Response to Biogeosciences

We thank both referees for their constructive comments.

RC1

Review of "A normalised framework for the Zero Emissions Commitment"

This article explores the contributions of thermal, carbon cycle, and radiative components to the temperature response after net zero CO_2 emissions. The analysis uses nine ESMs from the ZECMIP A1 protocol and an efficient Earth system model (WASP), which includes 1138 posterior ensemble simulations. A normalised ZEC framework is applied, where the ZEC is the temperature change relative to pre-industrial compared to the change at net zero. The ZEC response is determined by a competition between cooling from declining atmospheric CO_2 and warming from strengthening thermal contributions, as ocean heat uptake declines and climate feedbacks amplify surface warming. Different models achieve positive or negative ZEC through varying strengths of thermal and carbon contributions; for example, a strong thermal contribution drives positive ZEC in CNRM-ESM2, while large land and ocean carbon uptake leads to negative ZEC in NorESM2-LM. Inter-model differences are mainly driven by variations in ocean heat uptake and land carbon uptake, and diagnostics from WASP suggest that current model ensembles may underestimate the range of possible climate feedback responses.

Overall, this article is of excellent quality and makes an important contribution by clarifying the physical mechanisms that govern model behaviour after net zero emissions. The revisions suggested below are minor and primarily aimed at improving clarity.

We thank the referee for the positive comments.

General

It would enhance clarity by explaining the interpretation of some of the values once calculated. For example, in lines 210–212 the values for the normalised ZEC is given. I know that the interpretation of the normalised ZEC is provided in line 92. However, because there are many different variables used in this article, an explanation also in lines 210-212 here would improve understandability. This goes for many of the values throughout.

It is important to note that we are not changing the existing definition of ZEC as an absolute temperature change relative to the point of zero emissions. But for our framework we introduce an additional metric of relative change. We are switching to defining the arithmetic (i.e. existing) ZEC as DT(t) -DT(t_ze), and a new geometric ZEC as DT(t)/DT(t_ze), giving the fractional zero emission commitment (measuring the fraction of warming relative to the time of zero emissions).

For the geometric ZEC a value of 1 means that the arithmetic ZEC is 0, and a value of 0.97 means that there is a negative ZEC and that there is a 3% decrease in the temperature change compared with the temperature change at net zero.

Line Specific

Line 91: "A positive ZEC corresponds to ΔT (t)/ΔT (tZE) > 0 and a negative ZEC to ΔT (t)/ΔT (tZE) < 0."

Thank you. This is a slip as spotted by the referee, and these different regimes should be defined by 1 rather than 0.

Should this threshold be one rather than zero? A normalised ZEC less than one would indicate cooling relative to the net zero temperature, and greater than one would imply warming.

Correct

Additionally, moving this explanation to immediately follow the definition of the normalised ZEC would make more sense (line 85).

Agreed, and now call this the geometric ZEC measuring the fractional zero emission commitment (measuring the fraction of warming relative to the time of zero emissions).

Line 217: Values such as $\Delta T(t)/\Delta F(t)$ are given without units. Some values are given with units (such as ZEC), and some are given without units. This occurs throughout with several other values that I believe should also have units.

These variables have been normalised by their values at the time of net zero, so that these normalised variables do not have any units. The text does state that the normalised value is used.

Line 220: The explanation in this section would benefit from additional clarification. It appears that contributions are inferred from changes between years 50 and 90, but this is not explicitly stated. For example:

"The normalised carbon contribution, $\Delta IA(t)$, decreases from 0.70 ± 0.06 at year 50 to 0.63 ± 0.06 at year 90."

Clarifying the methodology used to calculate these contributions would make the reasoning more transparent.

Agreed that more explicit clarification is helpful. The atmospheric carbon inventory is defined at the time periods centred at the time of net zero and at years 50 and 90 years after net zero with all values evaluated relative to the pre industrial. For each time period, the average is taken over a time window centred on that time, so that the time period for year 50 is taken as an average of years 40 to 59 years. The normalised change in the atmospheric inventory is given by that value divided by the value at the time of net zero, \Delta I_A(t)/\Delta I_A(t_ze). These values are given in Table 1b.

To understand the changes in the carbon system, we find it useful to use the airborne fraction so normalise the atmospheric change in the carbon inventory by the cumulative carbon emission at the time of net zero. This choice enables a clearer comparison between the atmosphere, land and ocean contributions as shown in Table 1d and Figure 5. We will make our notation more explicit for the Table and figure.

