Response to Biogeosciences

We thank both referees for their constructive comments.

RC2

General Comments

This paper proposes framework for developing understanding of the drivers of the Zero Emissions Commitment (ZEC) by introducing a normalized ZEC. Normalized ZEC accounts for the warming that has already occurred at the time of zero emissions.

This additional climate metric appears potentially useful for assessing variability both across Earth system models and within a simpler Earth system model.

We thank the referee for the positive comments.

I think the paper would be improved by clarifying the intent of introducing Normalized ZEC. Are the authors arguing that normalized ZEC should be used instead of ZEC?

There are two parts to our response:

(i) We think that retaining the usual definition for the ZEC is useful, but that we are providing a framework to identify the drivers of the ZEC.

The important point is that our definition provides a simpler connection between the temperature change to the different drivers involving the top of the atmosphere energy budget, radiative forcing dependence and the carbon inventory changes.

If you wish to compare the relative importance of the different drivers for the temperature change to each other, then that comparison is clearest if each term is normalised.

(i) Labelling of a normalised ZEC

We agree that labelling our definition as a normalised ZEC leads to confusion as there are other choices for that normalisation (such as that suggested by yourself).

The existing ZEC (e.g. as per MacDougall et al) is defined as an arithmetic measure of the absolute change of global temperature in degrees compared to the time of zero emissions.

Instead our new definition (that we had called a normalised ZEC) is equivalent to a geometric measure of the ZEC, given by the fractional zero emission commitment (measuring the fraction of warming relative to the time of zero emissions).

Or that Normalized ZEC is useful for comparing drivers of ZEC?

Agreed that the normalised framework is useful for comparing the relative importance of the different drivers of the ZEC.

The authors don't actually do a comparison with the original ZEC formulation so it is a bit hard to decipher if the normalized ZEC introduced here provides new information.

The ZEC is given by DT(t)-DT(t_ze).

The geometric ZEC is given by DT(t)/DT(t_ze).

Our framework is explicitly designed to identify the drivers of the geometric ZEC, such that the product of the normalised thermal, radiative and carbon drivers are exactly the same as that as the geometric ZEC as in equation (20).

Figures 3 and 4 shows the relative importance of each of those drivers for the geometric ZEC, and that is detailed in Table 1 and Table S1.

So the manuscript is designed to provide the information needed to understand the drivers of the ZEC.

In more detail, the statistics included in the Tables 1 and 2 shows the coefficient of variation for the different terms. The comparison of those coefficients of variation then reveals the relative importance of the different drivers or the components of the system.

I can see that it might, but it would be helpful to have a more direct comparison, or other direct representation of the benefit of this new metric whatever the authors think that is.

The framework is designed to provide a quantitative measure of the different drivers of the ZEC. Without a quantitative measure, one is left making qualitative comparison of thermal and carbon effects when those variables are measured in different ways. Our framework provides a formal way of comparing the relative importance of each driver.

For example, for the ZECMIP diagnostics for the geometric ZEC, we find that

(i) The intermodal spread in the geometric ZEC is primarily controlled by the intermodal spreads in the normalised thermal contribution and normalised atmospheric carbon concentration, rather than that of the normalised radiative forcing dependence on atmospheric CO2 (Table 1b);
(ii) The intermodal spread of the normalised contribution to the warming dependence on radiative forcing is mainly determined in ZECMIP by the intermodal spread in the fraction of radiative forcing returned to space rather than that of the inverse climate feedback (Table 1c);
(iii) The intermodal spread of the airborne fraction is mainly determined by the intermodal spread of the landborne fraction, rather than the oceanborne fraction (Table 1c).

These detailed inferences were not the same for the inter-model spread for the TCRE, where inter-model differences in the thermal contribution were most important and they were primarily associated with inter-model differences in the climate feedback parameter (Williams et al., 2020, ERL, doi:10.1088/1748-9326/ab97c9).

