Response to the editor and reviewers

We thank the editor and the three reviewers for the critical assessment of our work and their very helpful and constructive comments. We have addressed all comments point by point and revised our manuscript accordingly.

Reviewer 1

Review of: AERA-MIP: Emission pathways, remaining budgets and carbon cycle dynamics compatible with 1.5 ºC and 2 ºC global warming stabilization

Overall Evaluation:

The paper presents the results of AERA-MIP, an effort to use Earth system models to quantify the emission pathway needed to reach global temperature stabilization. I commend the authors for the substantial effort needed to put together a model intercomparison of this complexity, and for this comprehensive manuscript. I have some relativity minor suggestions to clarify some of the methods and results.

We thank the reviewer for the positive assessment of our manuscript.

General Comments:

(1) I recommend that you add either a box or an appendix to explain CO2 forcing equivalent emissions to a more general Climate Science audience. Model intercomparison papers such of these are often read by audiences far beyond those immediately involved in the field, and without explaining CO2 forcing equivalent emissions that audience is going to be very confused. It is also important to explain if there is an assumed airborne fraction built into CO2 forcing equivalent emissions.

We appreciate the reviewer's suggestion to include a box explaining the CO_2-fe emissions concept. However, we haven't found any examples of papers in ESD that contain such a box. Therefore, we defer to the editor's decision on whether this is permissible. If it is not possible, we will incorporate the text as an additional paragraph in section 2.1, rather than placing it in the appendix, as it might be overlooked there. The new paragraph (or box) reads as follows:

"*The concept of CO_2-fe emissions is used to unify the emissions of various radiative forcing agents and precursors into a single metric (Jenkins et al. 2018, Allen et al. 2018, Smith et al. 2021). CO_2-fe emissions for all non-CO_2 agents represent the CO_2 emissions that would produce the same radiative forcing trajectory as these non-CO_2 emissions. While cumulative CO_2 emissions largely determine anthropogenic warming, non-CO_2 radiative forcing agents such as methane, nitrous oxide and aerosols also play an important role. Quantifying the impact of these non-CO_2 agents on global temperatures is complicated by existing methodologies, which often use conventional Global Warming Potentials or other metrics to convert the non-CO_2 radiative forcing agents into 'CO2-equivalent' emissions. The CO_2-fe emissions framework offers an alternative, well-suited for comparing emissions from different agents in the context of temperature stabilization pathways (Terhaar et al. 2022). It also offers an opportunity to compare emission reductions of different radiative forcing agents for ecosystem impacts (Terhaar et al. 2023). The CO_2-fe emissions from non-CO_2 agents, $E_{non-CO2-fe}$, are estimated based on the radiative forcing time series of non-CO_2 agents (Smith et al. 2021):*

$$E_{non-CO2-fe}(t) = \frac{1}{\alpha}\left(\frac{dF_{non-CO2}(t)}{dt} + \rho F_{non-CO2}(t)\right)$$

where $F_{non-CO2}$ is the radiative forcing of non-CO_2 agents, ρ is the rate of decline in radiative forcing under zero emission over decadal to centennial timescales (0.33%), and α is a constant representing the forcing impact of ongoing CO_2 emissions (1.08 Wm^{-2} per 1000 GtC). By varying the relative shares of CH_4 and N_2O emissions and radiative forcing from aerosols in the total CO_2-fe emissions, Terhaar et al. (2022) demonstrated the robustness of the CO_2-fe approach in translating contributions from different radiative forcing agents into CO_2-fe emissions."

(2) There are three explanations in the paper as to why many of the models project that continued fossil fuel CO2 emissions could be compatible with temperature stabilization:

I) Negative ZEC.

II) Net-negative forcing from non-CO2 forcing being compensated with fossil fuel CO2 emissions.

III) Net-negative carbon emissions from land use change being compensated with fossil fuel CO2 emissions.

The paper shows that all three mechanisms are at work at different times for at least some models. It would be good to collect these explanations together in the discussion to clarify what are the dominant mechanisms on what time-scale and how mechanism may translate to the natural world.

To emphasize the contributions of the fossil-fuel and non-CO_2 radiative forcing agents as well as land use changes, we have included a new figure in the main text that shows the CO_2-fe emissions from all potential sources that are either simulated by the model or prescribed to AERA. The new figure illustrates that CO_2 emissions from land use changes and CO_2-fe emissions from non-CO_2 agents are likely not the primary reasons for the continued positive total CO_2-fe emissions after temperature stabilization.

