CO_2 concentration increases exponentially until 1000 PgC has been emitted. Thereafter emissions are set to zero and models are configured to allow free evolution of atmospheric CO_2 concentration. Many models conducted additional second priority simulations with different cumulative emissions totals and an alternative idealized emissions pathway with a gradual transition to zero emissions. The inter-model range of ZEC 50 years after emissions cease for the 1000 PgC experiment is -0.36 to 0.29 °C with a model ensemble mean of -0.07°C, median of -0.05°C and standard deviation of 0.19 °C. Models exhibit a wide variety of behaviours after emissions cease, with some models continuing to warm for decades to millennia and others cooling substantially. ~~Analysis shows that both ocean carbon uptake and carbon uptake by the terrestrial biosphere are important for counteracting the warming effect from reduction in ocean heat uptake in the decades after emissions cease.~~ Analysis shows that both the carbon uptake by the ocean and the terrestrial biosphere are important for counteracting the warming effect from the reduction in ocean heat uptake in the decades after emissions cease. This warming effect is difficult to constrain due to high uncertainty in the efficacy of ocean heat uptake. Overall, the most likely value of ZEC on multi-decadal timescales is close to zero, consistent with previous model experiments and simple theory.

1 Introduction

The long-term temperature goal of the Paris Agreement is to hold global warming well below 2°C, and to endeavour to keep warming to no more than 1.5°C (United Nations, 2015). An important metric to assess the feasibility of this target is the ‘remaining carbon budget’ (e.g. Rogelj et al., 2018), which represents the total quantity of CO_2 that can still be emitted without causing a climate warming that exceeds the temperature limits of the Paris Agreement (e.g. Rogelj et al., 2019a). The remaining carbon budget can be estimated from five factors: 1) historical human induced warming to date; 2) the Transient Climate Response to cumulative CO_2 emissions (TCRE); 3) the estimated contribution of non-CO_2 climate forcings to future warming; 4) a correction for the feedback processes presently unrepresented by Earth System Models (ESMs); and 5) the unrealized warming from past CO_2 emissions, called Zero Emissions Commitment (ZEC) (e.g. Rogelj et al., 2019a). Of these five factors, ZEC is the only quantity whose uncertainty was not formally assessed in the recent Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5°C. Here we present the results of a multi-model analysis that uses the output of dedicated model experiments that were submitted to the Zero Emission Commitment Model Intercomparison Project (ZECMIP). This intercomparison project explicitly aims at quantifying the ZEC and identifying the processes that affect its magnitude and sign across models (Jones et al., 2019).

ZEC is the change in global temperature that is projected to occur following a complete cessation of net CO_2 emissions (Matthews and Weaver, 2010). After emissions of CO_2 cease, carbon is expected to be redistributed between the atmosphere, ocean, and land carbon pools, ~~such that the atmospheric CO_2 concentration continues to evolve over several millennia~~ such that the atmospheric CO_2 concentration continues to evolve over centuries to millennia (e.g. Maier-Reimer and Hasselmann, 1987; Cao et al., 2009; Siegenthaler and Joos, 1992; Sarmiento et al., 1992; Enting et al., 1994; Archer and Brovkin, 2008; Archer et al., 2009; Eby et al., 2009; Joos et al., 2013). In parallel, ocean heat uptake is expected to decline as the ocean comes into thermal equilibrium with the elevated radiative forcing (Matthews and Caldeira, 2008). In previous simulations of ZEC, the carbon cycle has acted to remove carbon from the atmosphere and counteract the warming effect from the reduction in ocean heat uptake, leading to values of ZEC that are close to zero (e.g. Plattner et al., 2008; Matthews and Caldeira, 2008; Solomon et al., 2009; Frölicher and Joos, 2010; Gillett et al., 2011). In the recent assessment of ZEC in the IPCC Special Report on Global Warming of 1.5 °C, the combined available evidence indicated that past CO_2 emissions do not commit to substantial further global warming (Allen et al., 2018). A ZEC of zero was therefore applied for the computation of the remaining carbon budget for the IPCC 1.5 °C Special Report (Rogelj et al., 2018). However, the evidence available at that time consisted of simulations from only a relatively small number of models using a variety of experimental designs. Furthermore, some recent simulations have shown a more complex evolution of temperature following cessation of emissions (e.g. Frölicher et al., 2014; Frölicher and Paynter, 2015). Thus a need to assess ZEC across a wider spectrum of climate models using a unified experimental protocol has been articulated (Jones et al., 2019).

ZEC was one of the metrics that emerged from the development of ESMs at the turn of the 21st century (Hare and Meinshausen, 2006). The concept was first conceptualized by Hare and Meinshausen (2006) who used the Model for the Assessment of Greenhouse gas Induced Climate Change (MAGICC), a climate model emulator, to explore temperature evolution following a complete cessation of all anthropogenic emissions. Matthews and Caldeira (2008) introduced the CO_2-only concept of ZEC which is used here. Their experiments used the intermediate complexity University of Victoria Earth System Climate Model (UVic ESCM) to show that stabilizing global temperature would require near zero CO_2 emissions. Plattner et al. (2008) used a wide range of different Earth System Models of Intermediate Complexity (EMICs) following a similar experiment and found that ZEC is close to (or less than) zero. These initial results with intermediate complexity models were subsequently supported by emission-driven ESM simulations (Lowe et al., 2009; Frölicher and Joos, 2010; Gillett et al., 2011). Zickfeld et al. (2013) quantified the ZEC under different scenarios and for a range of EMICs, but the resulting range is biased towards negative values as slightly negative instead of zero emissions were prescribed in some models. Some recent ESM simulations indicate that climate warming may continue after CO_2 emissions cease. For example, Frölicher and Paynter (2015) performed a simulation with the full ESM GFDL-ESM2M where emissions cease after 2°C of warming is reached. The simulations show some decades of cooling followed by a multi-centennial period of renewed warming resulting in an additional 0.5°C of warming 1000 years after emissions cease.

Two studies have examined in detail the underlying physical and biogeochemical factors that generate ZEC. Ehlert and Zickfeld (2017) examine ZEC with a set of idealized experiments conducted with the UVic ESCM. The study partitioned ZEC into a thermal equilibrium component represented by the ratio of global mean surface air temperature anomaly to unrealized warming, and a biogeochemical equilibrium component represented by the ratio of airborne fraction of carbon to equilibrium airborne fraction of carbon. The study found that the thermal equilibrium component of ZEC is much greater than the biogeochemical equilibrium component, implying a positive warming commitment. Williams et al. (2017) examine ZEC using the theoretical framework developed by Goodwin et al. (2007). The framework allows for the calculation of equilibrium atmospheric CO_2 concentration if the cumulative effect of the land carbon sink is known. The framework was applied to the same simulation conducted for Frölicher and Paynter (2015). The analysis showed that ZEC emerges from two competing contributions: 1) a decline in the fraction of heat taken up by the ocean interior leading to radiative forcing driving more surface warming; 2) uptake of carbon by the terrestrial biosphere and ocean system removing carbon from the atmosphere, causing a cooling effect. Both studies focused on the long-term value of ZEC after multiple centuries and thus neither study examined what drives ZEC in the policy relevant timeframe of a few decades following cessation of emissions.

While we focus here on the ZEC from CO_2 emissions only, the ZEC concept has also been applied to the climate commitment resulting from other greenhouse gas emissions and aerosols (Frölicher and Joos, 2010; Matthews and Zickfeld, 2012; Mauritsen and Pincus, 2017; Allen et al., 2018; Smith et al., 2019), wherein the ZEC is characterized by an initial warming due to the removal of aerosol forcing, followed by a more gradual cooling from the decline in non-CO_2 greenhouse gas forcing. ~~The ZEC from all emissions over multiple centuries is generally consistent with ZEC from CO_2 emissions only for moderate future scenarios~~ (Matthews and Zickfeld, 2012). The ZEC from all emissions over multiple centuries is generally consistent with ZEC from only CO_2 emissions, for moderate future scenarios (Matthews and Zickfeld, 2012).

In addition to the ZEC, other definitions of warming commitment have also been used in the literature. The 'constant composition commitment' is defined as the unrealized warming that results from constant atmospheric greenhouse gas and aerosol concentrations (Wigley, 2005; Meehl et al., 2005; Hare and Meinshausen, 2006). This variety of warming commitment was highlighted prominently in the 2007 IPCC report (Meehl et al., 2007), leading to a widespread misunderstanding that this additional 'warming in the pipeline' was the result of past greenhouse gas emissions. However, the constant composition commitment rather results primarily from the future CO_2 and other emissions that are required to maintain stable atmospheric concentrations over time (Matthews and Weaver, 2010; Matthews and Solomon, 2013). Another related concept is the future 'emissions commitment' which quantifies the committed future CO_2 (and other) emissions that will occur as a result of the continued operation of existing fossil fuel infrastructure (Davis et al., 2010; Davis and Socolow, 2014; Smith et al., 2019; Tong et al., 2019). This concept is also distinct from the ZEC, as it quantifies an aspect of socioeconomic inertia (rather than climate inertia), which has been argued to be an important driver of potentially unavoidable future climate warming (Matthews and Solomon, 2013; Matthews, 2014).

When considering climate targets in the range of 1.5 to 2.0°C and accounting for the approximately 1°C of historical warming to date (Allen et al., 2018; Rogelj et al., 2018), a ZEC on the order of ± 0.1°C can make a large difference in the remaining carbon budget. Hence there is a need for a precise quantification and in-depth understanding of this value. This can be achieved by a systematic assessment of ZEC across the range of available models and a dedicated analysis of the factors that control the value of ZEC in these simulations. Thus the goals of this study based on the simulations of the Zero Emissions Commitment Model Intercomparison Project (ZECMIP) are: 1) to estimate the value of ZEC in the decades following cessation of emissions in order to facilitate an estimate of the remaining carbon budget; 2) to test if ZEC is sensitive to the pathway of emissions; 3) to establish whether ZEC is dependent on the cumulative total CO_2 that are emitted before emissions cease; 4) to identify which physical and biogeochemical factors control the sign and magnitude of ZEC in models.

The most policy-relevant question related to ZEC is: will global temperature continue to increase following complete cessation of greenhouse gas and aerosol emissions? The present iteration of ZECMIP aims to answer part of this question by examining the temperature response in idealized CO_2-only climate model experiments. To answer the question in full, the behaviour of non-CO_2 greenhouse gases, aerosols, and land-use-change must be accounted for in a consistent way. Such efforts will be the focus of future iterations of ZECMIP.

2 Methods

2.1 Protocol and Simulations

Here we summarize the ZECMIP protocol, the full protocol for ZECMIP is described in Jones et al. (2019). The ZECMIP protocol requested modelling groups to conduct three idealized simulations of two different types each - A and B. Type A simulations are initialized from one of the standard climate model benchmark experiments in which specified atmospheric CO_2 concentration increases at a rate of 1% per year from its pre-industrial value of around 285 ppm until quadrupling, referred to as the 1pctCO2 simulation in the Climate Model Intercomparison Project (CMIP) framework (Eyring et al., 2016). The three type A simulations are initialized from the 1pctCO2 simulation when diagnosed cumulative emissions of CO_2 reach 750, 1000, and 2000 Pg C. After the desired cumulative emission is reached the models are set to freely evolving atmospheric CO_2 mode, with zero further CO_2 emissions. Since net anthropogenic emissions are specified to be zero in type A simulations, atmospheric CO_2 concentration is expected to decline in these simulations in response to carbon uptake by the ocean and land. A consequence of the protocol is that for the type A simulations each model branches from the 1pctCO2 simulations in a different year, contingent on when a model reaches the target cumulative emissions, which in turn depends on each model's representation of the carbon cycle and feedbacks. An example of emissions for the type A experiments is shown in Figure 1a. The three type B simulations are initialized from pre-industrial conditions and are emissions driven from the beginning of the simulation. Emissions follow bell-shaped pathways wherein all emissions occur within a 100 year window (Figure 1b). In all experiments land-use-change and non-CO_2 forcings are held at their pre-industrial levels.

Due to the late addition of ZECMIP to the CMIP Phase 6 (CMIP6) (Eyring et al., 2016), only the 1000 Pg C type A experiment (esm-1pct-brch-1000PgC) was designated as top priority ZECMIP simulation. The other simulations were designated as second priority simulations and were meant to be conducted if participating modelling groups had the resources and time. Both full ESMs and EMICs were invited to participate in ZECMIP. ESMs were requested to perform the top priority simulation for 100 years after CO_2 emissions cease, and more years and more experiments as resources allowed. EMICs were requested to conduct all experiments for at least 1000 years of simulations following cessation of emissions. Table 1 shows the experiments and experimental codes for ZECMIP.