There is quite a range of behavior across models for the individual component contributions to normalized ZEC. Can the authors do more to discuss why?

Explaining why the different Earth system models respond in different ways is challenging, but we can provide more insight for the carbon cycle. What we have done is identify which drivers are responsible for those different responses and how they link to different responses in the top of the atmosphere energy balance or how the airborne fraction is controlled.

We find that the model responses separate into different classes. For the carbon response, the land carbon sink either continues to increase in time or saturates. These different responses appear to be linked to whether there is a nutrient cycle that can inhibit the ability of the land to take up unlimited carbon.

For the top of the atmosphere response, the radiative response (returning heat to space) either weakens in time or remains relatively constant. These different responses connect to differences in the time evolution of the strength of climate feedbacks. Here there is not a simple message in terms of the complexity of the representation of climate processes (especially cloud processes) in determining the radiative response.

The main conclusions seem to be that ZEC is a balance between ocean heat uptake rate and carbon uptake rate (intermodel spread driven mostly by land). Isn't this already the view reported in review papers like Pallazo Corner et al 2023?

The review paper by Pallazo Corner et al 2023 only provided that insight in a qualitative manner. This framework provides insight into the relative importance of different drivers in a quantitative manner.

For example for the inter-model spread in the climate responses, the framework reveals

(i) The intermodal spread in the geometric ZEC is primarily controlled by the intermodal spreads in the normalised thermal contribution and normalised atmospheric carbon concentration, rather than that of the normalised radiative forcing dependence on atmospheric CO2 (Table 1b);
(ii) The intermodal spread of the normalised contribution to the warming dependence on radiative forcing is mainly determined in ZECMIP by the intermodal spread in the fraction of radiative forcing returned to space rather than that of the inverse climate feedback (Table 1c);
(iii) The intermodal spread of the airborne fraction is mainly determined by the intermodal spread of the landborne fraction, rather than the oceanborne fraction (Table 1c).

Can the authors provide further ideas about what might lead to the balance of thermal vs. carbon contributions to ZEC across models?

We think that crucial issues for differences in model responses for ZECMIP are

(i) for the top of the atmosphere energy balance is whether the radiative response stays constant or weakens (links to changes in climate feedbacks) and
(ii) for the carbon budget is whether the land carbon sink saturates in time and so the relative importance of the land and ocean carbon sinks. Whether the land carbon saturates in time is linked to whether there is nutrient limitation.

Specific Comments

line 30 - given that this sentence is describing ZEC in general it would make sense to cite more recent analyses of ZEC from flat10MIP (Sanderson et al. 2024)

We add a sentence after line 30 about the ZEC response to flat10MIP

line 54 - I had trouble remembering that I represented Carbon for the entire paper. Is there a reason the symbol is I and not C?

I is used for the carbon inventory throughout the whole paper.

C is often used for concentration.

Equation 4 - I think it would be helpful to write this as ZEC = DeltaT(t)-DeltaT(tze) to make it clear that this is the typical definition of ZEC

Agreed, happy to be more explicit.

line 80 - I wondered at first why you used DetltT(t)/DeltaT(tze) rather than ZEC/DeltaT(tze) since that is how I would think of a normalization.

Normalised warming relative to net zero

We switch to calling this ratio a geometric measure of the ZEC. Our choice is not done in an arbitrary manner, but instead chosen to reveal the drivers via equation (6), and then enable these variables to be connected to the top of the atmosphere energy budget and a carbon inventory budget.

One could normalise is a range of ways, but our choice enables a cleaner connection to the drivers.

