Response to reviews of manuscript:

Estimated effect of the permafrost carbon feedback on the zero emissions commitment to climate change

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

Reviewer 1:

Comments on MacDougall: "Estimated effect of the permafrost carbon feedback on the zero emissions commitment to climate change"
***General**:*
The study assesses the effects of permafrost soil carbon emissions on expected changes in global temperature after the cessation of CO2 emissions, called Zero Emissions Commitment (ZEC). Permafrost regions are the main potential carbon source due to warming and their long-term effects are not yet well understood. The study thus contributes to a very important topic. Methods are in most parts are well described, but I think results and discussion should be expanded to better understand the findings of the study. And the findings are not so clear formulated either. I would suggest to expanding both sections.

A main conclusion, which is only little touched in the discussion and the introduction, but not in the conclusion, is that the structural uncertainty seems to be much more important than parameter uncertainty. But of course it is always a great effort to investigate these structural uncertainties, but perhaps necessary to capture the full range of uncertainties.

The reviewers seems to have misinterpreted aspects of the results of this study. The structural uncertainty in ZEC quantified by the ZECMIP experiments (MacDougall et al. 2020) cannot be directly compared to the parameter uncertainty in the contribution of ZEC from the permafrost carbon feedback quantified in this study. To quantify structural uncertainty for the contribution of ZEC from the permafrost carbon feedback other Earth system models would have to do ZECMIP experiments with and without their permafrost components turned on.

To make this clear the following paragraph has been added to the discussion section of the paper.

"Here we have assessed the parameter uncertainty of the permafrost carbon cycle feedback contribution to ZEC, and have left structural uncertainty un-assessed. To quantify structural uncertainty other Earth system models would have to conduct ZECMIP experiments with and without their permafrost components turned on. As many of the models that participated in ZECMIP do have permafrost carbon capable versions of their models (e.g. Burke et al., 2012), such a study is possible and would make a valuable contribution to the next iteration of ZECMIP."

The scenario uncertainty seems to be of minor importance, pointed out here, which I doubt, but maybe you could exercise a bit more on understanding this minor importance.

The six experimental protocols used in ZECMIP (Jones et al. 2019) do give some sense of the scenario uncertainty in ZEC. That component of uncertainty was well discussed in the ZECMIP results paper (MacDougall et al. 2020).

***Methods**:*

Why is a separate pool needed to simulate permafrost carbon?

This was done to better match to properties of permafrost carbon, which is far more resistant to decay in incubation experiments than regular soil carbon (e.g. Schädel et al. 2014). The set-up also allows for perturbed parameter experiments like this study and MacDougall & Knutti, 2016.

Is there a second non permafrost-carbon pool in permafrost affected regions?

Yes, regular soil carbon exists along-side permafrost carbon. Permafrost carbon is created when regular soil carbon is advected across the permafrost table by the cryoturbation scheme. It can only be destroyed by heterotrophic respiration. Thus in thawed permafrost soils both pools exist simultaneously in the same soil layer.

I conclude that only permafrost soils have a passive pool in the UVic ESCM, right?

Yes. The scheme for regular soil carbon is in need of an overhaul to better match modern understanding of soil carbon stabilization. Such a scheme is high on the to-do list for UVic model development.

And you tune the passive pool to match observed driven permafrost carbon estimates.

The whole of the permafrost carbon pool is tuned by altering the saturation parameter. Changing this parameter is also how the size of the permafrost carbon pool is perturbed. This is stated in the methods section:

"A fourth parameter, the saturation factor (S) from the cryoturbation scheme allows the size of the permafrost carbon pool to be tuned"

These and the following information are important to understand the permafrost carbon feedback effect and how you have contacted the model experiments.