2.2 Model Descriptions

Eighteen models participated in ZECMIP: nine comprehensive ESMs and nine EMICs. The primary features of each model are summarized in Table A1 and A2 for ESMs, and Table A3 and A4 for EMICs. The ESMs in alphabetical order are: 1) CSIRO Australian Community Climate and Earth System Simulator, ESM version 1.5 – ACCESS-ESM1.5, 2) Canadian Centre for Climate Modelling and Analysis (CCCma) – CanESM5, 3) Community Earth System Model 2 – CESM2, 4) Centre National

Table 1. Experiments designed for ZECMIP

Name	Code	Cumulative Emissions (PgC)	Priority
A1	esm-1pct-brch-1000PgC	1000	1
A2	esm-1pct-brch-750PgC	750	2
A3	esm-1pct-brch-2000PgC	2000	2
B1	esm-bell-1000PgC	1000	2
B2	esm-bell-750PgC	750	2
B3	esm-bell-2000PgC	2000	2

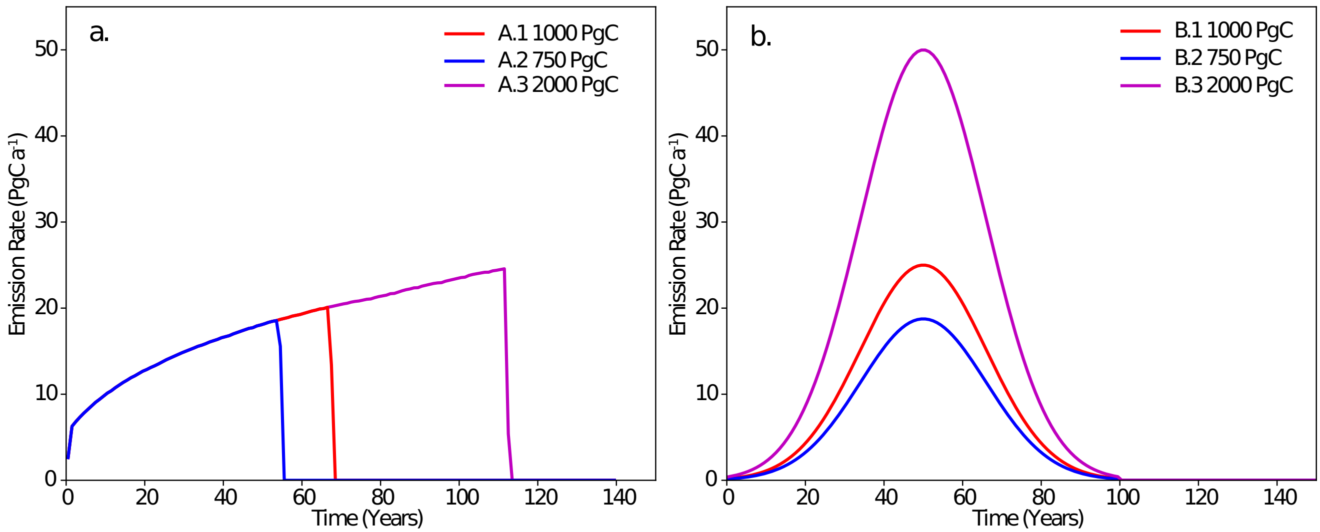

Figure 1. (a) Example of diagnosed emission from the UVic ESCM for the type A experiments. Emissions are diagnosed from the 1pctCO2 experiment which has prescribed atmospheric CO_2 concentrations. The target cumulative emissions total is reached part-way through the final year of emissions, thus that final year has a lower average emission rate than the previous year. (b) Time series of global CO_2 emissions for bell curve pathways B1 to B3. The numbers in the legend indicate the cumulative amount of CO_2 emissions for each simulation.

de Recherches Météorologiques (CNRM) – CNRM-ESM2-1, 5) Geophysical Fluid Dynamics Laboratory (GFDL) – GFDL-ESM2M, 6) Japan Agency for Marine-Earth Science and Technology (JAMSTEC/team MIROC) – MIROC-ES2L, 7) Max Planck Institute Earth System model, version 1.2, low resolution – MPI-ESM1.2-LR, 8) Norwegian Earth System Model 2 – NorESM2 and 9) UK (Met Office Hadley Centre and NERC) – UKESM1-0-LL. The nine EMICs in alphabetical order are: 1) Bern three dimensional Earth System Model – Bern3D-LPX, 2) Climate-Biosphere model, version 2 - CLIMBER-2, 3) Danish Centre for Earth System Science Earth System Model – DCESS1.0, 4) A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences – IAPRAS, 5) Loch-Vecode-ECbilt-Clio Model – LOVECLIM 1.2, 6) Massachusetts Institute of Technology Earth System Model – MESM, 7) Model for Interdisciplinary Research on Climate-lite/Japan Uncertainty Modelling Project-Loosely Coupled Model – MIROC-lite, 8) Planet Simulator - Grid-Enabled Integrated Earth system model

– PLASIM-GENIE, and 9) University of Victoria Earth System Climate Model – UVic ESCM 2.10. For brevity models are referred to by their short names in the remainder of the manuscript. Table 2 shows the ZECMIP experiments that each modelling group submitted.

Table 3 shows three benchmark climate metrics for each model, Equilibrium Climate Sensitivity (ECS), Transient Climate Response (TCR), and TCRE. ECS is the climate warming expected if atmospheric CO_2 concentration was doubled from the pre-industrial value and maintained indefinitely while the climate system is allowed to come into equilibrium with the elevated radiative forcing (e.g. Planton, 2013; Charney et al., 1979). There are a variety of methods to compute ECS from climate model outputs (e.g. Knutti et al., 2017). Here we use ECS values computed using the method of Gregory et al. (2004), called "effective climate sensitivity". The method of Gregory et al. (2004) computes ECS from the slope of the scatter plot between change in global temperature and planetary heat uptake, with values from the benchmark experiment where atmospheric CO_2 concentration is instantaneously quadrupled (4×CO2 experiment). ~~Usually the slope is computed from year 20 to year 140 of the 4×CO2 experiment~~ (Andrews et al., 2012). TCR is the atmospheric surface temperature change (relative to the preindustrial temperature) when atmospheric CO_2 is doubled in year 70 of the 1pctCO2 experiment, computed using a 20 year averaging window centred about year 70 of the experiment (e.g. Planton, 2013). TCRE is described in the introduction and is computed from year 70 of the 1% experiment (e.g. Planton, 2013).

Bern and UVic submitted three versions of their models with three different ECSs. For Bern ECSs of 2.0 °C, 3.0 °C, and 5.0 °C, and for UVic ECSs of 2.0 °C, 3.8 °C, and 5.0 °C. These ECS values are true equilibrium climate sensitivities computed by allowing each model to come fully into equilibrium with the changed radiative forcing. For each model the central ECS value was used for the main analysis, 3.0 °C for Bern and 3.8 °C for UVic. The remaining experiments were used to explore the relationship between ECS and ZEC.

Table 2. Experiments conducted for ZECMIP by model. Full ESMs are listed on top followed by EMICs.

Model	A1	A2	A3	B1	B2	B3
ACCESS	X	X	X	–	–	–
CanESM5	X	–	X	–	–	–
CESM2	X	–	–	–	–	–
CNRM	X	–	–	–	–	–
GFDL	X	X	X	X	X	X
MIROC-ES2L	X	X	X	–	–	–
MPI-ESM	X	–	–	–	–	–
NorESM2	X	–	–	–	–	X
UKESM	X	X	X	–	–	–
Bern	X	X	X	X	X	X
CLIMBER	X	–	–	–	–	–
DCESS	X	X	X	X	X	X
IAPRAS	X	X	X	X	X	X
LOVECLIM	X	X	–	X	–	–
MESM	X	X	X	X	X	X
MIROC-lite	X	X	X	X	X	X
P. GENIE	X	X	X	X	X	X
UVic	X	X	X	X	X	X

Table 3. Benchmark climate model characteristics for each model: Equilibrium Climate Sensitivity (ECS), Transient Climate Response (TCR), and Transient Climate Response to Cumulative CO_2 Emissions (TCRE). UKESM reported a maximum to minimum range for TCR and TCRE based on four ensemble members.

Model	ECS (°C)	TCR (°C)	TCRE (K EgC^{-1})
ACCESS	3.9	1.9	1.9
CanESM5	5.7	2.8	2.3
CESM2	5.1	2.0	2.0
CNRM	4.8	1.9	1.9
GFDL	2.4	1.4	1.2
MIROC-ES2L	2.7	1.5	1.3
MPI-ESM	2.8	1.8	1.6
NorESM2	2.6	1.5	1.5
UKESM	5.4	2.68 to 2.85	2.49 to 2.66
Bern	2.6	1.6	1.5
CLIMBER	2.8	1.8	1.7
DCESS	3.0	2.0	2.0
IAPRAS	2.2	1.5	1.5
LOVECLIM	2.8	1.5	1.4
MESM	2.9	1.8	1.7
MIROC-lite	1.7	1.2	1.1
P. GENIE	3.4	1.7	1.6
UVic	3.5	1.8	1.8

2.3 Quantifying ZEC

ZEC is the change in global average surface air temperature following the cessation of CO_2 emissions. Thus ZEC must be calculated relative to the global temperature when emissions cease. Typically such a value would be computed from a 20 year window centred on the year when emissions cease. However, for the ZECMIP type A experiments such a calculation underestimates the temperature of cessation, due to the abrupt change in forcing when emissions suddenly cease, leading to an overestimation of ZEC values. That is, a roughly linear increase in temperature pathway abruptly changes to a close to stable temperature pathway. Therefore we define the temperature of cessation to be the global mean surface air temperature from benchmark 1pctCO2 experiment averaged over a 20 year window centred on the year emissions cease in the respective ZECMIP type-A experiment (year the ZECMIP experiment branches from the 1% experiment). For the EMICs which lack internal variability this method provides an unbiased estimate of the temperature of cessation.

Earlier studies have examined ZEC from decadal (Matthews and Zickfeld, 2012; Mauritsen and Pincus, 2017; Williams et al., 2017; Allen et al., 2018; Smith et al., 2019) to multi-centennial timescales (Frölicher and Paynter, 2015; Ehlert and Zickfeld, 2017). One of the main motivations of this present study is to inform the impact of the ZEC on the remaining carbon budget. This remaining carbon budget is typically used to assess the consistency of societal emissions pathways with the international temperature target of the Paris Agreement (UNEP, 2018). In this emission pathway and policy context, the ZEC within a few decades of emissions cessation is more pertinent than the evolution of the Earth system hundreds or thousands of years into the future. Therefore, we define values of ZEC_X as a 20 year average temperature anomaly centred at year X after emissions cease. Thus, 50-year ZEC (ZEC_{50}) is the global mean temperature relative to the temperature of cessation averaged from year 40 to year 59 after emissions cease. We similarly define 25-year ZEC (ZEC_{25}) and 90-year ZEC (ZEC_{90}).

2.4 Analysis Framework

A key question of the present study is why some models have positive ZEC and some models have negative or close to zero ZEC. From elementary theory we understand that the sign of ZEC will depend on the pathway of atmospheric CO_2 concentration and ocean heat uptake following cessation of emissions (Wigley and Schlesinger, 1985). Complicating this dynamic is that atmospheric CO_2 change has contributions both from the net carbon flux from the ocean and the terrestrial biosphere. Using the forcing-response equation (Wigley and Schlesinger, 1985) and the common logarithmic approximation for the radiative forcing from CO_2 (Myhre et al., 1998), we can partition ZEC into contributions from ocean heat uptake, ocean carbon uptake, and net carbon flux into the terrestrial biosphere. The full derivation of the relationship is shown in Appendix B and the summary equations are shown below:

$$\lambda T_{ZEC} = -R \int\limits_{t=ze}^{\infty} \frac{f_O}{C_A} dt - R \int\limits_{t=ze}^{\infty} \frac{f_L}{C_A} dt - \epsilon(N - N_{ze}), \qquad (1)$$

where λ (W $m^{-2}K^{-1}$) is the climate feedback parameter, T_{ZEC} (K) is ZEC, R (W m^{-2}) is the radiative forcing from an e-fold increase in atmospheric CO_2 burden, t is time (a), ze is the time that emissions cease, f_O (PgC a^{-1}) is ocean carbon uptake,

f_L (PgC a^{-1}) is carbon uptake by land, C_A is atmospheric CO_2 content (PgC), N is planetary heat uptake (W m^{-2}), N_{ze} is planetary heat uptake at the time emissions cease, and ϵ is the efficacy of planetary heat uptake. The equation states that ZEC is proportional to the sum of three energy balance terms: 1) the change in radiative forcing from carbon taken up by the ocean; 2) the change in radiative forcing from carbon taken up or given off by land; and ~~3) the change in ocean heat uptake~~ 3) the change in effective ocean heat uptake. The two integral terms can be evaluated numerically from the ZECMIP model output, and thus can be simplified into two energy forcing terms F_{ocean} and F_{land}:

$$F_{ocean} = R \int_{t=ze}^{\infty} \frac{f_O}{C_A} dt, \tag{2}$$

and,

$$F_{land} = R \int_{t=ze}^{\infty} \frac{f_L}{C_A} dt, \tag{3}$$

and thus:

$$\lambda T_{ZEC} = -F_{ocean} - F_{land} - \epsilon(N - N_{ze}). \tag{4}$$

Values for R were computed from the effective radiative forcing value for the models that simulate internal variability, with effective radiative forcing provided by each modelling group. Bern, DCESS, and UVic prescribe exact values for R and thus these values were used for calculations with these models. Effective radiative forcing for a doubling of CO_2 is $\frac{1}{2}$ the y-intercept of a 4×CO2 Gregory plot (Gregory et al., 2004). R values and the effective climate sensitivities were used to calculate λ for each model. Efficacy (Winton et al., 2010) was calculated from:

$$\epsilon = \frac{\lambda T - R \ln\left(\frac{C_A}{C_{Ao}}\right)}{N}, \tag{5}$$

where C_{Ao} (PgC) is the pre-industrial CO_2 burden, and T (K) is the global mean temperature anomaly relative to pre-industrial temperature. T, N, and C_A values were taken from the benchmark 1pctCO2 for each model, as an average value from year 10 to year 140 of that experiment. Computed ϵ values are shown in Table 4. Effective climate sensitivity is here calculated as a time average fit and hence is assumed to be a constant, while efficacy values are expected to change in time. In CLIMBER planetary or ocean heat uptake is not included into standard output and hence is not analyzed using this framework. CESM2 and NorESM2 are also excluded as the 4×CO2 experiment results for these models are not yet available.

Efficacy has been shown to arise from spatial patterns in ocean heat uptake (Winton et al., 2010, 2013; Rose et al., 2014), with ocean heat uptake in the high latitudes being more effective at cooling the atmosphere than ocean heat uptake in low latitudes (Rose et al., 2014). This spatial structure in the effectiveness of ocean heat uptake in turn is suspected to originate from shortwave radiation cloud feedbacks (Andrews et al., 2015). The method we have used to calculated efficacy folds state-dependent feedbacks and temporal change in the climate feedback parameter (Rugenstein et al., 2016) into the efficacy parameter.

Notably, calculated effective climate sensitivities and effective radiative forcings vary slightly within models due to the internal variability (Gregory et al., 2015), hence the efficacy values calculated here are associated with some uncertainty. Efficacy values are known to evolve in time (Winton et al., 2010), thus the efficacy value from the 1pctCO2 experiment may be different than efficacy 50 years after emission cease in the ZECMIP experiments. To test this effect yearly efficacy values were calculated for the four EMICs without internal variability (Bern, DCESS, MESM and UVic). These tests showed that efficacy was 3.5% to 25% away from the values for the 1pctCO2 experiment 50 years after emission cease (Figure A1). Thus we have assigned efficacy a $\pm$ 30% uncertainty. Notably efficacy declines in three of the four models, consistent with previous work showing strong trends in efficacy over time (Williams et al., 2017). Radiative forcing from CO_2 is not precisely logarithmic (Gregory et al., 2015; Byrne and Goldblatt, 2014; Etminan et al., 2016) and therefore the calculated F_{ocean} and F_{land} values will be slightly different than the changes in radiative forcing experienced within each model, except for the three models that prescribe CO_2 radiative forcing. ~~As~~ Etminan et al. (2016) ~~used new line-by-line absorption data to compute radiative forcing, existing ESMs which internally compute CO_2 likely lie between the~~ Myhre et al. (1998) and Etminan et al. (2016) ~~parameterizations~~ (Etminan et al., 2016). Also accounting for the uncertainty in recovering R values from model output, we assign a $\pm$10% uncertainty to radiative forcing values.

Table 4. Efficacy ϵ and radiative forcing for $2{\times}CO_2$ R values for each model. Efficacy values are calculated from the 1pctCO2 experiment.