I can guess that the chosen definition in Eq5 looks cleaner, and since the two definitions are simply related it makes more sense to use the simpler form. I think it would be helpful to point this out to readers to make it clear. After being explicit about ZEC in Eq 4 I would suggest either writing out or describing briefly that ZEC/DeltaT(tze) = "normalized ZEC"-1

Decided not to call this a normalised ZEC, but instead a geometric measure of the ZEC. The geometric ZEC measures the fractional zero emission commitment (measuring the fraction of warming relative to the time of zero emissions).

line 192 - it would be useful to also add the % change for land vs. ocean sink

Agreed, add percentage changes as well as the absolute values.

line 194 - It would be helpful for intuition if the years could be translated into emissions, even if models have a range at this time.

We think that the referee means refer to the time after emissions cease. Agree that choice of time after net zero is preferable.

line 198 - how close to net zero is the maximum radiative forcing?

The time of net zero is defined by the branch point in the model integrations (Line 170). The maximum atmospheric CO2 and radiative forcing often coincides with that branch point, but sometimes can differ by a year or so. This difference is probably due to interannual variability.

line 216 - ZEC is also made up of competing thermal and carbon responses. I'd suggest rephrasing to say ZEC is made of competing responses... which are easier to cleanly quantify in the normalized framework.

Agreed. Happy to modify text.

line 223 - "For individual models, there are some large variations". This sentence then goes on to show that more than half of models fall into this category. Can the authors say anything more useful about what might drive these variations?

The subsequent analysis of the carbon contribution in section 2.6 and the thermal response in section 2.7 is designed to provide more information as to those different responses, including figure 5 revealing the model differences in airborne fraction and figure 6 model differences for the top of the atmosphere energy budget.

For the airborne fraction there are intermodal differences due to the presence of nutrient cycling limiting the land cycle in some models and not in others.

line 285 - The authors need to provide more information about how carbon, and in particular land carbon, is represented in WASP. Given that this carbon sink rate is a key component readers need a brief description of how it is represented.

The version of WASP used has carbon exchange between the atmosphere and surface ocean employing a numerical carbonate chemistry solver (Follows et al., 2006 https://doi.org/10.1016/j.ocemod.2005.05.004). Sub-surface ocean boxes then exchange carbon with the surface ocean with each sub-surface box having an e-folding timescale prescribed over which the sub-surface box becomes chemically equilibrated with the surface ocean.

The land carbon cycle in WASP contains a vegetation carbon pool and a soil carbon pool. The Net Primary Production (NPP) removes carbon from the atmosphere into the vegetation pool. NPP is dependent upon atmospheric CO_2 via a logarithmic relationship using a CO_2-fertilisation coefficient, and NPP is sensitive to global mean temperature via an NPP-T coefficient. The vegetation carbon to soil carbon pool flux is via leaf litter, which is only dependent upon the size of the vegetation pool. The soil carbon pool returns carbon to the atmosphere with an e-folding timescale, which is temperature dependent via a third coefficient.

line 289 - which parameters are being perturbed to create this ensemble? What aspects of carbon cycle parameters are being perturbed?

The three land carbon coefficients (CO_2 fertilisation, NPP-T and soil carbon residence timescale-T) and the ocean deep box timescales are varied between WASP ensemble members, leading to significant differences in the carbon cycle responses. In an initial prior ensemble the coefficients are varied independently. This prior ensemble is historically forced and compared to observational reconstructions. Only ensemble members that see historic land and ocean carbon uptake agree with historic observational reconstructions are used in the final WASP ensemble (<1% of prior ensemble members).

figure 9 - panel d, should the y-axis label be \Delta I_A and not _a?
correct

figure 9 - it would be helpful to add the intermodel spread from the full ESMs to these plots as well

We can only do that for the 1% CO2 experiments and not the flat10 experiments, as shown in Figure 8a. To address this concern, we will add extra figure panels to figures 9 and 10 to include the WASP experiments for the 1% CO2 experiments, which then will include the intermodal spread from the full ESMs.

figure 9 - why such a low spread in carbon? What is being perturbed about the carbon cycle in the ensemble?