We have extended section 3.3 (Emissions from fossil fuel, non-CO_2 agents and land use change) as follows:

"*The prescribed CO_2-fe emissions from non-CO_2 agents (Figure 3d; colored lines for models that were able to estimate their internal radiative forcing; black line for the others; see Methods) exhibit a rapid decrease after year 2026, reaching maximum negative emissions around year 2054 of -1.4 PgC yr^{-1} and stabilizing at slightly positive levels of 0.2 PgC yr^{-1} after 2100 for the default prescribed emissions (black line). CO2 emissions from land use change (Figure 3c) generally remain slightly positive throughout the 21^{st} century, except in the NASA-GISS, EC-Earth and ACCESS models, where they are temporarily negative. Post-2100, the land-use change CO_2 emissions prescribed to AERA stabilize around zero in all models. Both the non-CO_2 and the land-use change CO_2-fe emissions follow identical trajectories for the 1.5°C and 2.0°C global warming level simulations, as they follow the SSP126 scenario for both warming levels.*

It is important to mention that the simulated model-specific CO2 emissions from land use change and CO2-fe emissions from non-CO2 agents are not available as output from all models. Nevertheless, negative CO2-fe emissions from non-CO2 radiative forcing agents are only possible if the radiative forcing from these agents is decreasing (see equation above). However, the radiative forcing agents follow the SSP126 or RCP26 scenario and after 2100 they are set to constant values for all models suggesting that substantial negative non-CO2 radiative forcing is unlikely post-2100. In addition, land-use is also set to be constant after 2100. Considering that CO_2 emissions from both land use change and non-CO_2 agents are likely to be zero or slightly above zero after temperature stabilization, it is reasonable to conclude that the positive CO2-fe and fossil fuel CO2 emissions after stabilizing warming are more likely a consequence of the overall negative ZEC rather than net negative forcing from non-CO2 forcing or from land use change."