Model	Efficacy	Radiative forcing $2{\times}CO_2$ ($W\,m^{-2}$)
ACCESS	1.2	2.9
CanESM5	1.0	3.4
CNRM	0.9	3.2
GFDL	1.3	3.6
MIROC-ES2L	1.0	4.1
MPI-ESM	1.1	4.1
UKESM	1.0	4.0
Bern	1.0	3.7
DCESS	1.1	3.7
IAPRAS	1.1	3.7
LOVECLIM	1.0	3.7
MESM	0.8	4.1
MIROC-lite	1.0	3.0
P. GENIE	0.9	4.2
UVic	1.0	4.1

3 Results

3.1 A1 Experiment results

Figure 2 shows the evolution of atmospheric CO_2 concentration and temperature for the 100 years after emissions cease for the A1 experiment (1% branched at 1000 PgC). In all simulations atmospheric CO_2 concentration declines after emissions cease, with a rapid decline in the first few decades followed by a slower decline thereafter. The rates of decline vary across the models. By 50 years after emissions cease in the A1 experiment the change in atmospheric CO_2 concentration ranged from -91 to -52 ppm, with a mean of -76 ppm and median of -80 ppm. Temperature evolution in the 100 years following cessation of emissions varies strongly by model, with some models showing declining temperature, others having ZEC close to zero, and others showing continued warming following cessation of emissions. Some models such as UKESM, CNRM, and UVic exhibit continued warming in the ~~century~~ centuries following cessation of emissions. Other models such as IAPRAS and DCESS exhibit a temperature peak, then decline. Still other models show ZECs that hold close to zero (e.g. MPI-ESM), while some models show continuous decline in temperature following cessation of emissions (e.g. P. GENIE). Table 5 shows the ZEC_{25}, ZEC_{50}, and ZEC_{90} values for the A1 experiment. The table shows values of ZEC_{50} ranging from -0.36 to 0.29 °C with a model ensemble mean of -0.06°C, median of -0.05°C and a standard deviation of 0.19°C. Tables C1 and C2 show ZEC_{25}, ZEC_{50}, and ZEC_{90} for the A2 and A3 experiment. Figure 3 shows the evolution of atmospheric CO_2 concentration, temperature anomalies (relative to the year emissions cease), and ocean heat uptake for 1000 years following cessation of emissions in the A1 experiment. All models show continued decline in atmospheric CO_2 concentration for centuries after emissions cease. ~~One model (P. GENIE) shows a renewed growth in atmospheric CO_2 concentration beginning about 600 years after emissions cease. The renewed growth in atmospheric CO_2 in P. GENIE results from release of carbon from soils overwhelming the residual ocean carbon sink.~~ One model (P. GENIE) shows a renewed growth in atmospheric CO_2 concentration beginning about 600 years after emissions cease, resulting from release of carbon from soils overwhelming the residual ocean carbon sink. ~~Of the eight models that extended simulations beyond 150 years, five show temperature peaking then declining (Bern, MESM, DCESS, LOVECLIM and MIROC-ES2L), GFDL shows temperature declining and then increasing but ultimately remaining close to the temperature at cessation, and the UVic model shows continuous, if slow, warming.~~ Of the nine models that extended simulations beyond 150 years, seven show temperature on a long-term decline (Bern, MESM, DCESS, IAPRAS, LOVECLIM, P. GENIE, and MIROC-ES2L), GFDL shows temperature declining and then increasing within 200 years after cessation but ultimately remaining close to the temperature at cessation, and the UVic model shows slow, warming. Most models show continuous decline in ocean heat uptake with values approaching zero. Three models (GFDL, LOVECLIM and IAPRAS) show the ocean transition from a heat sink to a heat source.

Table 5. Temperature anomaly relative to the year emissions cease averaged over a 20 year time window centred about the 25th, 50th, and 90th year following cessation of anthropogenic CO_2 emissions (ZEC_{25}, ZEC_{50}, and ZEC_{90} respectively) for the A1 (1% to 1000 PgC experiment).

Model	ZEC_{25} (°C)	ZEC_{50} (°C)	ZEC_{90} (°C)
ACCESS	0.04	0.01	-0.03
CanESM5	-0.04	-0.13	-0.17
CESM2	-0.11	-0.31	-0.34
CNRM	0.11	0.06	0.25
GFDL	-0.18	-0.27	-0.19
MIROC-ES2L	-0.02	-0.08	-0.21
MPI-ESM	-0.22	-0.27	-0.37
NorESM	-0.27	-0.33	-0.32
UKESM	0.21	0.28	0.33
Bern	0.05	0.01	-0.08
DCESS	0.11	0.06	-0.04
CLIMBER	0.0	-0.07	-0.14
IAPRAS	0.34	0.29	0.03
LOVECLIM	-0.02	-0.04	-0.03
MESM	0.05	0.01	-0.06
MIROC-lite	-0.02	-0.06	-0.09
P. GENIE	-0.19	-0.36	-0.71
UVic	0.04	0.03	0.02
Mean	-0.01	-0.07	-0.12
Median	-0.01	-0.05	-0.08
Standard Deviation	0.15	0.19	0.23

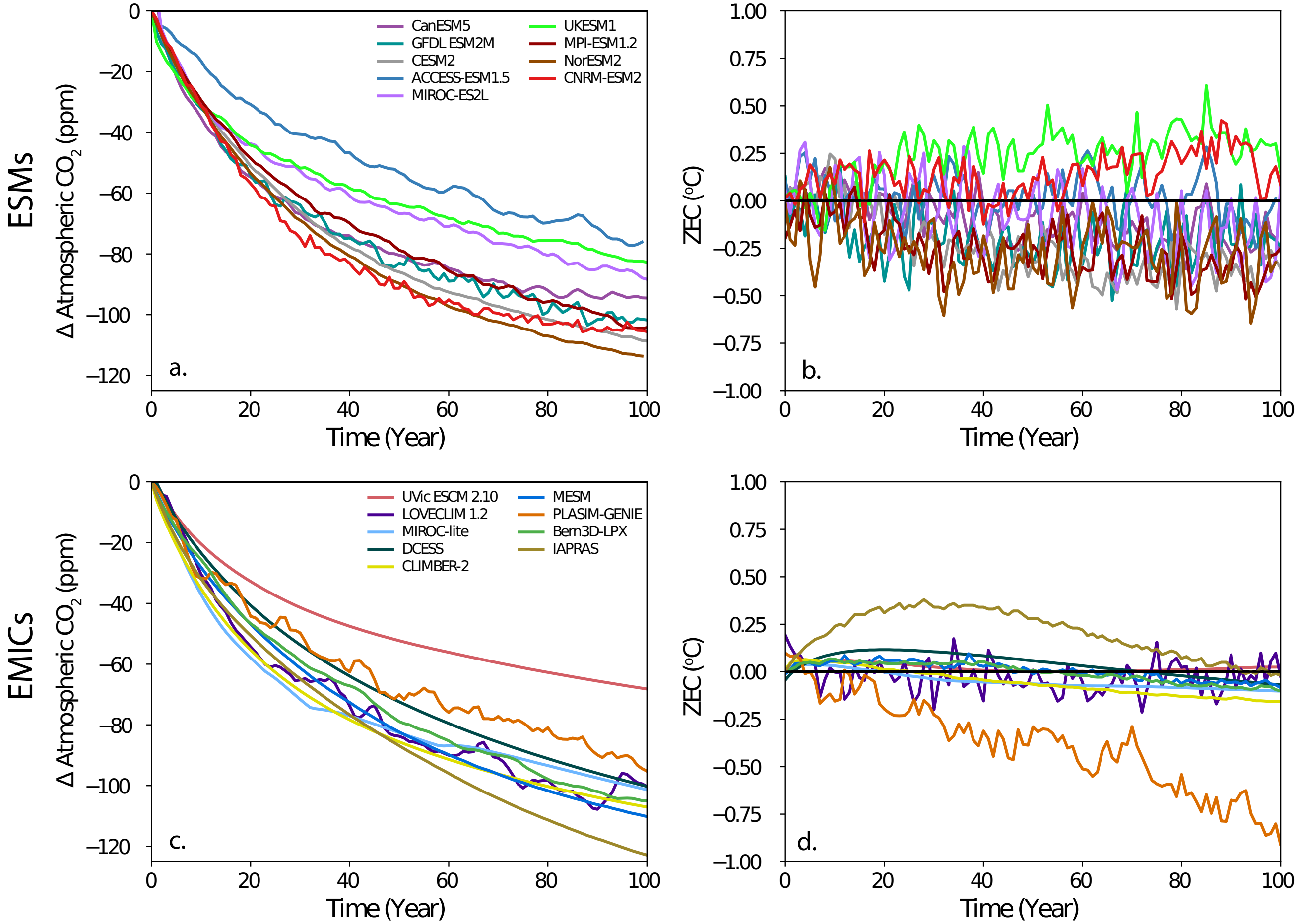

Figure 2. (a,c) Atmospheric CO_2 concentration anomaly and (b,d) Zero Emissions Commitment following cessation of emissions under the experiment where 1000 PgC was emitted following the 1% experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation. Top row shows output for ESMs and bottom row for EMICs.

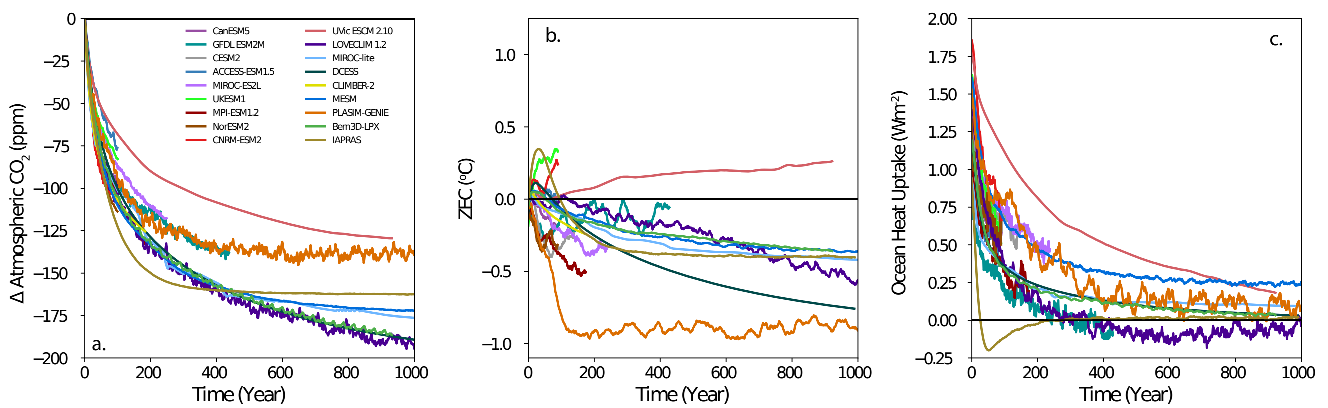

Figure 3. (a) Change in atmospheric CO_2 concentration, (b) change in temperature, and (c) ocean heat uptake following cessation of emissions for the A1 experiment (1000 PgC following 1%) for 1000 years following cessation of emissions.

3.2 Effect of emissions rate, 1% vs. Bell

The bell experiments were designed to test whether temperature evolution following cessation of emissions depends on the pathway of emissions before emissions cease. These experiments also illustrate model behaviour during a gradual transition to zero emissions (e.g. MacDougall, 2019), a pathway that is consistent with most future scenarios (Eyring et al., 2016). Nine of the participating models conducted both the A1 and B1 experiments, GFDL and eight of the EMICs (CLIMBER is the EMIC which did not conduct the B1 experiment). Figure 4 shows the temperature evolution (relative to pre-industrial temperature) for both experiments. All models show that by the 100th year of the experiments, when emissions cease in the bell experiment, the temperature evolution is very close in the two experiments. For seven of the models, GFDL, Bern, DCESS, LOVECLIM, MESM, MIROC-lite, and UVic, the temperature evolution in the A1 and B1 experiments is indistinguishable after emissions cease in the Bell experiment. That is, models suggest that in the long term the past pathway of CO_2 is largely irrelevant to total temperature change, and determined only by the total amount of cumulative emissions.

Figure 5 shows ZEC for both experiments. There is no sharp discontinuity in forcing in the Bell experiments and thus the temperature of cessation for these experiments is simply calculated relative to a temperature average from a 20 year window centred about the year 100 when emissions cease. Despite the long-term temperature evolution being the same for both experiments, the change in temperature relative to time of cessation is different in most models. This feature is not unexpected as theoretical work on the TCRE relationship suggest that direct proportionality between cumulative emissions of CO_2 and temperature change should break down when emission rates are very low (MacDougall, 2017), as emissions are near the end of the Bell experiments. That is, in the type-B experiments emissions decline gradually and hence the Earth system is closer to thermal and carbon cycle equilibrium when emissions cease. These results support using the type-A experiment (1% followed by sudden transition to zero emissions) to calculate ZEC for providing a correction to the remaining carbon budget, as the experiment provides a clear separation between TCRE and ZEC, while for a gradual transition to zero emissions scenario the two effects are mixed as emissions approach zero.

The B2 experiment (750 PgC) was designed to assess ZEC for an emissions total that would imply a climate warming of close to 1.5°C (Jones et al., 2019). The mean change in emission rate for the B2 experiment during the ramp-down phase of the experiment (year 50 to 100) is -0.39 PgC a^{-2}. This rate is similar to the rate of -0.29 [-0.05 to -0.64] PgC a^{-2} for stringent mitigation scenarios from the IPCC Special Report on 1.5° for the period from year 2020 to 2050 CE (Rogelj et al., 2018). Therefore we would expect similar behaviour in the stringent mitigation scenarios and the type-B experiments. That is, for the effect of ZEC to manifest while emissions are ramping down. The A2 experiment (1% 750 PgC) branches from the 1pctCO2 experiment between year 51 and 60 in the models that performed that experiment. Emission in the A2 experiment cease in year 100. Thus the temperature correction expected by time emission cease for the stringent mitigation scenarios would be in the range of ZEC_{40} to ZEC_{50} for the B2 experiment.