The WASP carbon cycle sees a relatively wide distribution, but the normalised carbon cycle sees a relatively narrow distribution (Figure 9d). This is likely because the carbon cycle coefficients (e.g. CO_2 fertilisation, NPP-T etc) are varied between ensemble members but within each ensemble member are held constant in time. So, when normalisation occurs to the point of zero emission, if a WASP ensemble member has had high anthropogenic carbon uptake up to that point then it will likely continue with high carbon uptake into the future.

figure 10 - it would be particularly helpful to put the intermodel spread (or the individual models? onto panel b so readers can compare the large spread in ESMs to the spread in WASP.

Agreed, we will add extra figure panels to figures 9 and 10 to include the WASP experiments for the 1% CO2 experiments, which then will include the intermodal spread from the full ESMs.

line 347 - "coefficient of variation being larger for the landborne and oceanborne fractions than the airborne fraction" - I'd like the authors to discuss what about the model structure of WASP could cause this?

There are two reasons for this "coefficient of variation being larger for the landborne and oceanborne fractions than the airborne fraction", one to do with the WASP ensemble and another to do with the system itself.

The WASP ensemble aspect is not really to do with the structure of WASP itself, but the method through which the final WASP ensemble is generated. In the prior ensemble, many model coefficients are varied independently. These simulations are then forced historically and an posterior ensemble is generated, where each simulation accepted into the posterior agrees with historic observations. In the posterior ensemble the coefficient values are dependent upon one another: the combination of coefficient values must produce a historically consistent simulation.

The historic constraints on atmospheric carbon are much narrower than the historic constraints on land carbon and ocean carbon, and therefore the posterior ensemble contains simulations whose combined land and ocean carbon cycle responses produce a very narrow atmospheric carbon history. This compensation in the posterior ensemble may carry through when the ensemble is forced with idealised scenarios, since the WASP model coefficient values are dependent upon one another in the posterior ensemble.

For ZECMIP, we see that the coefficient of variation for the landborne fraction is much larger than that for the atmosphere and ocean. Hence there are some aspects of the land response that are being compensated for by the ocean response. This compensation will also apply to the WASP ensemble: If land carbon fraction were high, then the atmosphere fraction would be lower, in turn making the ocean fraction lower. Therefore, the atmosphere fraction is reduced by less than initially expected from the high land carbon fraction – while a high land carbon fraction takes directly from the air, this results in reduced ocean fraction which compensates to reduce the impact on atmospheric fraction. This effect is seen in both the WASP and ZECMIP ensembles.

line 365 - "carbon feedbacks" - I don't see that carbon feedbacks are discussed at all in this paper.

Carbon feedbacks are connected to the carbon inventory changes, but agreed in this study we have not explicitly diagnosed the carbon feedbacks (we have done this in Arora et al. (2020) doi:10.5194/bg-2019-473). Will rephrase to carbon responses.

line 386 - no discussion of carbon or the range of carbon uptake? The carbon contribution is only minimally smaller than the thermal contribution so warrants further discussion.

We agree with this concern. We have added text referring to the spread in the land carbon responses, which connect to the effect of nutrient limitations on land carbon uptake. It is known that those CMIP6 models with a land nitrogen cycle have smaller carbon feedbacks (Arora et al., 2020). This reduction in the land carbon response is because vegetation growth is limited by nitrogen availability – and this is also visible in ZECMIP results where the models with a land nitrogen cycle have a lower mean land fraction of 0.31 compared to 0.41 in the 3 models without a nitrogen-cycle (here CanESM, CNRM and FGDL). These models are already identified in the paper as having higher land-fraction, but we will add brief discussion of this response to the process-inclusion of land nitrogen cycle in the manuscript.

line 398-402 - is there a way to visualize the tradeoffs described in this paragraph?

This information is already conveyed in Figure 4 where the magnitude of the different lines correspond to the strength of that process. For example, a strong thermal amplification is represented by the red line being greater than 1, while a strong carbon cycle is represented by a large decrease in the green line. The product of these factors then defines the geometric ZEC. We will add text to refer back to this figure.

line 406 - how are carbon climate feedbacks being assessed in this paper?