The subsection of the methods describing the soil carbon and permafrost schemes has been modified to clarify the points made by the reviewer, from:

"The terrestrial subsurface of the model is composed of 14 layers, reaching a total depth of 250m (Avis et al., 2011). The top 8 layers (10 m) are active and the hydraulic cycle and deeper layers are impermeable bedrock (Avis et al., 2011). The freeze-thaw physics of the soil accounts for the effect of soil valence forces on freezing point and the frozen and unfrozen fraction of the soil water is calculated using equations the minimize Gibbs free energy (Avis, 2012). The top 6 layers of the model (3.35 m) are active in the carbon cycle. Carbon is assigned to soil layers from Triffid based on the root density in each soil layer, with remaining dead plant matter added to the top soil layer (MacDougall et al., 2012). Root density varies by plant function type and the temperature of the soil layer (roots do not grow in frozen soil) (MacDougall et al., 2012). In model grid cells where permafrost exists (where soil layers have been below 0 ^{o}C for two or more consecutive years) a diffusion based cryoturbation scheme is used to redistribute soil carbon in the soil column. The scheme was originally developed by Koven et al. (2009) and modified for implementation in the UVic ESCM in MacDougall and Knutti (2016). The scheme allows for a permafrost carbon pool to be generated in permafrost soils. The modifications made to the scheme by MacDougall and Knutti (2016) allow the permafrost carbon pool to come into equilibrium during the 5000 year model spin-up. The version of the UVic ESCM used here does not have a methane production module. Thus emissions of carbon from soils to the atmosphere happens only as CO_2.

In the version of the UVic ESCM used here (MacDougall and Knutti, 2016) permafrost carbon is a separate carbon pool. Permafrost carbon is created when carbon is advected across the permafrost table by the cryoturbation scheme and can only be destroyed by being respired into CO2. The pool is characterized by a decay rate constant (κ_p), a fraction of the pool that is available for decay (available fraction, Af), and a passive pool transformation rate (κ_{tf}), which is the rate at which the passive permafrost carbon becomes part of the available fraction. The available fraction is essentially the combined size of the fast and slow carbon pools as conceptualized in incubation experiments (Schädel et al., 2014; MacDougall and Knutti, 2016). This scheme accounts for the large fraction of permafrost carbon that is very resistant to decay (Schädel et al., 2014), while still allowing the pool to decay over millennial time periods (MacDougall and Knutti, 2016). A fourth parameter, the saturation factor (S) from the cryoturbation scheme allows the size of the permafrost carbon pool to be tuned (MacDougall and Knutti, 2016).”

To:
“The terrestrial subsurface of the model is composed of 14 layers, reaching a total depth of 250m (Avis et al., 2011). The top 8 layers (10 m) are active and the hydraulic cycle and deeper layers are impermeable bedrock (Avis et al., 2011). The freeze-thaw physics of the soil accounts for the effect of soil valence forces on freezing point and the frozen and unfrozen fraction of the soil water is calculated using equations the minimize Gibbs free energy (Avis, 2012). The top 6 layers of the model (3.35m) are active in the carbon cycle. Carbon is assigned to soil layers from Triffid based on the root density in each soil layer, with remaining dead plant matter added to the top soil layer (MacDougall et al., 2012). Root density varies by plant function type and the temperature of the soil layer (roots do not grow in frozen soil) (MacDougall et al., 2012). In model grid cells where permafrost exists (where soil layers have been below 0ºC for two or more consecutive years) a diffusion based cryoturbation scheme is used to redistribute soil carbon in the soil column. The scheme was originally developed by Koven et al. (2009) and modified for implementation in the UVic ESCM in MacDougall and Knutti (2016). The scheme allows for a permafrost carbon pool to be generated along-side regular soil carbon in permafrost soils. The modifications made to the scheme by MacDougall and Knutti (2016) allow the permafrost carbon pool to come into equilibrium during the 5000 year model spin-up. The version of the UVic ESCM used here does not have a methane production module. Thus emissions of carbon from soils to the atmosphere happens only as CO2.