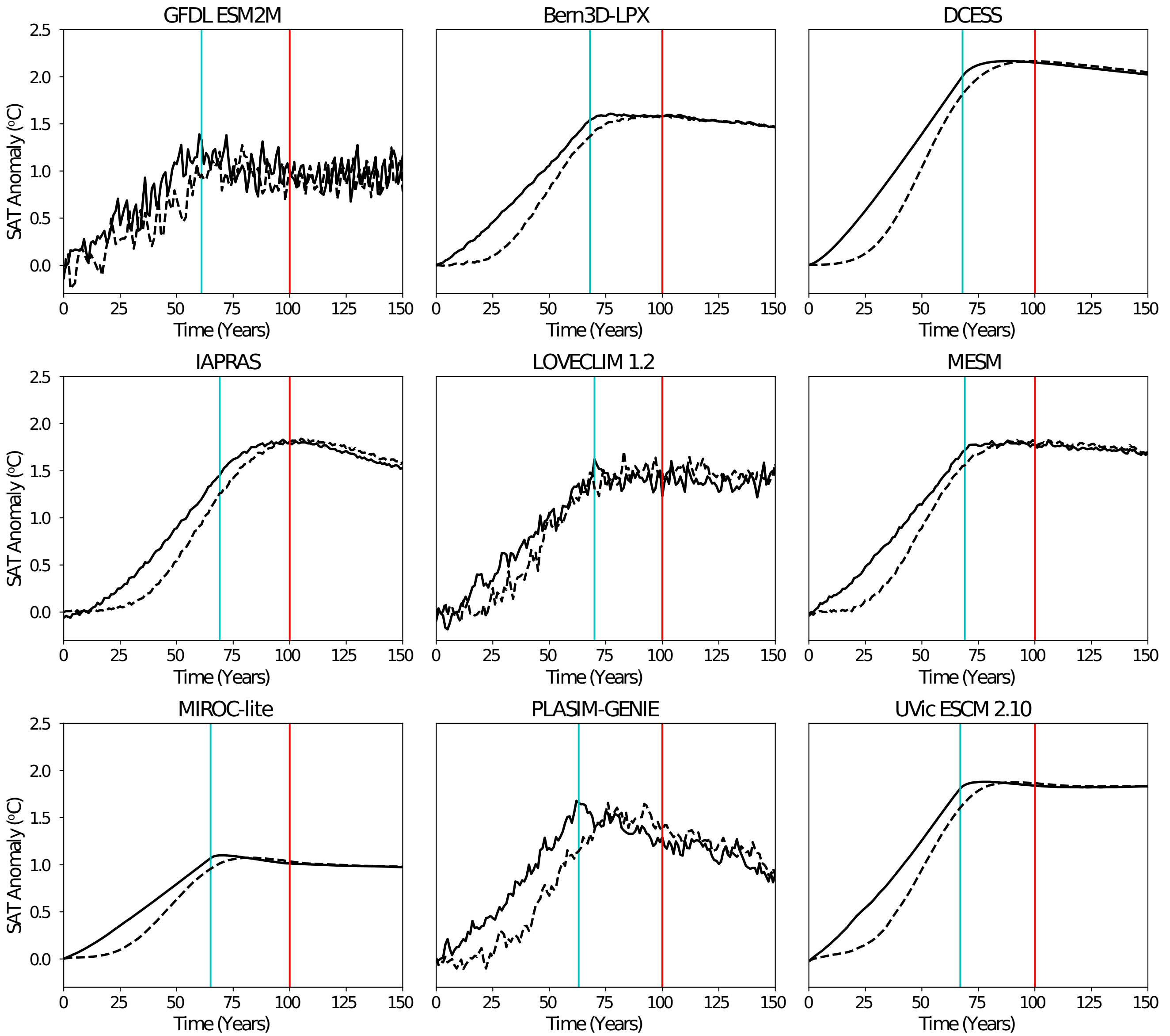

Figure 4. Temperature evolution of A1 (1% to 1000 PgC) and B1 (Bell shaped emissions of 1000 PgC over 100 years) experiments relative to pre-industrial temperature. Solid lines are the A1 experiment and dashed lines are the B1 experiment. Vertical blue line shows when emissions cease in the A1 experiment and vertical red line shows where emissions cease in the B1 experiment.

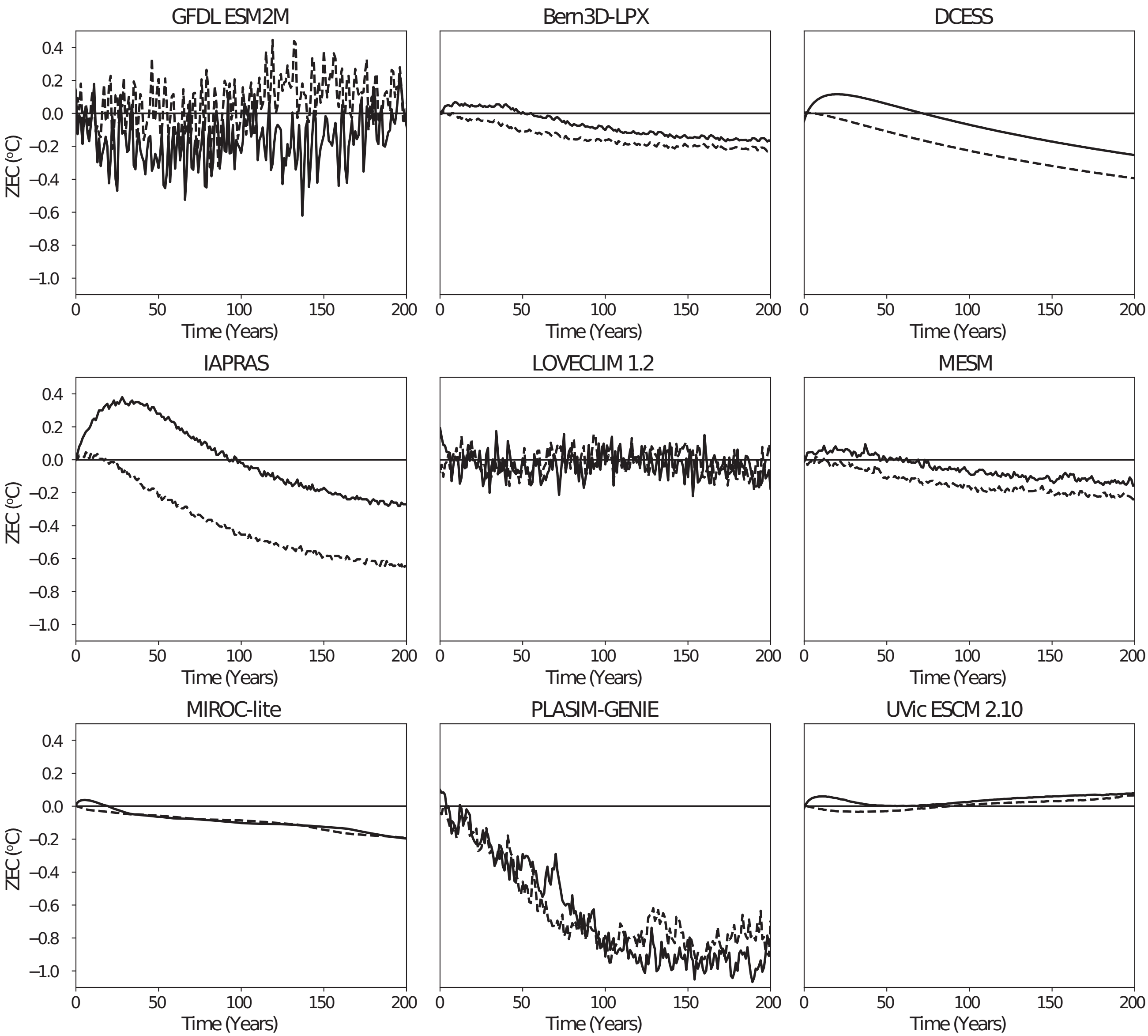

Figure 5. ZEC for the A1 (1% to 1000 PgC) and B1 (Bell shaped emissions of 1000 PgC over 100 years) experiments. Solid lines are the A1 experiment and dashed lines are the B1 experiment.

3.3 Sensitivity of ZEC to Cumulative Emissions

Twelve models conducted at least two type-A (1%) experiments such that ZEC could be calculated for 750 PgC, 1000 PgC, and 2000 PgC of cumulative emissions, five ESMs (ACCESS, CanESM5, GFDL, MIROC-ES2L, and UKESM), and all of the EMICs except CLIMBER. Two of the models conducted only two of the type-A experiments, CanESM5 conducted the A1 and A3 experiments, while LOVECLIM conducted the A1 and A2 experiments. Figure 6 shows the ZEC_{50} for each model for the three experiments. All of the full ESMs exhibit higher ZEC_{50} with higher cumulative emissions. The EMICs have a more mixed response with Bern, MESM, LOVECLIM and UVic showing increased ZEC_{50} with higher cumulative emissions, DCESS and IAPRAS showing slightly declining ZEC_{50} with higher cumulative emissions, and P. GENIE showing a strongly declining ZEC_{50} with higher emissions. The inter-model range for the ZEC_{50} of the A2 (750 PgC) experiment is -0.31 to 0.30 °C with a mean value of -0.03°C, a median of -0.06°C and standard deviation of 0.15°C . The inter-model range A3 (2000 PgC) experiment -0.40 to 0.52°C with a mean of 0.10°C, a median of 0.10°C and standard deviation of 0.26°C. Note that different subsets of models conducted each experiment, such that ranges between experiments are not fully comparable.

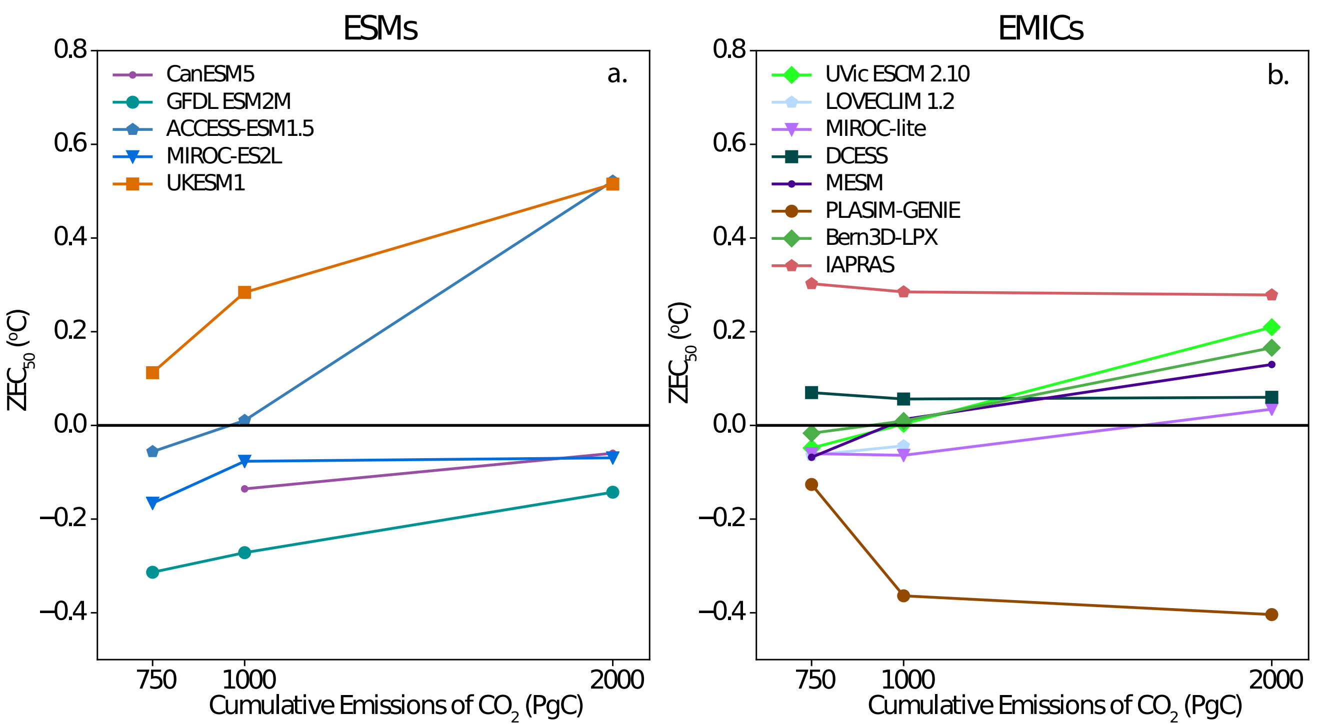

Figure 6. Values of ZEC_{50} for the 750, 1000 and 2000 PgC experiments branching from the 1% experiment (type-A). Panel (a) shows results for full ESMs and panel (b) for EMICs

3.4 Analysis of Results

~~The framework introduced in section 2.4 was applied to the ZECMIP output to partition the energy balance components of ZEC into contributions from the warming effect of the reduction in ocean heat uptake ($-\Delta N$), and the effect of the change in radiative forcing from the ocean and terrestrial carbon fluxes. Figure 7 shows the results of this analysis for each model averaged over the period 40 to 59 years after emissions cease for the 1000 PgC 1% (A1) experiment (the same time interval as ZEC$_{50}$).~~ The framework introduced in Section 2.4 was applied to the ZECMIP output to partition the energy balance components of ZEC into contributions from the warming effect of the reduction in ocean heat uptake ($-\Delta N$), and the effect of the change in radiative forcing from the ocean (F_{ocean}) and terrestrial carbon fluxes (F_{land}). Figure 7 shows the results of this analysis for each model averaged over the period 40 to 59 years after emissions cease for the 1000 PgC 1% (A1) experiment (the same time interval as ZEC$_{50}$). The components of the bars in Figure 7a are the terms of the right hand side of Equation 4. The results suggest that both ocean carbon uptake and terrestrial carbon uptake are critical for determining the sign of ZEC in the decades following cessation of emissions. Previous efforts to examine ZEC, while acknowledging the terrestrial carbon sink, have emphasized the role of ocean heat and carbon uptake (Ehlert and Zickfeld, 2017; Williams et al., 2017). These studies also focused on ZEC on timescales of centuries, not decades. In CanESM5 and CNRM the terrestrial carbon sink dominates the reduction in radiative forcing, while in ACCESS, IAPRAS, MESM, P. GENIE, and UVic the ocean carbon uptake dominates the reduction in radiative forcing. ~~The remaining models have substantial contributions from both carbon sinks. In all models the reduction in forcing from ocean carbon uptake is smaller than the reduction in ocean heat uptake, suggesting that the post-cessation net land carbon sink is critical to determining ZEC values. Given that the behaviour of the terrestrial carbon cycle varies strongly between models~~ (Friedlingstein et al., 2006; Arora et al., 2013, 2019) ~~and that many models lack feedbacks such as nutrient limitation and permafrost carbon pools, the strong dependence of ZEC$_{50}$ on terrestrial uptake is concerning. Notably the three ESMs with the weakest modelled terrestrial carbon sink response (ACCESS, MIROC-ES2L, and UKESM) are three which include terrestrial nutrient limitations (Table A1, A2). The UVic model includes permafrost carbon and has a relatively weak terrestrial carbon uptake (Table A4). However, Bern and MPI-ESM also have nutrient limitations and have a terrestrial carbon uptake in the middle (Bern) and upper (MPI-ESM) parts of the inter-model range. IAPRAS does not account for either nutrient limitations or permafrost carbon and has the weakest terrestrial carbon uptake of all (Table A3). Ocean carbon uptake also varies substantially between models, with some of the EMICs (P. GENIE, MESM, and IAPRAS) having very high ocean carbon uptake, and two of the ESMs (CanESM5 and CNRM) and having very low ocean carbon uptake.~~ The remaining models have substantial contributions from both carbon sinks. In all models the reduction in forcing from ocean carbon uptake is smaller than the reduction in ocean heat uptake, suggesting that the post-cessation net land carbon sink is critical to determining ZEC values. The ocean carbon uptake itself varies substantially between models, with some of the EMICs (P. GENIE, MESM, and IAPRAS) having very high ocean carbon uptake, and two of the ESMs (CanESM5 and CNRM) having very low ocean carbon uptake. Given that the behaviour of the terrestrial carbon cycle varies strongly between models (Friedlingstein et al., 2006; Arora et al., 2013, 2019) and that many models lack feedbacks related to nutrient limitation and permafrost carbon pools, the strong dependence of ZEC$_{50}$ on terrestrial carbon uptake is concerning for the robustness of ZEC_{50} estimates. Notably, the three ESMs, with the weakest terrestrial carbon sink response (ACCESS, MIROC-ES2L, and UKESM), include terrestrial nutrient limitations (Table A1, A2). However, despite including terrestrial nutrient limitation Bern and MPI-ESM simulate a terrestrial carbon uptake in the middle and upper parts of the inter-model range, respectively. The UVic model includes permafrost carbon and has a relatively weak terrestrial carbon uptake (Table A4). IAPRAS does not account for either nutrient limitations or permafrost carbon and has the weakest terrestrial carbon uptake among all models studied here (Table A3).