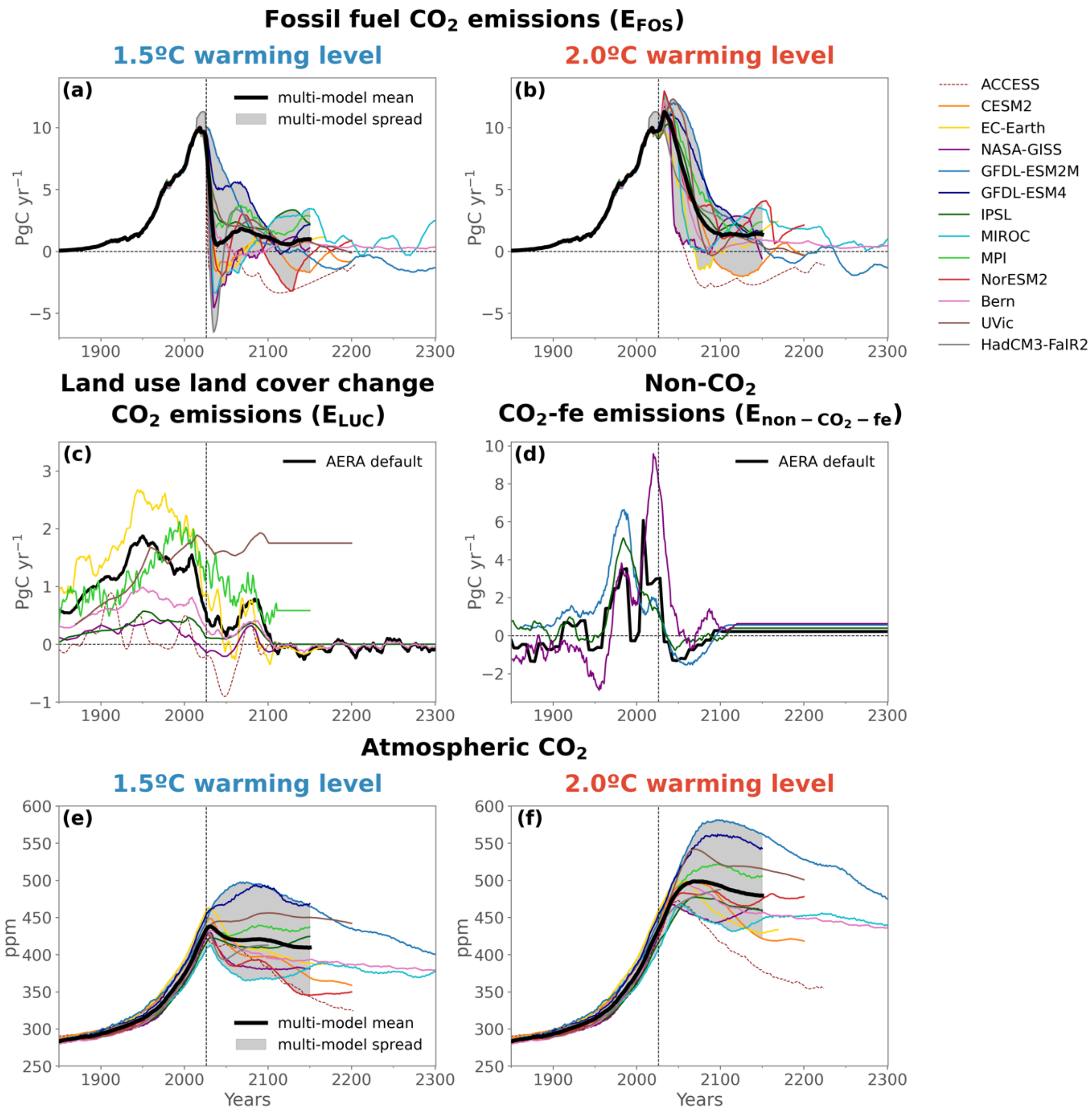

Figure 3: Simulated fossil fuel CO_2 emissions, emissions from land use change and non-CO_2 forcing agents, and atmospheric CO_2. The multi-model mean, excluding the ACCESS model, is displayed by the black thick line, with the grey shading indicating the min-max spread. The

ensemble mean is shown for models that have several ensemble members. The vertical dotted line at the year 2026 marks the beginning of the AERA simulations. In panels c and d, the black line shows the default AERA input for both warming levels, whereas the colored lines show the diagnosed land-use change or non-CO_2 forcing equivalent emissions for models that do not use AERA default values.

As a result of the revisions, figure 2 of the main text has also been slightly modified. It now only shows the temperature and CO_2-fe emissions response.

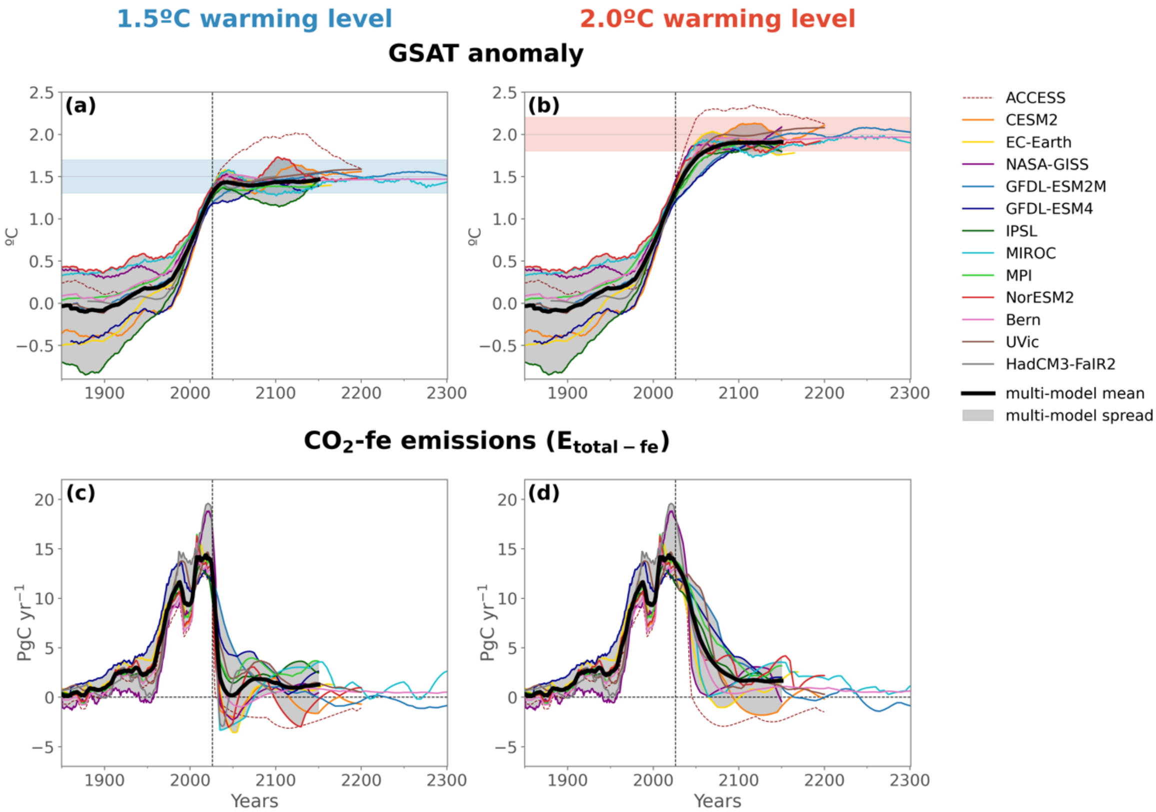

Figure 2: Simulated temperature anomaly CO2-fe emissions and fossil fuel CO2 emissions for the 1.5°C and 2.0°C warming levels. Panels a) and b) display the 31-year running mean of the global surface air temperature (GSAT) anomaly, aligned with the observed value in 2020. Panels c) and d) illustrate CO2-fe emissions. The multi-model mean, excluding the ACCESS model, is displayed by the black thick line, with the grey shading indicating the min-max spread. The ensemble mean is shown for models that have several ensemble members. The vertical dotted line at year 2026 marks the beginning of the AERA simulations.