It is the climate feedbacks that are assessed and diagnosed in Figure 7 red line and reported in Table 1c. We do not separately diagnose the carbon-climate feedbacks in this study, but they are diagnosed in Arora et al. (2020) doi:10.5194/bg-2019-473.

Technical Corrections

Eqn 7, Eqn 19, Eqn 20 - labels for terms are offset

OK, we will align.

References

B. M. Sanderson, V. Brovkin, R. Fisher, D. Hohn, T. Ilyina, C. Jones, T. Koenigk, C. Koven, H. Li, D. Lawrence, P. Lawrence, S. Liddicoat, A. Macdougall, N. Mengis, Z. Nicholls, E. O'Rourke, A. Ro- manou, M. Sandstad, J. Schwinger, R. Seferian, L. Sentman, I. Simpson, C. Smith, N. Steinert, A. Swann, J. Tjiputra, and T. Ziehn. flat10mip: An emissions-driven experiment to diagnose the climate response to positive, zero, and negative co2 emissions. EGUsphere, 2024:1–39, 2024. https://doi.org/10.5194/egusphere-2024-3356

S. Palazzo Corner, M. Siegert, P. Ceppi, B. Fox-Kemper, T. L. Fr¨olicher, A. Gallego-Sala, J. Haigh, G. C. Hegerl, C. D. Jones, R. Knutti, C. D. Koven, A. H. MacDougall, M. Meinshausen, Z. Nicholls, J. B. Sall´ee, B. M. Sanderson, R. S´ef´erian, M. Turetsky, R. G. Williams, S. Zaehle, and J. Rogelj. The zero emissions commitment and climate stabilization. Frontiers in Science, Volume 1 - 2023, 2023.

Both above references are cited.

Thank you for the detailed points raised, which have been helpful in making the manuscript clearer and more explicit as to the benefits of the geometric ZEC and the normalised framework.

New versions of figures 2 and 3.