To further investigate the effect of nutrient limitation on ZEC we have compared models with and without terrestrial nutrient limitations. Eight of the models that participated in ZECMIP included a representation of the terrestrial nitrogen cycle, ACCESS, CESM2, MIROC-ES2L, MPI-ESM, NorESM, UKESM, Bern and MESM. One model (ACCESS) includes a representation of the terrestrial phosphorous cycle. Figure 8 shows behaviour of the terrestrial carbon cycle before and after emissions cease for models with and without terrestrial nutrient limitations. Figure 8a shows that consistent with Arora et al. (2019) models with a terrestrial nitrogen cycle have on average a lower carbon uptake than those without. However, after emissions cease there is little difference in the terrestrial uptake of carbon between models with and without nutrient limitations. For both sets of model the median uptake is almost the same at 68 PgC and 63 PgC respectively, and the range for models without nutrient limitation fully envelops the range for those with nutrient limitations. Thus, while nutrient limitations do not appear to have a controlling influence on the *magnitude* of the post cessation terrestrial carbon uptake they have a marked impact on its uncertainty. As with carbon cycle feedbacks (Arora et al., 2019) those models including terrestrial nitrogen limitation exhibit substantially smaller spread than those which do not. This offers hope for future reductions in ZEC uncertainty as more models begin to include nitrogen - and thereafter phosphorus - limitations on the land carbon sink.

Figure 9a shows the relationship between ocean heat uptake (Figure 9b), cumulative ocean carbon uptake (Figure 9c), and the cumulative terrestrial carbon uptake when emissions cease and 50 years after emissions cease. Excluding the clear outlier of IAPRAS Figure 9 shows a clear negative relationship (R=-0.80) between ocean heat uptake before emissions cease and the change in ocean heat uptake 50 years after emissions cease in the A1 experiment. That is, models with high ocean uptake before emissions cease tend to have a strong reduction in ocean heat uptake after emissions cease. Similarly there is a strong (R=0.88) positive relationship between ocean carbon uptake before emissions cease and uptake in the 50 years after emissions cease. The relationship between uptake (or in one case net release) of carbon by the terrestrial biosphere before and after emissions cease is weaker (R=0.72) but clear. Therefore explaining why the energy balance components illustrated by Figure 7 vary between models would seem to relate strongly to why models have varying ocean heat, ocean carbon uptake, and terrestrial carbon cycle behaviour before emissions cease.

~~It has long been suggested that the reason that long-term ZEC was close to zero is compensation between ocean heat and ocean carbon uptake~~ (Matthews and Caldeira, 2008; Solomon et al., 2009; Frölicher and Paynter, 2015), ~~which are both partially controlled by deep ocean circulation~~ (Banks and Gregory, 2006; Xie and Vallis, 2012; Frölicher et al., 2015). It has long been suggested that the reason that long-term ZEC was close to zero is compensation between ocean heat and ocean carbon uptake (Matthews and Caldeira, 2008; Solomon et al., 2009; Frölicher and Paynter, 2015), which are both dominated by the ventilation of the thermocline (Sabine et al., 2004; Banks and Gregory, 2006; Xie and Vallis, 2012; Frölicher et al., 2015;

Goodwin et al., 2015; Zanna et al., 2019). However, Figure 7 shows that this generalization is not true for decadal time-scales. The two quantities do compensate one-another but in general the effect from reduction in ocean heat uptake is larger than the change in radiative forcing from the continued ocean carbon uptake. Thus going forward additional emphasis should be placed on examining the role of the terrestrial carbon sink in ZEC for policy relevant timescales. Also notable is the large uncertainty in effective ocean heat uptake, which originates from the uncertainty in efficacy. As efficacy is related to spatial patterns in ocean heat uptake and coupled shortwave cloud feedbacks (Rose et al., 2014; Andrews et al., 2015), shifts in these patterns in time thus likely affect the values of ZEC and hence represents an important avenue for further investigation.

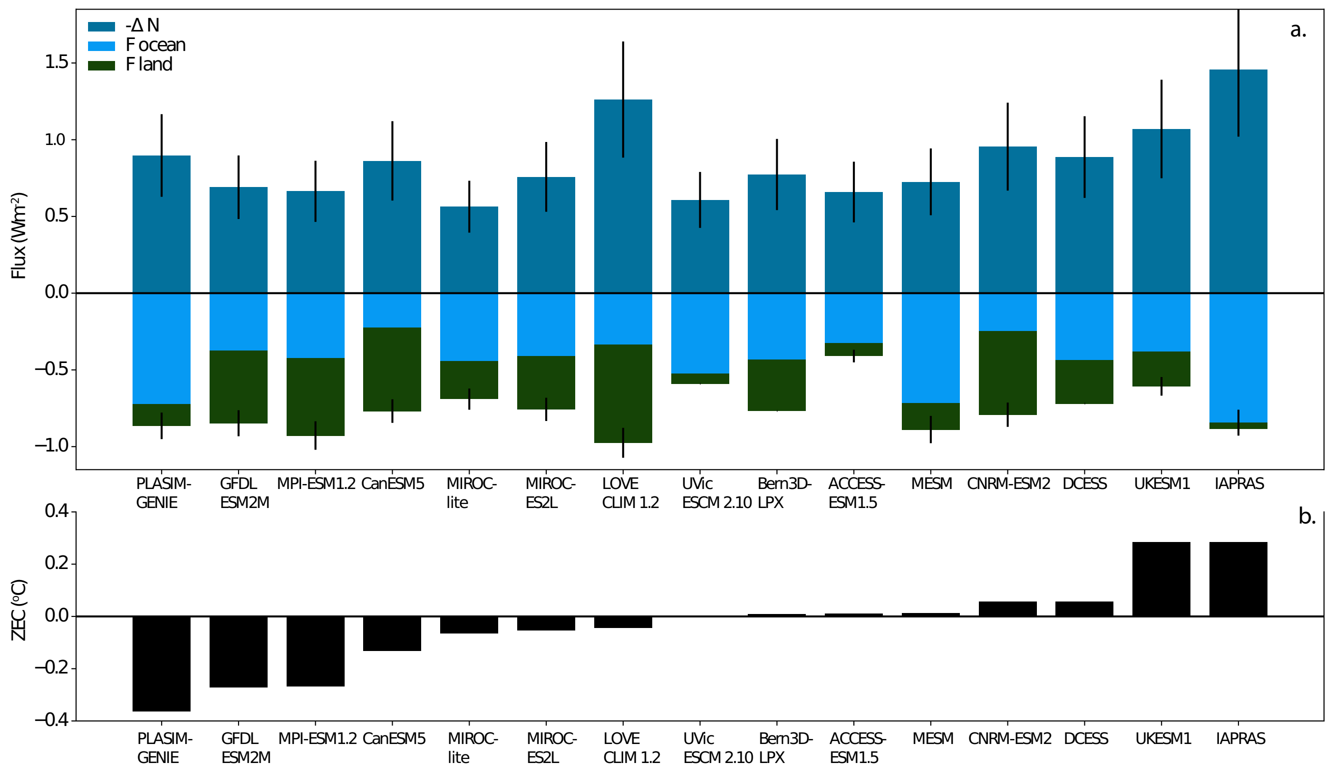

Figure 7. (a) Energy fluxes following cessation of CO_2 emissions for the 1000 PgC 1% (A1) experiment. ΔN is the change in ocean heat uptake relative to the time emissions ceased. A reduction in ocean heat uptake will cause climate warming, hence $-\Delta N$ is displayed. F_{ocean} is the change in radiative forcing caused by ocean carbon uptake, and F_{land} is the change in radiative forcing caused by terrestrial carbon uptake. Vertical black lines are estimated uncertainty ranges. (b) ZEC_{50} values for each model. Models are arranged in ascending order of ZEC_{50}

Figure 10 compares the energy fluxes for the ten models that conducted all of the type-A (1%) experiments. All three energy balance components seem to be affected by the cumulative emissions leading up to cessation of emissions, however there is no universal pattern. Most models show a larger reduction in ocean heat uptake with higher cumulative emissions, but UKESM has the largest reduction for the 1000 PgC experiment. Variations in the reduction in radiative forcing from ocean carbon uptake tend to be small between simulations within each model but show no consistent patterns between models. Most of the

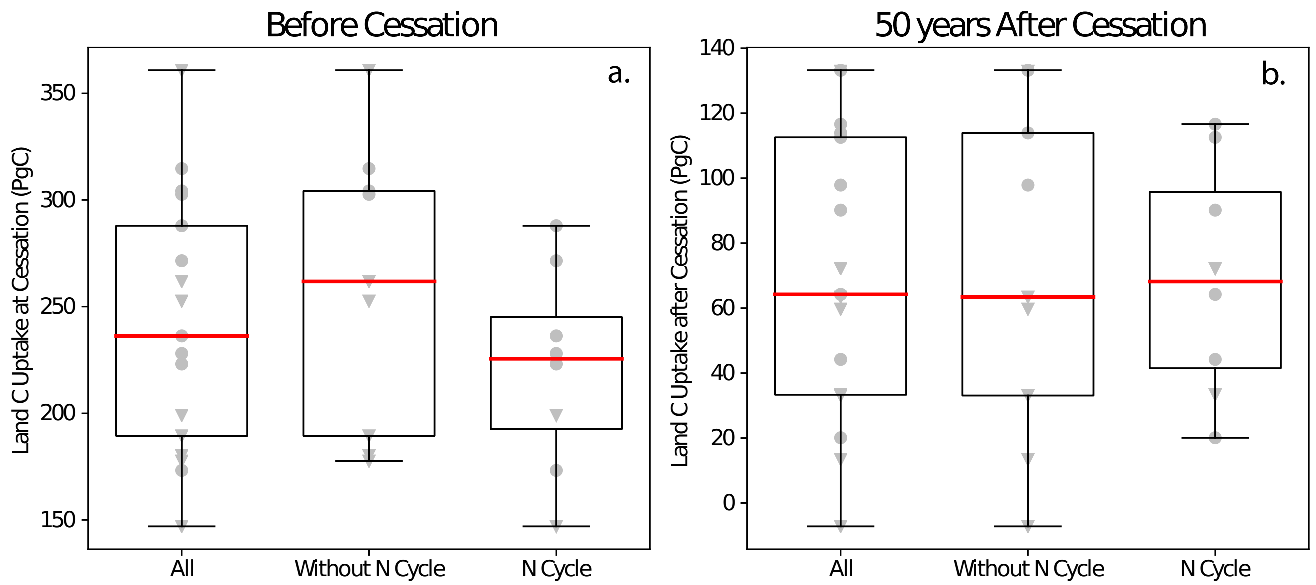

Figure 8. Terrestrial carbon uptake for models with and without a nitrogen cycle, before emissions cease and after emissions cease. Eight models have a representation of nutrient limitations and ten do not. Circles indicate data points for ESMs and triangle indicate data points for EMICs.

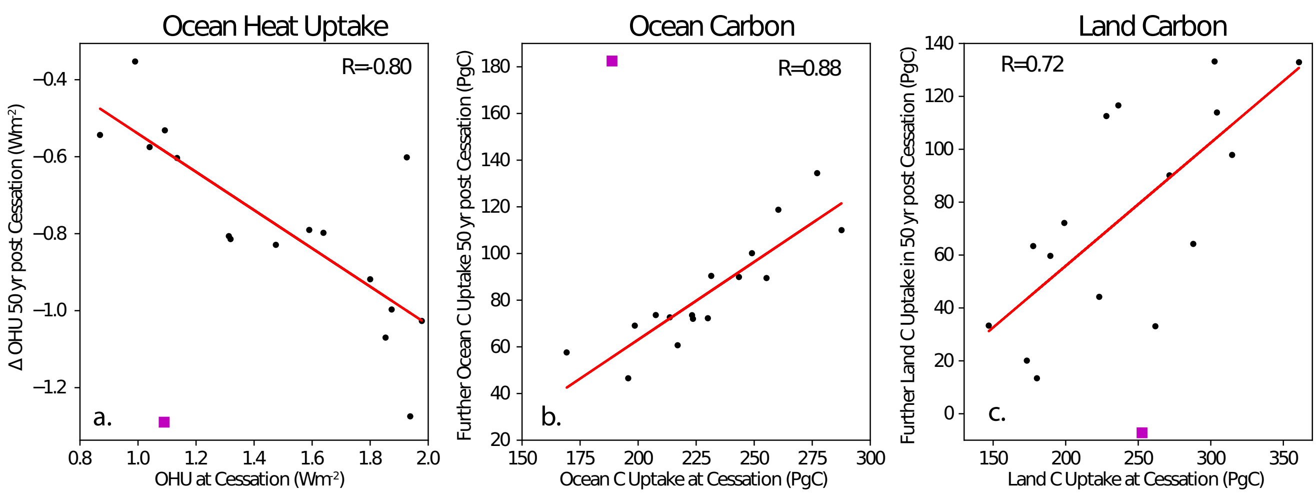

Figure 9. Relationship between variables before emissions cease and 50 years after emissions cease. (a) Ocean Heat Uptake (OHU) is computed for 20 year windows with the value at cessation taken from the 1pctCO2 experiment analogous to the how temperature of cessation is computed. (b) Cumulative ocean carbon uptake, (c) Cumulative land carbon uptake. Each marker represents value from a single model. Line of best fit excludes the outlier model IAPRAS which is marked with a magenta square.

models show a smaller terrestrial carbon sink for the 2000 PgC experiment than the other two experiments, the exception being IAPRAS which shows the opposite pattern. Examining in detail why these factors change in each model could be a productive avenue for future research.