In the version of the UVic ESCM used here (MacDougall and Knutti, 2016) permafrost carbon is a separate carbon pool. Permafrost carbon is created when carbon is advected across the permafrost table by the cryoturbation scheme and can only be destroyed by being respired into CO_2. The pool is characterized by a decay rate constant (κ_p), a fraction of the pool that is available for decay (available fraction, Af), and a passive pool transformation rate (κ_{tf}), which is the rate at which the passive permafrost carbon becomes part of the available fraction. The available fraction is essentially the combined size of the fast and slow carbon pools as conceptualized in incubation experiments (Schädel et al., 2014; MacDougall and Knutti, 2016). This scheme accounts for the large fraction of permafrost carbon that is very resistant to decay (Schädel et al., 2014), while still allowing the pool to decay over millennial time periods (MacDougall and Knutti, 2016). A fourth parameter, the saturation factor (S) from the cryoturbation scheme allows the size of the permafrost carbon pool to be tuned (MacDougall and Knutti, 2016). The saturation factor is indexed to the mineral porosity of soils (which vary by grid cell and soil layer), and accounts for the diminishing concentration of soil carbon at depth in permafrost regions (Hugelius et al., 2014)."

What are the assumptions for the non-permafrost experiment, which carbon amount do you assume?

The soil carbon pool is generated by Triffid, not prescribed or assumed by the model. In the non-permafrost experiment at the end of model spin-up the model has 1837PgC in soils, well within the uncertainty of the estimated pre-industrial value 1700±250 PgC for non-permafrost soils (Batjes, 2016; Jackson et al., 2017).

The non-permafrost carbon pool appears to be different in both experiment due to the existence resp. non-existence of cryoturbation.

The difference is real but not large. In the permafrost versions of the model the non-permafrost carbon has a range of 1844 to 1871 PgC, with a median of 1853PgC at the beginning of the simulation.

What are the differences in global soil carbon amount after emission cease? It seems to be important as you compare always to this time.

For the A1 experiment (1000PgC) the permafrost versions of the model have 2002 to 2149 PgC, median 2077 PgC. For the non permafrost versions it is 1992 to 2135 PgC, median 2060 PgC.

Do you assume a vertical soil carbon distribution in regions which are not affected by permafrost?

Yes, see above for explanation of how carbon is distributed from plants to soils.

These now have now been added to the paragraph that explains Figure B1 in section 2.3. The new sentences read:

"The difference in regular (non-permafrost) soil carbon is also small between the two simulation. The simulation without cryoturbation has 1837 PgC of regular soil carbon in the pre-industrial state and simulation with cryoturbation has 1853 PgC in the regular soil carbon pools in the pre-industrial state."

***Results and discussion**:*
Figure 3: Can you explain why ZEC (°C) declines after fossil fuel emission cease in both permafrost and no permafrost carbon case. Or does it decline until fossil fuel emission cease, but than I do not understand the caption, it states: "relative to the year emission cease"

The value of ZEC is determined by a balance of the warming effect of diminishing ocean heat uptake, and the cooling effect of declining atmospheric CO_2 concentration (MacDougall et al. 2020). We can see in the lower panels of the figure that CO_2 concentration drops rapidly immediately after emissions cease, then more gradually latter on. In the figure added below in response to another comment we see that the rapid initial drop in CO_2 is driven by a residual land based carbon sink.

Sentences have been added to the end of the paragraph discussing these results to make this clearer. The sentences read:

"The value of ZEC is determined by a balance of the warming effect of diminishing ocean heat uptake, and the cooling effect of declining atmospheric CO_2 concentration (MacDougall et al., 2020), thus the initial cooling after emissions cease is likely caused by the initial rapid drop in atmospheric CO2 concentration (3c,d)."

Secondly, is that really relative, it seems to be absolute values.

ZEC is a temperature anomaly taken relative to the global mean temperature when emissions cease. That is the difference in temperature at a given time and the time that emissions cease.