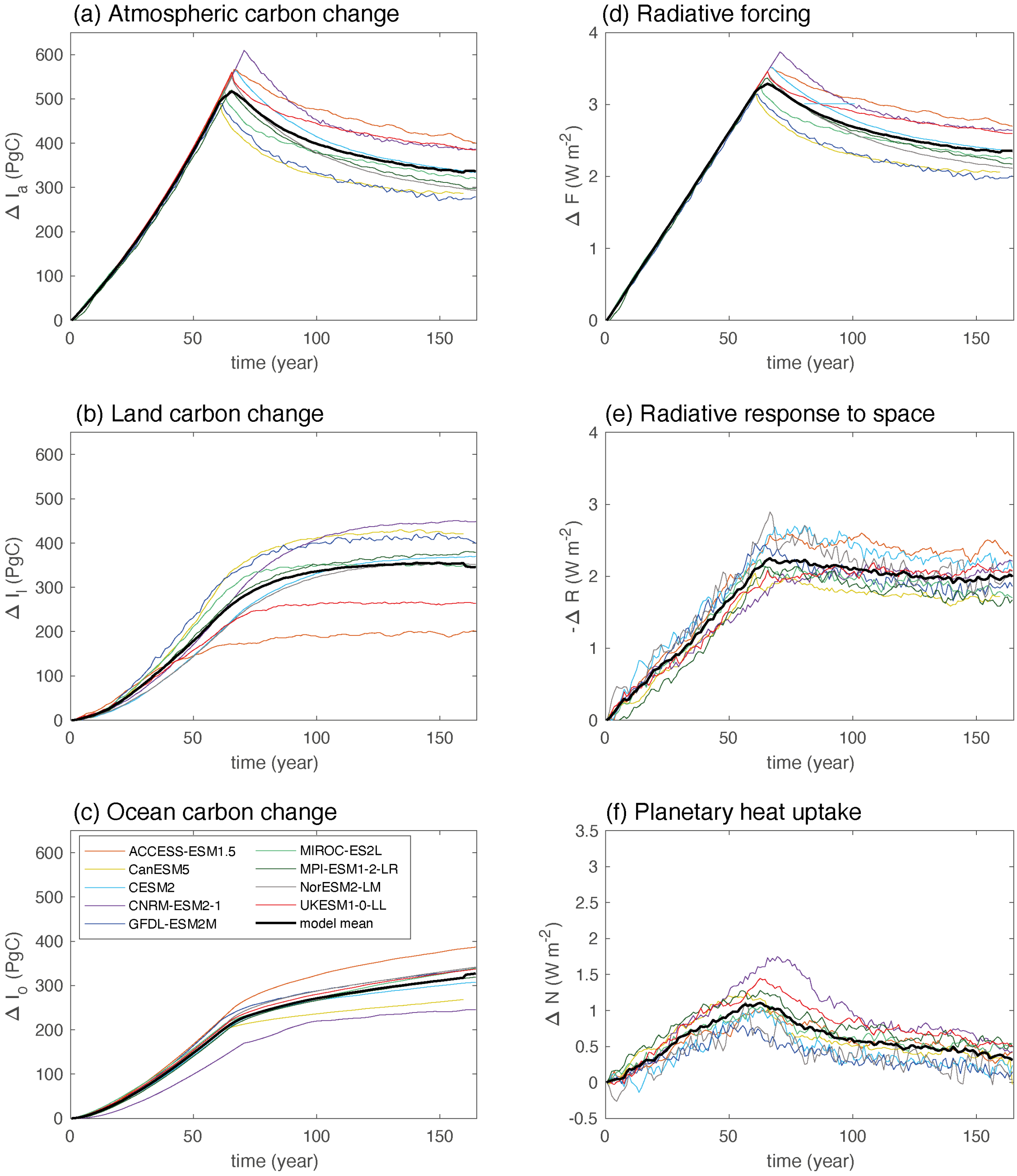

Figure 2. Climate response during emissions and post emissions versus time (year) since the pre industrial for the 9 Earth system models: changes in (a) atmospheric carbon inventory, ΔI_A (PgC); (b) land carbon inventory, ΔI_L (PgC); (c) ocean carbon inventory, ΔI_O (PgC); (d) radiative forcing supplying heat to the climate system, F (W m^{-2}); (e) radiative response representing a heat loss to space, $-\Delta R$ (W m^{-2}); and (f) planetary heat uptake, ΔN (W m^{-2}), positive representing a gain in heat. The plot includes smoothing of planetary heat uptake with a 10 year running mean.