Figures 2 and 3 The lines in these figures are difficult to distinguish, and the legend overlaps with the x-axis. Using more distinct colours or varied line styles would improve figure readability.

Agreed. We have provided Figures 2 and 3 in a new layout and modified the line colour for one of the models.

New versions of figures 2 and 3.

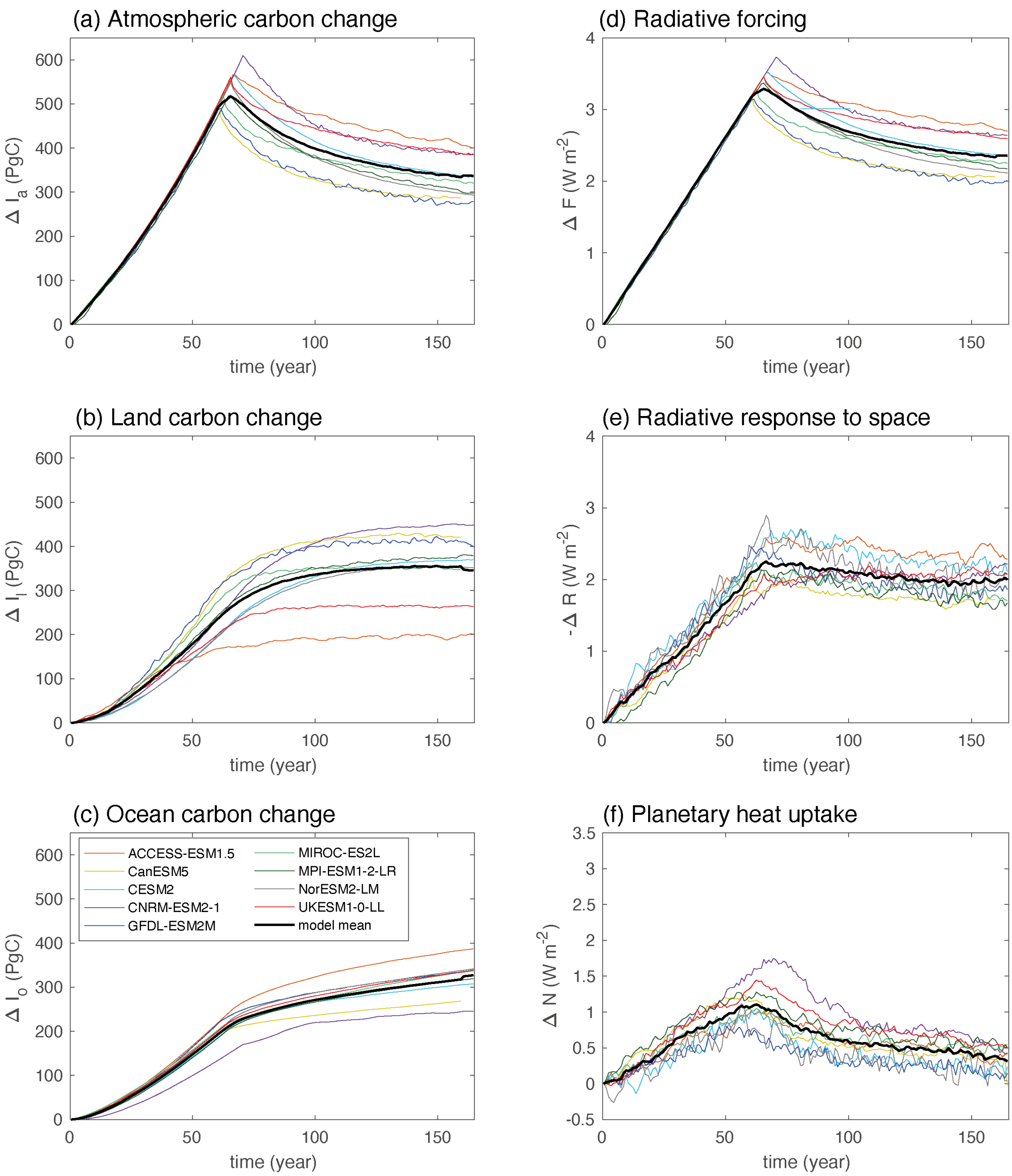

Figure 2. Climate response during emissions and post emissions versus time (year) since the pre industrial for the 9 Earth system models: changes in (a) atmospheric carbon inventory, ΔI_A (PgC); (b) land carbon inventory, ΔI_L (PgC); (c) ocean carbon inventory, ΔI_O (PgC); (d) radiative forcing supplying 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.