Figure 4,5 (b) no numbers are given in the result section Comparing figure 4 and 5, we see carbon emissions of about an additional fourth of the total emissions in both cases, but only minor effects on the temperature change. Could you give a number of the mean temperature effect of both experiments without permafrost carbon when fossil fuel emissions cease. Now I have seen it in the supplement for the 1pctCO2 experiment, but there you state that it is concentration driven experiment that does not result in changes in atmospheric CO2 due to permafrost soil carbon changes.

The temperature at cessation has now been added to the results. The final sentence of the first paragraph of the results was:

"The carbon released from permafrost soils by the time emissions ceases causes 0.04 [0.01 to 0.12]^{0}C of additional warming in the model versions with permafrost carbon."

And has been changed to:

"The global mean temperature anomaly at the time emissions cease is 1.51 [1.41 to 1.58] ºC for the non-permafrost carbon experiment and 1.55 [1.47 to 1.67]ºC for the permafrost carbon experiment. Thus, the carbon released from permafrost soils by the time emissions ceases causes 0.04 [0.01 to 0.12]ºC of additional warming in the model versions with permafrost carbon."

Please explain why it is different after fossil fuel emission cease. At least I didn't find it that easy to understand.

The additional warming caused by the release of carbon from permafrost soils is closely in line with what would be expected from TCRE values. For example in the median case of the A1 experiment 29 PgC is released 50 years after emissions cease, leading to a warming of 0.059K. This gives an implied TCRE value of 0.059K/0.029EgC = 2.0K/EgC.

What about the other carbon pools? It would be helpful if you could also show ocean carbon pools and vegetation carbon pools to better understand why permafrost soil carbon emissions do not lead to stronger warming.

A new figure has been drafted which shows mean change in the global carbon pools in A1 experiments with and without permafrost carbon. The figure is:

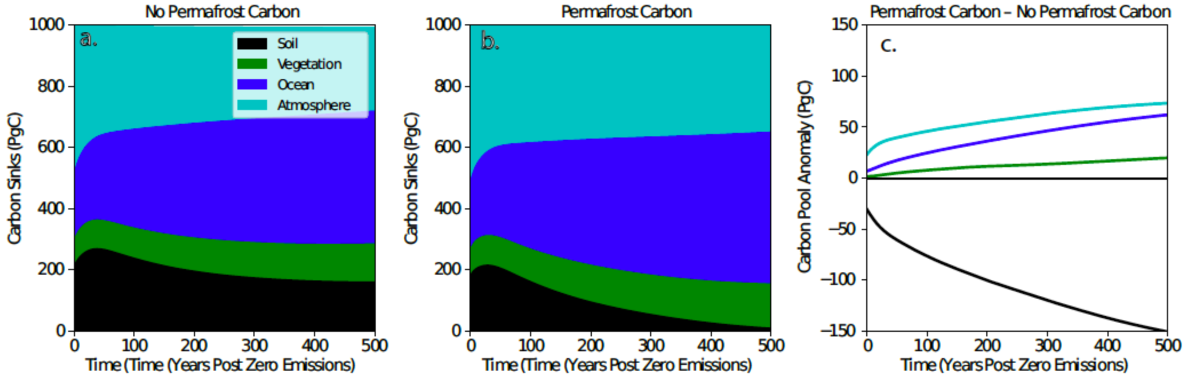

Figure 4. (a,b) Size of carbon sinks following cessation of emissions in the A1 (1000 PgC) experiments with and without permafrost carbon. (c) Difference in size of carbon pools between the simulation with, and the simulation without permafrost carbon. The total of all carbon sinks remains 1000 PgC after emissions cease.