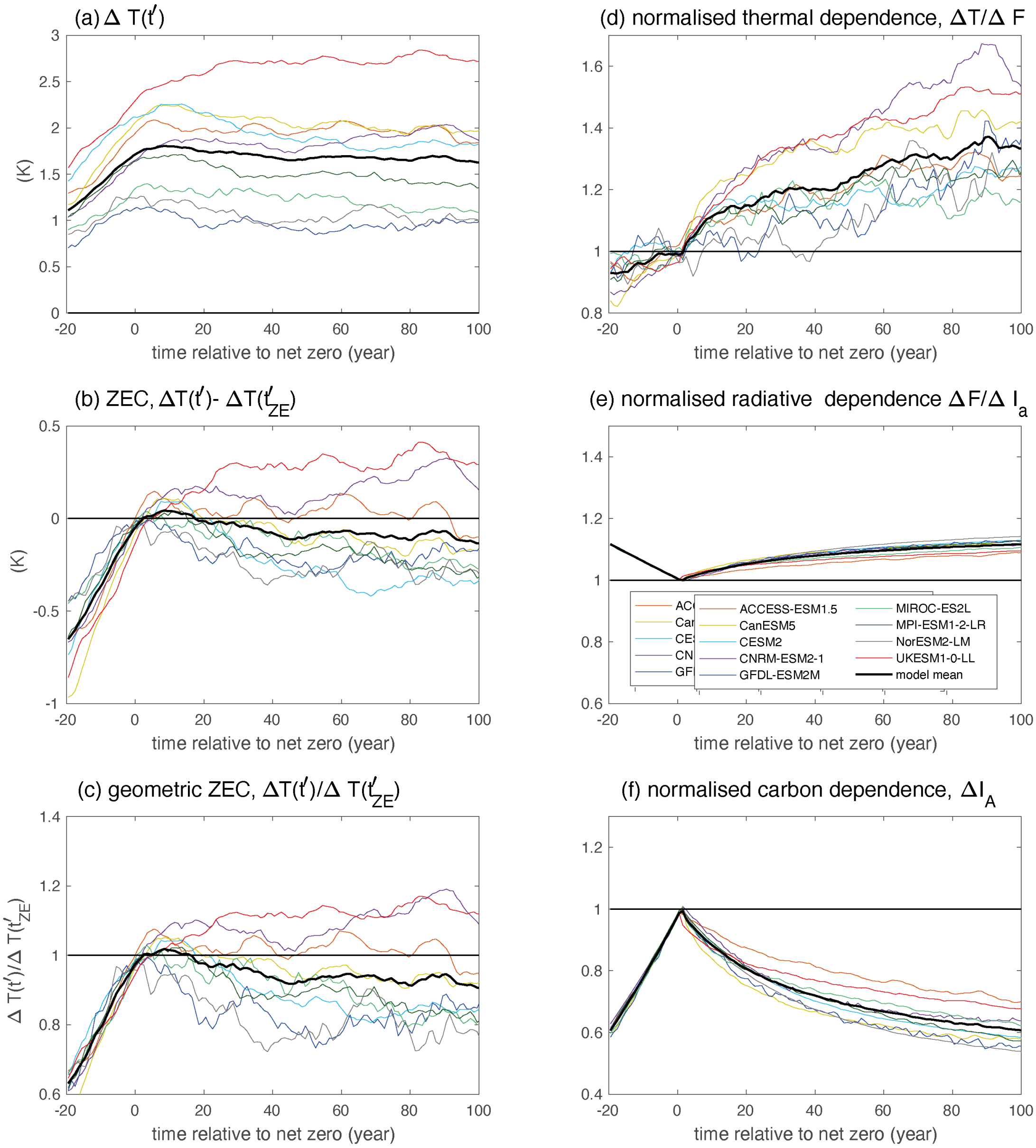

Figure 3. Temporal evolution of the temperature response, the ZEC and its components after net zero when emissions cease: (a) the surface temperature change, $\Delta T(t')$ in K, after net zero is reached (year); (b) the ZEC, surface temperature change, $\Delta T(t') - \Delta T(t'_{ZE})$ in K, after net zero is reached (year); (c) the geometric ZEC, $\Delta T(t')/\Delta T(t'_{ZE})$, a value greater than 1 defines a positive ZEC and a value less than 1 defines a negative ZEC; (d) the thermal contribution from the normalised dependence of surface temperature on radiative forcing, $\Delta T(t')/\Delta F(t')$; (e) the radiative contribution from the normalised dependence of radiative forcing on atmospheric carbon, $\Delta F(t')/\Delta I_A(t')$; (f) the carbon contribution from the normalised atmospheric carbon, $\Delta I_A(t')$. The time series for each individual model is aligned so that the timing of net zero coincides. The normalisation is taken from the average value of the variable over a 20 year period centered on net zero based on the linear response of the 1pct continually-forced experiment. The plot includes smoothing of temperature with a 10 year running mean.

We will also update figures 9 and 10 using WASP to include both flat10 and 1pct scenarios with the ZECMIP range added to the 1pct panels.