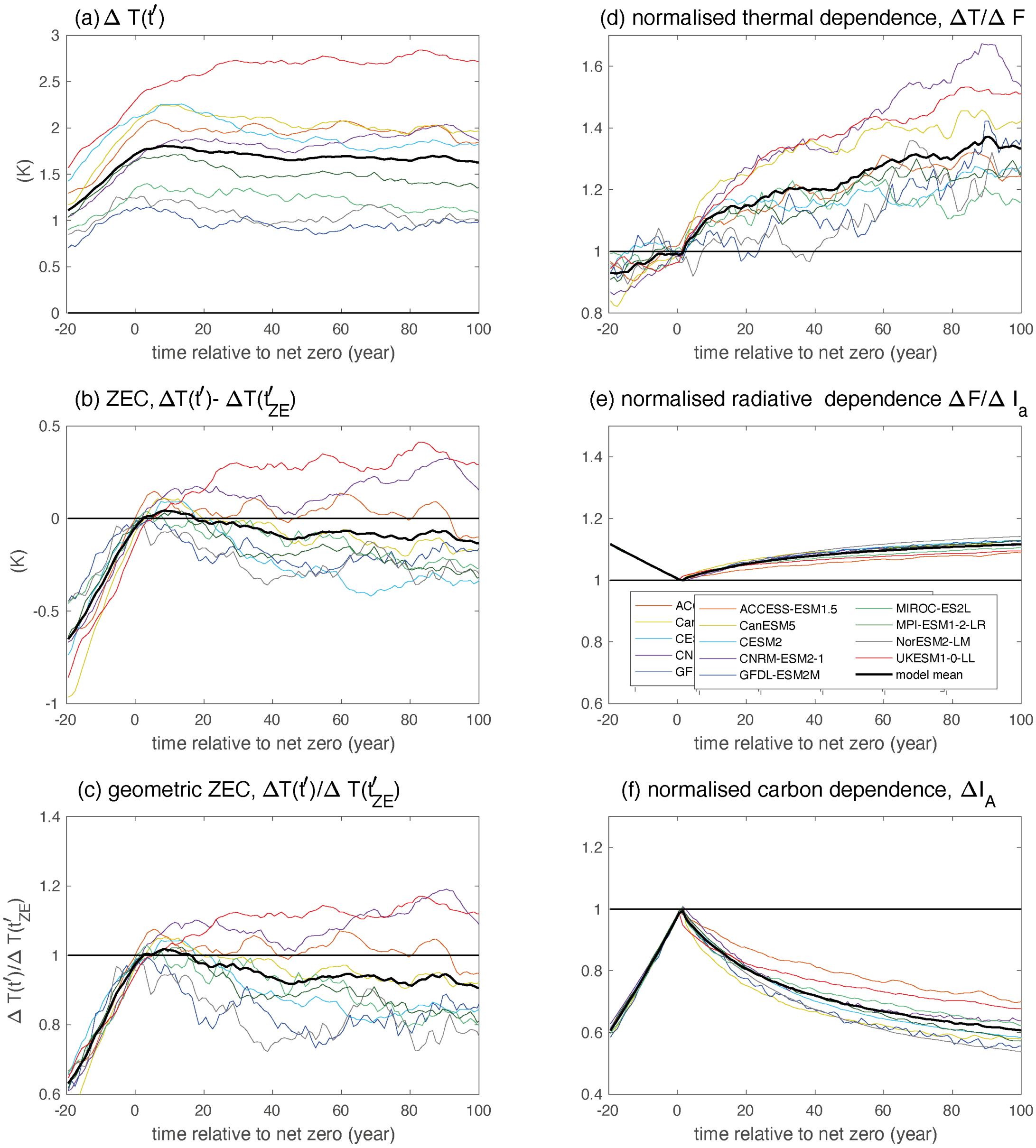

Figure 3. Temporal evolution of the temperature response, the ZEC and its components after net zero when emissions cease: (a) the surface temperature change, $\Delta T(t')$ in K, after net zero is reached (year); (b) the ZEC, surface temperature change, $\Delta T(t') - \Delta T(t'_{ZE})$ in K, after 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.