A description of the figure is included in the results as the second paragraph. The paragraph reads:
“Figure 4 shows mean difference in global carbon pool sized in the simulations with and without permafrost carbon, averaged across all of the model variants, for the A1 (1000 PgC) experiment. The excess carbon released from permafrost soils is taken up by vegetation, the ocean, and the atmosphere. Most of the excess carbon resides in the atmosphere for centuries after emissions cease, with the ocean gradually becoming a more significant sink. Vegetation remains a relatively small sink throughout the experiments. Figure 4 also suggests that the source of the rapid fall in atmospheric CO2 in the decades after emissions cease is continued growth of the vegetation and soil carbon sinks. Within a century of cessation of emissions the terrestrial biosphere transitions from a carbon sink to carbon source, a process exacerbated by the existence of permafrost carbon pool. ”

Figure 6a Isn’t it a relative change?

No as stated above ZEC is taken relative to the time emissions cease. The values are not normalized.

And if we look at the trajectory of the permafrost carbon change seems only to decline even if higher vegetation growth due to the CO2 fertilization effect and higher local temperatures could enhance soil carbon sequestration, no simulation shows this possibility. All show a release of soil carbon, could you explain this in the text please.

The figure has been redrafted to change the upper bound of the y-axis, showing the may variants do actually show an initial small increase of soil carbon in the permafrost region. The 1000 year length of the simulations and 600PgC y-axis visually obscures this effect, but it is there.

The new figure is:

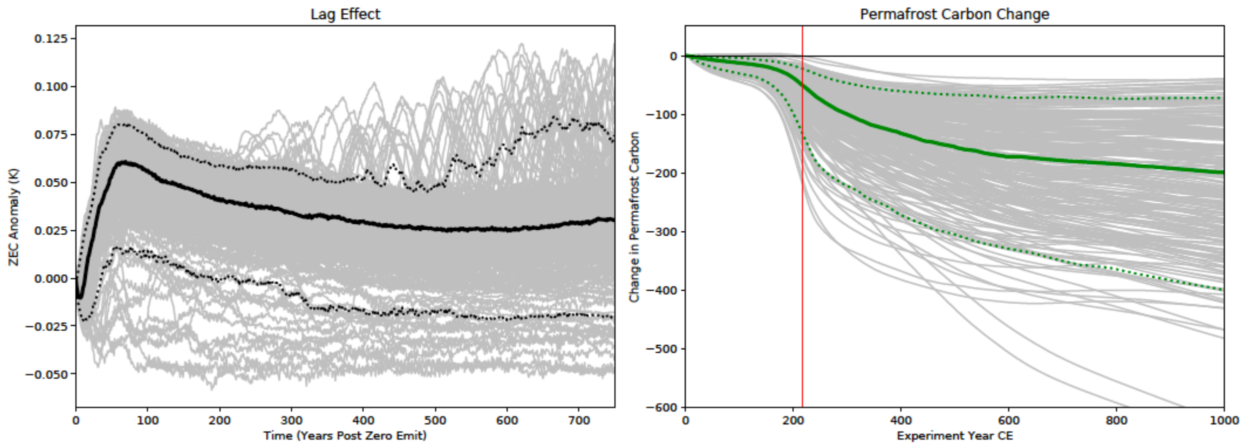

Figure 7 again relative temperature changes?

Change relative to a specific point in time, not normalized plots.

Page 11, line 221: Again, I couldn't follow why a higher emissions from permafrost carbon emissions do not lead to higher temperatures. How different is the atmospheric CO2 concentration?

At the time emissions cease CO_2 concentration has a median value of 514ppm in the 1000 PgC experiments and 800 ppm in the 2000 PgC experiments. Essentially at the higher CO_2 concentration seen in the 2000 PgC experiment the logarithmic forcing of CO_2 is becoming the dominant effect. Recall the radiative forcing from CO_2 is approximately the same for every doubling of atmospheric CO_2 concentration.

Some minor remarks:
Perhaps it will be easier to follow if you would distinguish more precisely between fossil fuel emissions and permafrost soil carbon emissions in the text.

Clarification have been made.

Does temperature change means global mean temperature change?

Yes. This has been clarified in the text where ambiguous.

The author often speaks of "we" which seems very strange with just one author.

I have tried to use 'we' when the audience is included. I did make several mistakes. These have been fixed.