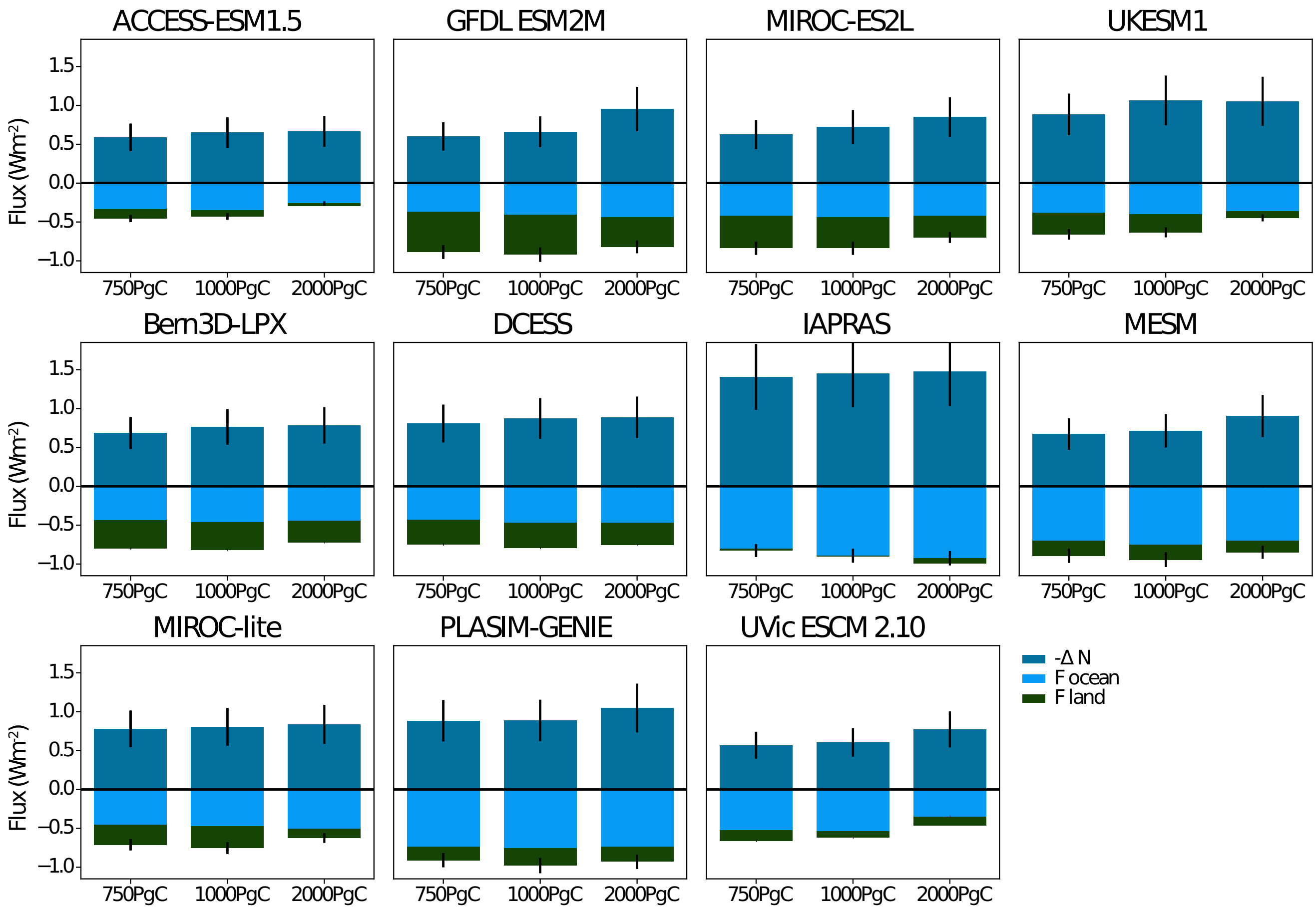

Figure 10. Energy fluxes following cessation of CO_2 emissions for the type-A experiments (1%) for each model. ΔN is the change in ocean heat uptake relative to the time emissions ceased. A reduction in ocean heat uptake will cause climate warming, hence $-\Delta N$ is displayed. F_{ocean} is the change in radiative forcing caused by ocean carbon uptake, and F_{land} is the change in radiative forcing caused by terrestrial carbon uptake. All fluxes are computed for averages from 40 to 59 years after emissions cease.

3.5 Relationship to other climate metrics

Figure 11 shows the relationship between ECS, TCR, TCRE, Realized Warming and ZEC_{50} for the A1 (1000 PgC) experiment. Realized warming is the ratio of TCR to ECS. TCR is transient warming when CO_2 is doubled and ECS is warming at equilibrium following doubling of CO_2, their ratio is the fraction of warming from CO_2 that has been realized, hence 'Realized Warming' (e.g. Frölicher et al., 2014). ECS shows virtually no correlation with ZEC_{50} (R=0.04) and thus ZEC and ECS appear to be independent. Both TCR and Realized Warming show weak positive correlations with ZEC_{50} (R= 0.25 and 0.30 respectively). TCRE shows the strongest relationship to ZEC_{50} with a correlation coefficient of 0.34. ~~However the relationship is weak and several models with high TCRE values have low ZEC values.~~ However, these relationships may not be robust due to small number of non-independent models. The poor correlation between ZEC and other climate metrics is not unexpected as ZEC is determined by the difference in warming caused by reduction in ocean heat uptake and cooling caused by continued land and ocean carbon uptake after the cessation of emissions. Small differences between large quantities are not expected to correlated well to the quantities used to calculate them.

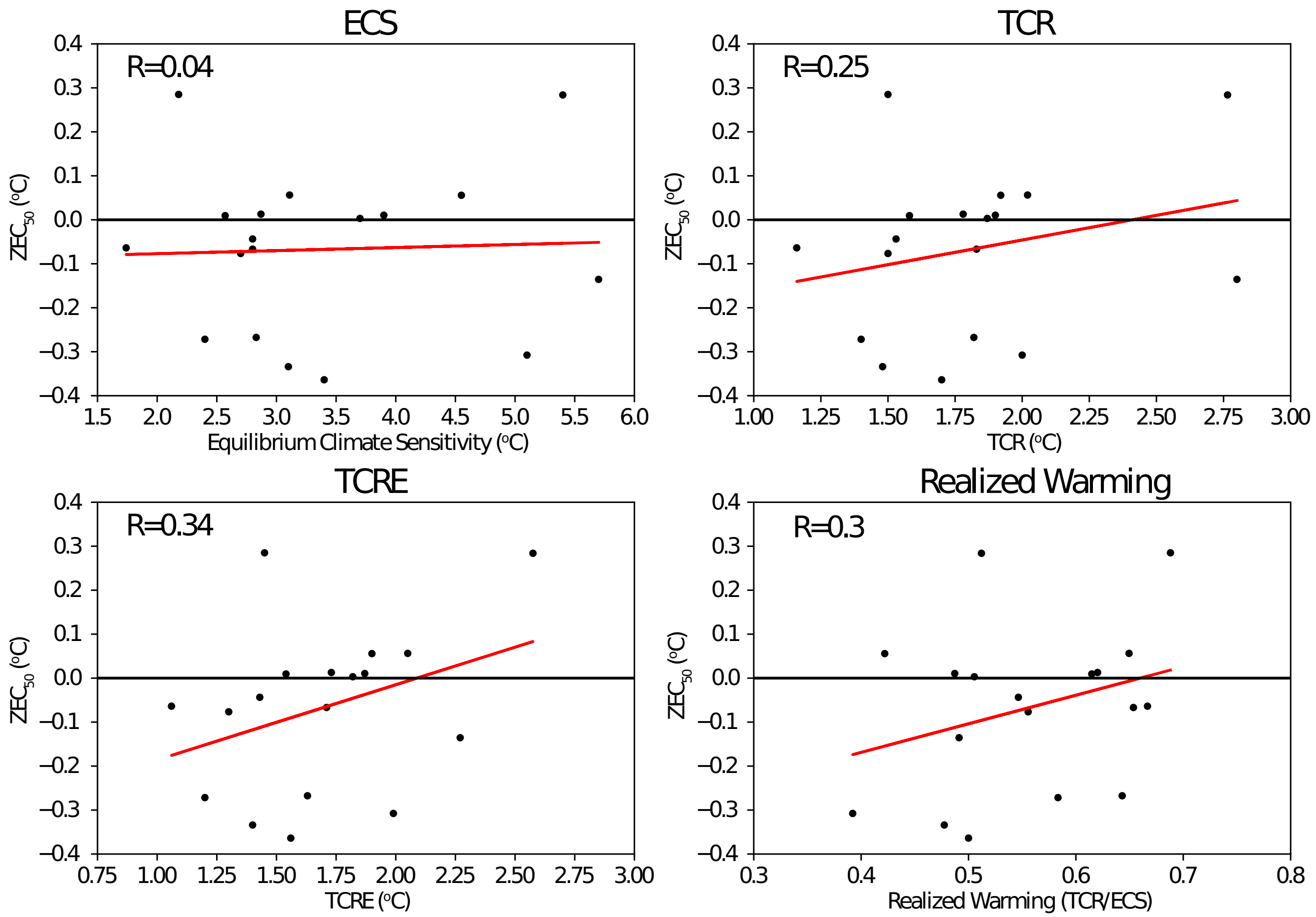

Figure 11. Relationship between: ECS (a), TCR (b), TCRE (c), Realized Warming (d) and ZEC_{50}. Line of best fit is shown in red. Correlation coefficients are displayed in each panel.

Bern and UVic both conducted the ZECMIP experiments with three versions of their models with different equilibrium climate sensitivities, allowing for examination of the effect of ECS on ZEC. Figure 12 shows the ZEC_{50} for these simulations. The figure shows that for both Bern and UVic higher ECS corresponds to higher ZEC. For Bern for the A1 (1% 1000 PgC) experiment ZEC_{50} is 0.01, 0.03, and 0.18°C for ECSs of 2.0, 3.0 and 5.0 °C respectively. For UVic for the A1 (1% 1000 PgC) experiment ZEC_{50} is -0.15, 0.01, and 0.22 for ECSs of 2.0, 3.8 and 5.0 °C respectively. Note that the ECS values given here are for true equilibrium climate sensitivity, not effective climate sensitivities as used in the remainder of this study. Figure 13 compares the energy fluxes for the three versions of Bern and UVic. For Bern ocean carbon uptake is unaffected by climate sensitivity, while for UVic there is a small decline in ocean carbon uptake for an ECS of 5.0°C. For Bern the reduction in ocean heat uptake is larger at higher climate sensitivity, while for UVic this quantity is almost the same for ECSs of 3.8 and 5.0 °C. In Bern the terrestrial carbon sink is weaker in versions with higher climate sensitivity. In UVic the terrestrial carbon sink is weakest for a climate sensitivity of 3.8 °C. Overall the results suggest a relationship between higher ECS and higher ZEC within these models.

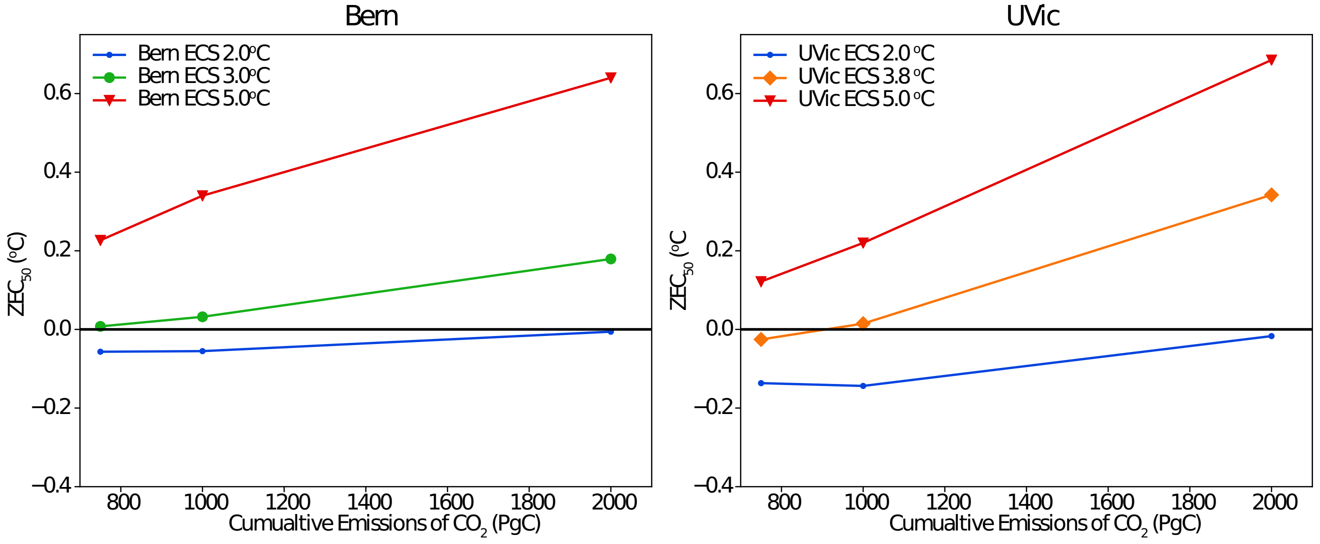

Figure 12. Values of 50 year ZEC for the 750, 1000 and 2000 PgC experiments branching from the type-A (1%), for versions of Bern and UVic with varying Equilibrium Climate Sensitivity. Note that the ECS values given here are for true equilibrium climate sensitivity, not effective climate sensitivities as used in the remainder of the study.