Figure 6a and B1 have some label problems, double "ff" seems to be a problem

Yes this is a weird Latex compiling bug. Will be fixed for final version.

Reviewer 2:

This paper examines the effect of the permafrost carbon feedback as included in the UVic ESM on the zero emissions commitment (ZEC). The author concludes that this does not change the assessment that the ZEC is close to zero on decadal timescales but likely to become more important at longer timescales.

Scientifically I don't have a lot of comments. However, whilst I don't want to suggest making the paper much longer I do feel that the results section is rather sparse and some of the figures are not really discussed- these either should be discussed or removed.

In response to comments from Reviewer 1 more description of figures has been added to the manuscript (See above).

In addition, there is a lot of description about the perturbed parameters but no real analysis of them in the results or discussion. Again - is there some insight to be found from the perturbations? If not, maybe these could go in an appendix/supplementary?

The perturbations are what create the uncertainty ranges given with each numerical result in the results section. The reviewer is correct that the sensitivity of the relationship between permafrost carbon and changes in ZEC were not analyzed in the original manuscript. Computations have now been done to examine the correlations between each perturbed parameter and the change in ZEC from the inclusion of permafrost carbon. The results of this analysis are included in the table below.

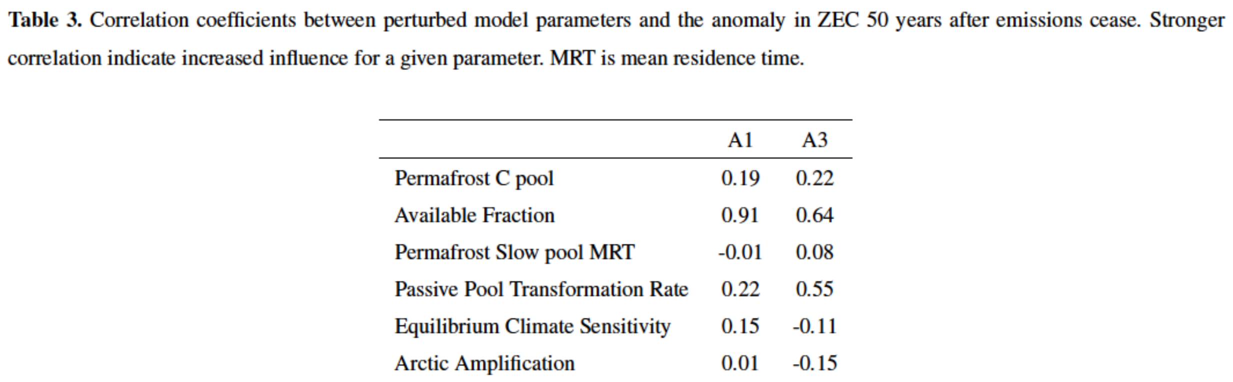

Table 3. Correlation coefficients between perturbed model parameters and the anomaly in ZEC 50 years after emissions cease. Stronger correlation indicate increased influence for a given parameter. MRT is mean residence time.

	A1	A3
Permafrost C pool	0.19	0.22
Available Fraction	0.91	0.64
Permafrost Slow pool MRT	-0.01	0.08
Passive Pool Transformation Rate	0.22	0.55
Equilibrium Climate Sensitivity	0.15	-0.11
Arctic Amplification	0.01	-0.15

The results show that for the A1 (1000 PgC) experiment the contribution to ZEC from permafrost carbon is strongly dominated by the Available fraction of carbon. For the A3 experiment both available fraction and the passive pool transformation rate exhibit controlling influences.

These results are now discussed in a paragraph at the end of the results section. The paragraph reads:

"To explore which of the perturbed parameters has the greatest effect on the anomaly in ZEC created by the inclusion of permafrost carbon, correlations where computed between the perturbed parameter values and the anomaly in ZEC 50 years after emissions cease. These correlations are shown 235 in Table 2. For the A1 (1000 PgC) experiment the Available Fraction parameter has by far the strongest influence with a correlation of 0.91. None of the other parameters have large correlations. For the A3 (2000 PgC) experiment both the Available Fraction (r= 0.64) and the Passive Pool Transformation Rate (r=0.55) have substantial correlation values. These results contrast those for release of carbon from permafrost soils under future scenarios computed by MacDougall and Knutti (2016) where both Available Fraction and Equilibrium Climate Sensitivity played the most important roles, and the Passive Pool Transformation Rate had little effect on results. The difference may partly be due to the reduced uncertainty range in Equilibrium Climate Sensitivity used here. The prominence of the Passive Pool Transformation Rate in the A3 experiment results is concerning as this parameter is the most poorly constrained of all parameters considered. The Available Fraction parameter is effectively the combined size of the fast and slow pools as conceptualized in incubation experiments MacDougall and Knutti (2016). Thus these results suggest that increased field sampling of, and incubation experiments on, permafrost carbon could substantially reduce the uncertainty in permafrost carbon's contribution to ZEC."

Minor comments:

- *How does the UVic ESM ZEC relate to the other models involved in ZECMIP? I think this should be reflected in the paper. This gives us a further idea of the structural uncertainty.*

The UVic ESCM 2.10 has a benchmark ZEC_{50} metric of 0.03°C ranking 8th highest ZEC of the 18 participating models, placing the model comfortably close to the centre of inter-model range. The paragraph is the discussion about the UVic ESCM has been modified to include its ranking compared to other models that participated in ZECMIP. The paragraph did read:

"UVic ESCM 2.10 was one of the two models that participated in ZECMIP that included a permafrost carbon scheme (the other was CESM). The ZEC 50 years after CO_2 emissions cease for the A1 experiment (1000 PgC) for the model version with permafrost carbon used here is -0.02 [-0.07 to 0.08]ºC. The equivalent metric for UVic ESCM 2.10 from ZECMIP was 0.03ºC (MacDougall et al. 2020) 750 years after emission cease ZEC is 0.70 [0.35 to 1.06]ºC for the A1 experiment for UVic ESCM 2.9pf and was 0.20ºC for UVic ESCM 2.10 in MacDougall et al., 2020

And has been modified to:

"UVic ESCM 2.10 was one of the two models that participated in ZECMIP that included a permafrost carbon scheme (the other was CESM). The ZEC 50 years after CO2 emissions cease for the A1 experiment (1000 PgC) was 0.03ºC for the model version that participated in ZECMIP (UVic ESCM 2.10). This value places UVic ESCM close to the centre of the inter-model range ranking 8th highest of the 18 models that participated in ZECMIP (MacDougall et al., 2020). The model version with permafrost carbon used here ZEC 50 years after emissions cease is -0.02 [-0.07 to 0.08]ºC. 750 years after emission cease ZEC is 0.70 [0.35 to 1.06]ºC for the A1 experiment for UVic ESCM 2.9pf and was 0.20ºC for UVic ESCM 2.10 in MacDougallet al. (2020)."

- *I think the numerous emissions/temperatures in the results section could be more easily read by being included within a table.*

A table has been added to include these values.