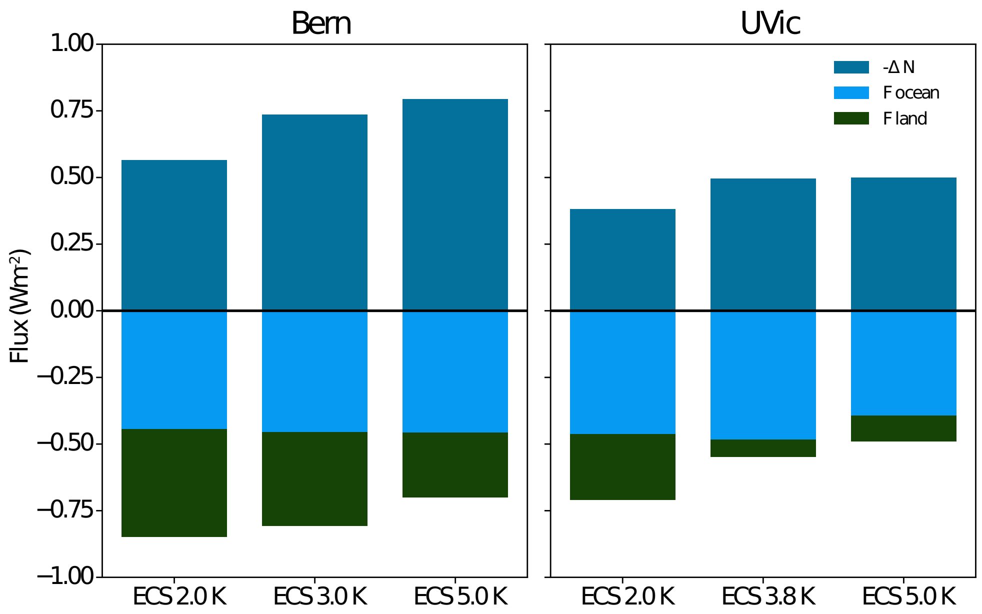

Figure 13. Energy fluxes following cessation of CO_2 emissions for the type-A experiments (1%) for versions of Bern and UVic with varying Equilibrium Climate Sensitivity. ΔN is the change in ocean heat uptake relative to the time emissions ceased. A reduction in ocean heat uptake will cause climate warming, hence $-\Delta N$ is displayed. F_{ocean} is the change in radiative forcing caused by ocean carbon uptake, and F_{land} is the change in radiative forcing caused by terrestrial carbon uptake. All fluxes are computed for averaged from 40 to 59 years after emissions cease.

4 Discussion

4.1 Drivers of ZEC

~~The analysis here has shown that ZEC is poorly correlated to other metrics of climate warming, such as TCR and ECS.~~ The analysis here has shown that across models decadal-scale ZEC is poorly correlated to other metrics of climate warming, such as TCR and ECS, though relationships may exist within model frameworks (Figure 12). However, the three factors that drive ZEC, ocean heat uptake, ocean carbon uptake and net land carbon flux correlate relatively well to their states before emissions cease. Thus it may be useful to conceptualize ZEC as a function of these three components each evolving in their own way in reaction to the cessation of emissions. Ocean heat uptake evolves due to changes in ocean dynamics (e.g. Frölicher et al., 2015) as well as the complex feedbacks that give rise to changes in ocean heat uptake efficacy (Winton et al., 2010). Ocean carbon uptake evolution is affected by ocean dynamics, changes to ocean biogeochemistry, and changes in atmosphere-ocean CO_2 chemical disequilibrium, where the latter is also influenced by land carbon fluxes (e.g. Sarmiento and Gruber, 2006). The response of the land biosphere to cessation of emissions is expected to be complex with contributions from the response of photosynthesis to declining atmospheric CO_2 concentration, a continuation of enhanced soil respiration (e.g. Jenkinson et al., 1991), and release of carbon from permafrost soils (Schuur et al., 2015), among other factors. Investigating the evolution of the three components in detail may be a valuable avenue of future analysis. Similarly, given their clearer relationships to the state of the Earth system before emissions cease, focusing on the three components independently may prove useful for building a framework to place emergent constraints on ZEC. Future work will explore evaluation opportunities by assessing relationships between these quantities in the idealized 1% simulation and values at the end of the historical simulations up to present day.

Our analysis has suggested that the efficacy of ocean heat uptake is crucial for determining the temperature effect from ocean heat uptake following cessation of emissions. Efficacy itself is generated by spatial patterns in ocean heat uptake and shortwave cloud feedback processes (Rose et al., 2014; Andrews et al., 2015). Thus, evaluating how these processes and feedbacks evolve after emissions cease is crucial for better understanding ZEC. As the spatially resolved outputs for ZECMIP are now available (see Section 5), evaluating such feedbacks presents a promising avenue for future research.

4.2 Policy Implications

One of the main motivations to explore ZEC are its implications for policy and society's ability to limit global warming to acceptable levels. Climate policy is currently aiming at limiting global mean temperature increase to well below 2 °C and pursuing to limit it to 1.5 °C (United Nations, 2015). To stay within these temperature limits, emission reduction targets are being put forward. These targets can take the form of emissions reductions in specific years, like the Paris Agreement nationally determined contributions for the years 2025 or 2030 (Rogelj et al., 2016), but also of net zero emissions targets that cap the cumulative CO_2 emissions a country is contributing to the atmosphere (Haites et al., 2013; Rogelj et al., 2015; Geden, 2016). Because ZEC does affect the required stringency of emissions reductions or of the maximum warming one can expect, it is important to clearly understand its implications within a wider policy context. First, for policy analysts and scientists, the quantification of ZEC_{50} will help inform better estimates of the remaining carbon budget compatible with limiting warming to 1.5 °C or well below 2 °C over the course of this century. Analysts need to be clear, however, that ZEC_{50} is only then an adequate adjustment for TCRE-based carbon budget estimates if the TCRE values are based on 1% CO_2 increase simulations. In contrast, however, our results also show that when CO_2 emissions ramp down gradually (c.f. the B-series of ZECMIP experiments) ZEC_{50} is generally much smaller, because part of it is already realized during the emissions ramp down. Hence this means that in a situation in which society successfully gradually reduces its global CO_2 emissions to net zero at rates comparable to the B2 experiment (see Section 3.2), the expected additional warming on time scales of decades to maximum a century is small. Finally, over multiple centuries, warming might still further increase or decrease. In the former case, a certain level of carbon-dioxide removal ~~will~~ would be required over the coming centuries. The level implied by the long-term ZEC, however, represents much less a challenge than the urgent drastic emissions cuts required to limit warming to either 1.5 °C or 2 °C over the next decades (Rogelj et al., 2019b).

4.3 Moving towards ZECMIP-II

For the first iteration of ZECMIP the experimental protocol has focused solely on the response of the Earth system to zero emission of CO_2. However, many other non-CO_2 greenhouse gases, aerosol, and land-use-changes all affect global climate (e.g. IPCC, 2013). To truly explore the question whether global temperature will continue to increase following complete cessation of greenhouse gas and aerosol emissions the effect of each anthropogenic forcing agent must be accounted for (e.g. Frölicher and Joos, 2010; Matthews and Zickfeld, 2012; Mauritsen and Pincus, 2017; Allen et al., 2018; Smith et al., 2019). We envision a second iteration of ZECMIP accounting for these effects with a set of self-consistent idealized experiments, as part of the formal CMIP7 process.

5 Conclusions

Here we have analysed model output from the 18 models that participated in ZECMIP. We have found that the inter-model range of ZEC 50 years after emissions cease for the A1 (1% to 1000 PgC) experiment is -0.36 to 0.29 °C with a model ensemble mean of -0.07°C, median of -0.05°C, and standard deviation of 0.19°C. Models show a range of temperature evolution after emissions cease from continued warming for centuries to substantial cooling. All models agree that following cessation of CO_2 emissions, the atmospheric CO_2 concentration will decline. Comparison between experiments with a sudden cessation of emissions and a gradual reduction in emissions show that long term temperature change is independent of the pathway of emissions. ~~However, in experiments with a gradual reduction in emissions the temperature adjustment from the values expected from TCRE (i.e. ZEC) begin to manifest while emissions are ramping-down.~~ However, in experiments with a gradual reduction in emissions a mixture of TCRE and ZEC effects occur as the rate of emissions declines. As the rate of emission reduction in these idealized experiments is similar to that in stringent mitigation scenarios, a similar pattern may emerge if deep emission cuts commence.

ESM simulations agree that higher cumulative emissions lead to a higher ZEC, though some EMICs show the opposite relationship. Analysis of the model output shows that both ocean carbon uptake and the terrestrial carbon uptake are critical for reducing atmospheric CO_2 concentration following the cessation of CO_2, and thus counteracting the warming effect of reduction in ocean heat uptake. ~~ZEC is poorly correlated to other Earth system metrics,~~ The three factors that contribute to ZEC (ocean heat uptake, ocean carbon uptake and net land carbon flux) correlate well to their states prior to the cessation of emissions.

The results of the ZECMIP experiments are broadly consistent with previous work on ZEC, with a most likely value of ZEC close to zero and a range of possible model behaviours after emissions cease. In our analysis of ZEC we have shown that terrestrial uptake of carbon plays a more important role in determining that value of ZEC on decadal timescales than has been previously suggested. However our analysis is consistent with previous results from Ehlert and Zickfeld (2017) and Williams et al. (2017) in terms of ZEC arising from balance of physical and biogeochemical factors.

Overall, the most likely value of ZEC on decadal time-scales is assessed to be close to zero, consistent with prior work. However substantial continued warming for decades or centuries following cessation of emission is a feature of a minority of the assessed models and thus cannot be ruled out purely on the basis of models.

Data availability. ESM data will be published and freely available as per CMIP6 data policy on the Earth System Grid Federation (https://esgf-node.llnl.gov/projects/cmip6/). EMIC data will be published and freely available on a dedicated server (terra.seos.uvic.ca/ZEC). The annual global mean variables used for the present analysis will also be made available on the server.

Appendix A: Model Description Tables

Table A1. Model descriptions of the atmospheric, oceanic, and carbon cycle components for the full Earth System Models (ESMs) that participated in this study.

Model	ACCESS-ESM1.5	CanESM5	CESM2	CNRM-ESM2-1	GFDL ESM2M
Short Name	ACCESS	CanESM5	CESM2	CNRM	GFDL
Model Expansion	CSIRO Australian Community Climate and Earth System Simulator, ESM version 1.5	Canadian Earth System Model, version 5	Community Earth System Model 2	CNRM-CERFACS Earth System Model, version 2	Geophysical Fluid Dynamics Laboratory Earth system model version 2
Atmosphere	Unified Model (UM) 7.3, 1.875°x1.25°, L38	CanAM5, 2.81° x 2.81°, L49	CAM6, 0.9°x1.25°	ARPEGE-Climat T127 (1.4°), 91 levels	AM2, 2° x 2.5°, L24
Ocean	MOM5, 1° tripolar grid, finer 10S-10N and S. Ocean, L50	NEMO, 1° finer 20°N - 20°S, L45	POP2	NEMO, 1° tripolar grid, L75	MOM4p1, 1° tripolar grid finer at equator, L50
Z-coordinate or Isopycnal	Z-coordinate	Z-coordinate	Z-coordinate	Z-coordinate	Z-coordinate
Sea Ice	CICE4.1	LIM2	POP2	GELATOv6	SIS
Land Carbon Cycle					
Model Name	CABLE	CLASS-CTEM	CLM5	SURFEX (ISBA-CTRIP)	LM3.0
Dynamic Vegetation	No	No	No	No	Yes
Nitrogen Cycle	Yes	No	Yes	No	No
Phosphorus Cycle	Yes	No	No	No	No
Permafrost Carbon	No	No	Yes	No	No
Ocean Carbon Cycle					
Model Name	WOMBAT	CMOC	MARBL	PISCESv2-gas	TOPAZ2
Explicit Nutrients	Yes	Yes	yes	yes	Yes
If Yes List	P, Fe	N	N, P, Si, Fe	N, P, Si, Fe	N, P, Si, Fe
Reference	(Law et al., 2017; Ziehn et al.)	(Swart et al., 2019)	(Danabasoglu and Others, 2019; Lawrence et al., 2019)	(Séférian et al., 2019; Decharme et al., 2019; Delire et al., 2020)	(Dunne et al., 2012, 2013; Burger et al., 2020)

Table A2. Model descriptions of the atmospheric, oceanic, and carbon cycle components for the full Earth System Models (ESMs) that participated in this study.

Model	MIROC-ES2L	MPI-ESM1.2-LR	NorESM2-LM	UKESM1-0-LL
Short Name	MIROC-ES2L	MPI-ESM	NorESM2	UKESM
Model Expansion	Model for Interdisciplinary Research on Climate, Earth System version2 for Long-term simulations	Max-Planck-Insitute Earth System model, version 1.2, low resolution	Norwegian Earth System Model 2	United Kingdom Earth System Model, vn1
Atmosphere	CCSR-NIES AGCM, T42, L40	ECHAM6, T63 (ca.1.8°x1.8°), L47	CAM6, 0.9°x2.5°, L32	HadGAM3. N96 (1.25° x 1.875°), L85
Ocean	CCSR Ocean Component model (COCO) , 360x256 grids with tripolar grid, L62	MPIOM1.6, GR1.5 (1.5°x1.5°)	Bergen Layered Ocean Model, 1° finer near Equator, L53	NEMO, 1° tripolar grid, L75
Z-coordinate or Isopycnal	Z-coordinate	Z-coordinate	Isopycnal	Z-coordinate
Sea Ice	COCO	Thermodynamic – Dynamic	Community Sea-ice model	CICE sea ice model
Land Carbon Cycle				
Model Name	MATSIRO/ VISIT-e	JSBACH 3.2	CLM5	JULES
Dynamic Vegetation	No	Yes	No	Yes
Nitrogen Cycle	Yes	Yes	Yes	Yes
Phosphorus Cycle	No	No	No	No
Permafrost Carbon	No	No	Yes	No
Ocean Carbon Cycle				
Model Name	OECO2	HAMOCC6	iHAMOCC	MEDUSA-2
Explicit Nutrients	Yes	Yes	Yes	Yes
If Yes List	N, P, Fe	N, P, Si, Fe	P, N, Fe	N, Si, Fe
Reference	(Hajima et al., 2019)	(Ilyina et al., 2013; Mauritsen et al., 2019; Goll et al., 2017)	(Tjiputra et al., 2020)	(Sellar et al., 2019; Best et al., 2011; Clark et al., 2011; Yool et al., 2013)

Table A3. Model descriptions of the atmospheric, oceanic, and carbon cycle components for Earth system models of intermediate complexity (EMICs) that participated in this study.