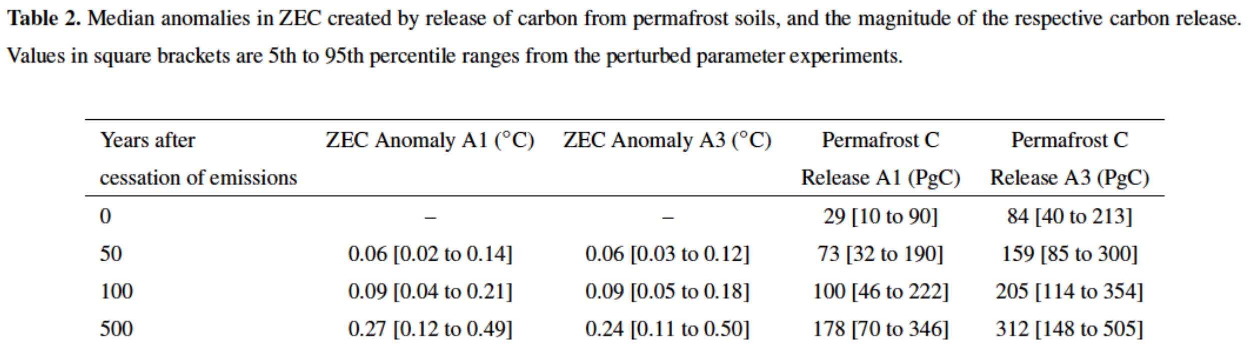

Table 2. Median anomalies in ZEC created by release of carbon from permafrost soils, and the magnitude of the respective carbon release. Values in square brackets are 5th to 95th percentile ranges from the perturbed parameter experiments.

Years after cessation of emissions	ZEC Anomaly A1 (°C)	ZEC Anomaly A3 (°C)	Permafrost C Release A1 (PgC)	Permafrost C Release A3 (PgC)
0	–	–	29 [10 to 90]	84 [40 to 213]
50	0.06 [0.02 to 0.14]	0.06 [0.03 to 0.12]	73 [32 to 190]	159 [85 to 300]
100	0.09 [0.04 to 0.21]	0.09 [0.05 to 0.18]	100 [46 to 222]	205 [114 to 354]
500	0.27 [0.12 to 0.49]	0.24 [0.11 to 0.50]	178 [70 to 346]	312 [148 to 505]

- *I wonder whether it is possible to make the simulations used clearer in section 2.3 maybe through the use of a table?*

A table has been added to describing the model experiments.

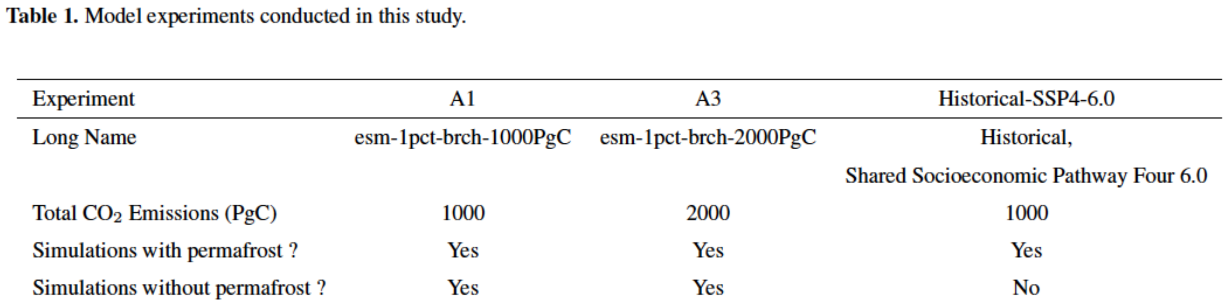

Table 1. Model experiments conducted in this study.

Experiment	A1	A3	Historical-SSP4-6.0
Long Name	esm-1pct-brch-1000PgC	esm-1pct-brch-2000PgC	Historical, Shared Socioeconomic Pathway Four 6.0
Total CO_2 Emissions (PgC)	1000	2000	1000
Simulations with permafrost ?	Yes	Yes	Yes
Simulations without permafrost ?	Yes	Yes	No

- *line 68 - "full representation" not precisely true*

‘full’ has been deleated.

References:

Batjes, N. H. (2016). Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks. Geoderma 269, 61–68. doi:10.1016/j.geoderma.2016.01.034.

Jackson, R. B., Lajtha, K., Crow, S. E., Hugelius, G., Kramer, M. G., and Piñeiro, G. (2017). The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls. Annu. Rev. Ecol. Evol. Syst. 48, 419–445. doi:10.1146/annurev-ecolsys-112414-054234.