Model	Bern3D-LPX	CLIMBER-2	DCESS	IAPRAS	LOVECLIM 1.2
Short Name	Bern	CLIMBER	DCESS	IAPRAS	LOVECLIM
Model Expansion	Bern3D-LPX	Climate-Biosphere model, version 2	Danish Center for Earth System Science Earth System Model version 1.0	A.M. Obukhov Institute of Atmopsheric Physics, Russian Academy of Sciences	LOVECLIM v1.2
Atmosphere	2D Energy-Moisture Balance, 4.5° $9^{\circ}(onaverage)$	Statistical-Dynamical, 51° x 10°	Energy-Moisture Balance model	Statistical-Dynamical model, 4.5° 6.0° ,L11	ECBilt, 5.625° x 5.625°, L3
Ocean	4.5° x 9° (on average) , L32	2D, 3-basin zonally-averaged, 2.5° lat, L21	2 box in lat, 100 m Z resolution	Statistical-Dynamical model 4.5° 6.0°,L3	CLIO, 3° 3°,L20
Z-coordinate or isopycnal	Z-coordinate	Z-coordinate	Z-coordinate	Z-coordinate	Z-coordinate
Sea Ice	4.5°,9° (on average)	Thermodynamic-Dynamic	Mean Surface Temperature Parameterization	Mean Surface Temperature Parameterization	Thermodynamic-dynamic
Land Carbon Cycle					
Model Name	LPX v1.4	VECODE			VECODE
Dynamic Vegetation	Yes	Yes	Yes	No	Yes
Nitrogen Cycle	Yes	No	No	No	No
Phosphorus Cycle	No	No	No	No	No
Permafrost Carbon	No	No	No	No	No
Ocean Carbon Cycle					
Model Name	Bern3D v2.0s				LOCH
Explicit Nutrients	Yes	Yes	Yes	No	Yes
If Yes List	P, Si, Fe	P	P		P, Si
Reference	(Ritz et al., 2011; Roth et al., 2014; Jeltsch-Thömmes et al., 2019; Lienert and Joos, 2018)	(Brovkin et al., 2002; Ganopolski et al., 2001)	(Shaffer et al., 2008)	(Eliseev, 2011; Eliseev and Mokhov, 2011; Mokhov and Eliseev, 2012; Eliseev et al., 2014; Mokhov et al., 2020)	(Menviel et al., 2008; Goosse et al., 2010; Mouchet, 2011)

Table A4. Model descriptions of the atmospheric, oceanic, and carbon cycle components for Earth system models of intermediate complexity (EMICs) that participated in this study.

Model	MESM	MIROC-lite/JUMP-LCM	PLASIM-GENIE	UVic ESCM 2.10
Short Name	MESM	MIROC-lite	P. GENIE	UVic
Model Expansion	MIT Earth System Model	Model for Interdisciplinary Research on Climate-lite/Japan Uncertainty Modelling Project-Loosely Coupled Model	Planet Simulator - Grid-ENabled Integrated Earth system model	University of Victoria Earth System Climate Model version 2.10
Atmosphere	Zonally averaged 4° lat., L11	2D Energy-Moisture Balance, 6°x 6°	PLASIM, T21, L10	2D Energy-Moisture Balance, 3.6°1.8°,L1
Ocean	4°x5° mixed layer, anomaly diffusing model	CCSR Ocean Component model (COCO), 6°x 6°, L15	GOLDSTEIN, T21, L16	MOM2, 3.6°1.8°,L19
Z-coordinate or isopycnal	NA	Z-coordinate	Z-coordinate	Z-coordinate
Sea Ice	Thermodynamic-Dynamic	COCO	GOLDSTEIN	Thermodynamic-Dynamic
Land Carbon Cycle				
Model Name	TEM	Sim-CYCLE	ENTS	TRIFFID
Dynamic Vegetation	No	No	Yes	Yes
Nitrogen Cycle	Yes	No	No	No
Phosphorus Cycle	No	No	No	No
Permafrost Carbon	No	No	No	Yes
Ocean Carbon Cycle				
Model Name	OCM		BIOGEM	2NZPD
Explicit Nutrients	No	Yes	Yes	Yes
If Yes List		N	P	N, P
Reference	(Sokolov et al., 2018)	(Tachiiri et al., 2010; Oka et al., 2011)	(Holden et al., 2018, 2019)	(Mengis et al., 2020)

Appendix B: Analytical framework

A key question for this study is explaining why some models have positive ZECs and some models have negative or close to zero ZECs. From elementary theory we understand that the sign of ZEC will depend on the pathway of atmospheric CO_2 concentration and ocean heat uptake following cessation of emissions. Complicating this dynamic is that atmospheric CO_2 change has contributions both from ocean carbon uptake and the net flux from the terrestrial biosphere. Here we devise a simple method for partitioning the contribution to ZEC from the ocean carbon flux, net land carbon flux, and the ocean heat uptake.

We begin with the forcing response equation (Wigley and Schlesinger, 1985):

$$F = \lambda T + \epsilon N, \quad \text{(B1)}$$

where F ($\mathrm{W\,m^{-2}}$) is radiative forcing, N ($\mathrm{W\,m^{-2}}$) is planetary heat uptake, ϵ (dimensionless) is the efficacy of planetary heat uptake, λ ($\mathrm{W\ m^{-2}K^{-1}}$) is the climate feedback parameter, and T (K) is the change in global temperature (relative to pre-industrial). This equation can be re-written as:

$$\lambda T = F - \epsilon N. \quad \text{(B2)}$$

To compute the rate of change of temperature we take the derivative of equation B2 in time giving:

$$\lambda \frac{dT}{dt} = \frac{dF}{dt} - \epsilon \frac{dN}{dt}. \quad \text{(B3)}$$

Radiative forcing from CO_2 can be approximated using the classical logarithmic relationship (Myhre et al., 1998):

$$F = R \ln\left(\frac{C_A}{C_{Ao}}\right), \quad \text{(B4)}$$

where R ($\mathrm{W\,m^{-2}}$) is the radiative forcing from an e-fold increase in atmospheric CO_2 concentration, C_A (PgC) is atmospheric CO_2 burden and C_{Ao} (PgC) is the original atmospheric CO_2 burden. Recalling that the derivative of $\frac{d\ln(x)}{dx} = \frac{1}{x}$ the derivative of equation B4 is:

$$\frac{dF}{dt} = R\left(\frac{C_{Ao}}{C_A}\right)\left(\frac{dC_A}{dt}\right)\frac{1}{C_{Ao}}, \quad \text{(B5)}$$

which simplifies to:

$$\frac{dF}{dt} = \frac{R}{C_A}\left(\frac{dC_A}{dt}\right). \quad \text{(B6)}$$

After emissions cease atmospheric CO_2 concentration can be expressed as:

$$C_A = C_{ze} - (C_O - C_{Oze}) - (C_L - C_{Lze}), \tag{B7}$$

Where C_{ze} (PgC) is atmospheric CO_2 burden at the time emissions reach zero, C_O (PgC) is the carbon content of the ocean, and C_L (PgC) is the carbon content of land. C_{Oze} (PgC) is the carbon content of the ocean at the time emissions reach zero and C_{Lze} (PgC) is the carbon content of land when emissions reach zero. Thus the derivative of C_A is:

$$\frac{dC_A}{dt} = -\frac{dC_O}{dt} - \frac{dC_L}{dt} \tag{B8}$$

$\frac{dC_O}{dt}$ is the flux of carbon into the ocean f_O, and $\frac{dC_L}{dt}$ is the flux of carbon into land f_L.

$$\frac{dC_A}{dt} = -f_O - f_L. \tag{B9}$$

Substituting equation B9 in equation B6 we find:

$$\frac{dF}{dt} = -R\frac{f_O + f_L}{C_A}, \tag{B10}$$

which can be split into:

$$\frac{dF}{dt} = -R\frac{f_O}{Ca} - R\frac{f_L}{C_A}, \tag{B11}$$

which can be substituted into equation B3:

$$\lambda\frac{dT}{dt} = -R\frac{f_O}{C_A} - R\frac{f_L}{C_A} - \epsilon\frac{dN}{dt}. \tag{B12}$$

If we integrate equation B12 from time emissions reach zero we get:

$$\lambda T_{ZEC} = -R\int\limits_{t=ze}^{\infty}\frac{f_O}{Ca}dt - R\int\limits_{t=ze}^{\infty}\frac{f_L}{C_A}dt - \epsilon(N - N_{ze}), \tag{B13}$$

where T_{ZEC} (K) is ZEC, N_{ze} ($\mathrm{W\,m^{-2}}$) is the planetary heat uptake when emissions cease.The integrals $\int_{t=ze}^{\infty}\frac{f_O}{C_A}dt$ and $\int_{t=ze}^{\infty}\frac{f_L}{C_A}dt$ can be computed numerically from ZECMIP output. Therefore we define:

$$F_{ocean} = R\int\limits_{t=ze}^{\infty}\frac{f_O}{C_A}dt, \tag{B14}$$

and,

$$F_{land} = R \int\limits_{t=ze}^{\infty} \frac{f_L}{C_A} dt; \tag{B15}$$

and thus:

$$\lambda T_{ZEC} = -F_{ocean} - F_{land} - \epsilon(N - N_{ze}), \tag{B16}$$

Appendix C: ZEC values for A2 and A3 experiments

Table C1. Temperature anomaly relative to the year emissions cease averaged over a 20 year time window centred about the 25th, 50th, and 90th year following cessation of anthropogenic CO_2 emissions (ZEC_{25}, ZEC_{50}, and ZEC_{90} respectively) for the A2 (750 PgC 1% experiment).

Model	ZEC_{25} (°C)	ZEC_{50} (°C)	ZEC_{90} (°C)
ACCESS	-0.03	-0.06	-0.12
GFDL	-0.26	-0.31	-0.26
MIROC-ES2L	-0.04	-0.17	-0.20
UKESM	0.13	0.11	0.08
Bern	0.03	-0.02	-0.09
DCESS	0.12	0.07	-0.02
IAPRAS	0.34	0.30	0.08
LOVECLIM	-0.06	-0.06	0.05
MESM	0.0	-0.07	-0.13
MIROC-lite	0.0	-0.06	-0.09
P. GENIE	0.03	-0.13	-0.12
UVic	0.02	-0.03	-0.06
Mean	0.02	-0.03	-0.07
Median	0.0	-0.06	-0.09
Standard Deviation	0.13	0.15	0.10

Table C2. Temperature anomaly relative to the year emissions cease averaged over a 20 year time window centred about the 25th, 50th, and 90th year following cessation of anthropogenic CO_2 emissions (ZEC_{25}, ZEC_{50}, and ZEC_{90} respectively) for the A3 (2000 PgC 1% experiment).

Model	ZEC_{25} (°C)	ZEC_{50} (°C)	ZEC_{90} (°C)
ACCESS	0.21	0.52	0.65
CanESM5	0.01	-0.06	-0.05
GFDL	-0.12	-0.14	-0.06
MIROC-ES2L	0.03	-0.07	-0.12
UKESM	0.37	0.51	0.75
Bern	0.17	0.17	0.15
DCESS	0.09	0.06	-0.01
IAPRAS	0.34	0.28	0.0
MESM	0.12	0.13	0.11
MIROC-lite	0.08	0.03	-0.02
P. GENIE	-0.15	-0.40	-0.48
UVic	0.11	0.21	0.33
Mean	0.11	0.10	0.10
Median	0.10	0.10	-0.01
Standard Deviation	0.16	0.26	0.34

Appendix D: Efficacy Evolution

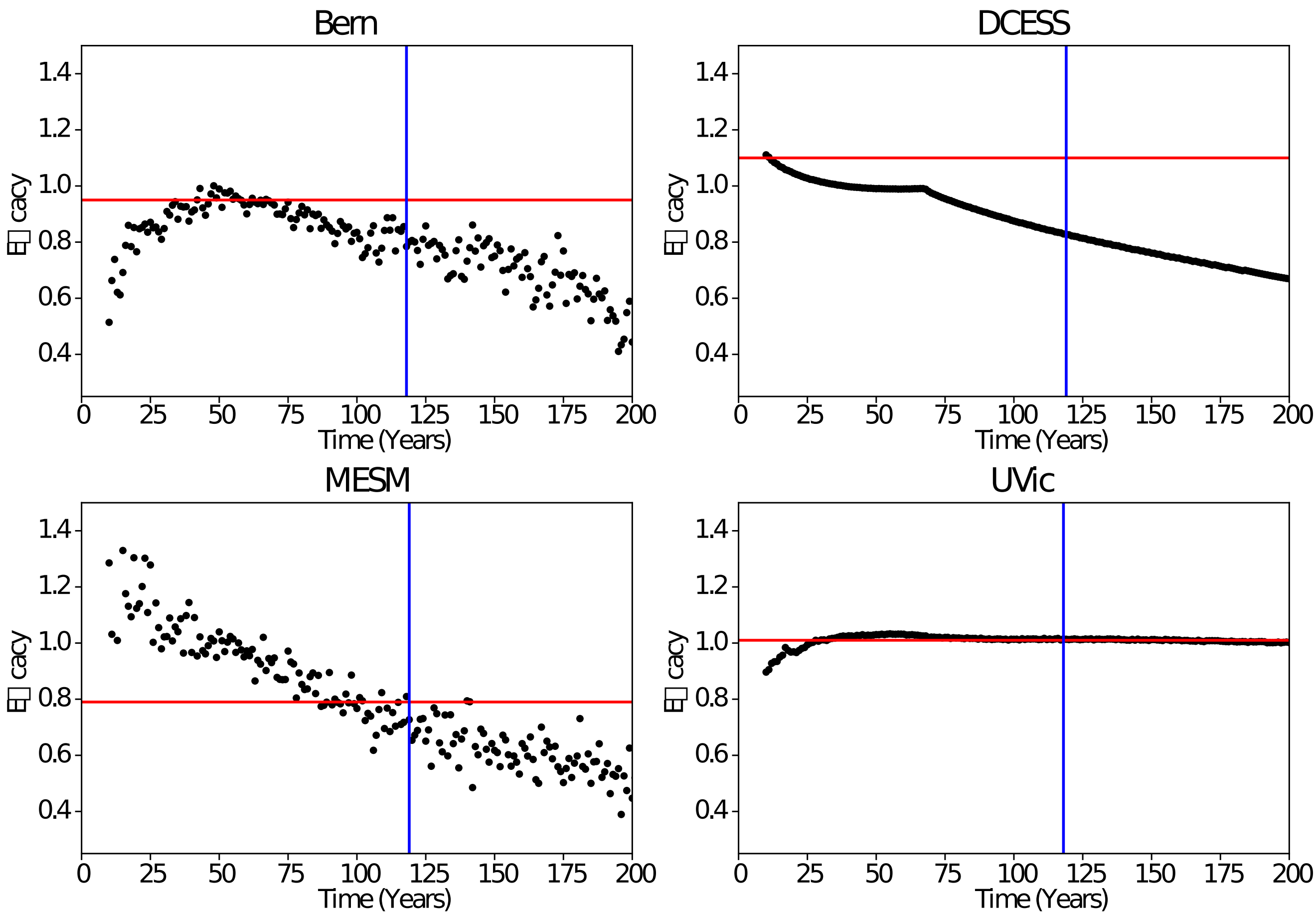

Figure A1. Evolution of efficacy for the four EMICs without substantial internal variability. Red horizontal line is the efficacy value estimated from the 1pctCO2 experiment and vertical blue line marks 50 years after emissions cease.

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