(3) Related to comment 2, I suggest adding a section on anthropogenic carbon emissions similar to section 3.3. That is, I think it is also important to highlight what the sum of fossil fuel and land use change emissions to distinguish between true continued net CO2 emissions and fossil fuel emissions being compensated by net-negative land use change emissions.

The combined CO2 emissions from fossil fuels and land use change are only marginally different from fossil fuel alone, as land use change CO2 emissions after 2026, especially during the stabilization phase, are minimal. Please see Figure R1 for the combined CO2 emission from fossil fuel and land use change. As we have already included a new Figure 3 with land use change CO2 emissions in the main text, along with a paragraph describing land-use change emissions (refer to the reply to the previous comment), we do not include Figure R1 in the manuscript.

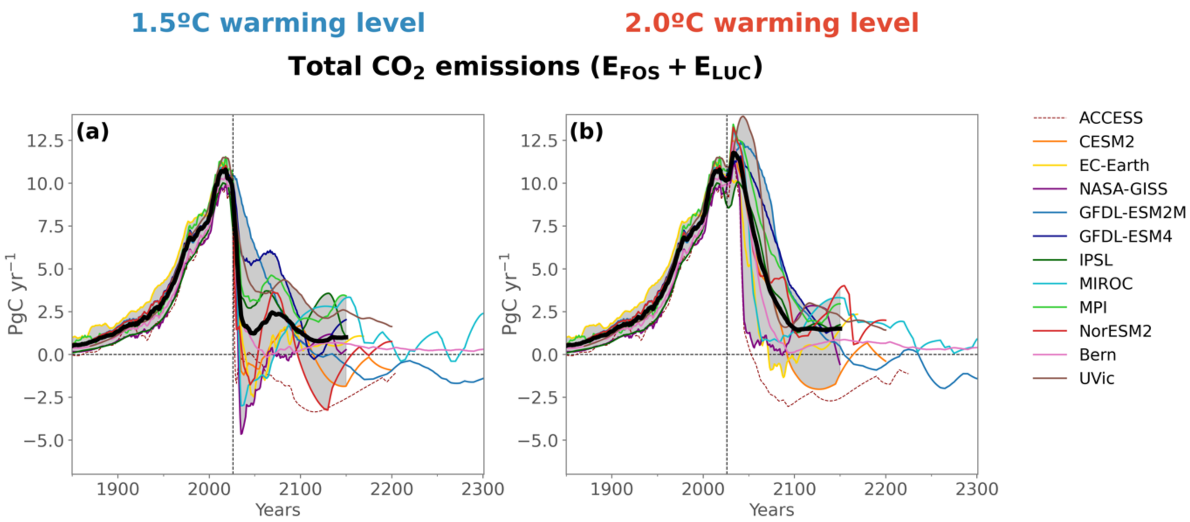

Figure R1: Simulated CO2 emissions from fossil fuel and land use change for the 1.5°C and 2.0°C warming levels.

(4) When examining the model's carbon cycle responses you should examine whether models with a terrestrial nitrogen cycle have a different response.

We have now added a paragraph to the discussion section and also included a new Figure in the Appendix.

"Using CMIP6 models, Arora et al. (2020) demonstrated that those models with a terrestrial nitrogen cycle typically show lower carbon uptake than those without, because of widespread nitrogen limitation of the vegetative carbon sink. This finding has been corroborated by the ZECMIP analysis (MacDougall et al. (2020)). A lower terrestrial carbon sink in models with a terrestrial nitrogen cycle implies stronger reductions in CO_2-fe emissions in those models. This is indeed simulated in both the 1.5°C and 2.0°C global warming level scenarios (see Figure A4). For example, under the 1.5°C global warming scenario, the multi-model mean CO2-fe emissions in 2050 for the six models including a terrestrial nitrogen cycle are -1.6 PgC yr^{-1}, compared to 2.0 PgC yr^{-1} without it. Averaged between 2100-2150, the CO2-fe emissions are 0.8 PgC yr^{-1} for models with a terrestrial nitrogen cycle and 1.5 PgC yr^{-1} without. The minimum CO2-fe emissions in the 1.5ºC scenario between 2026 and 2150 are -1.6 PgC yr^{-1} in the models with a nitrogen cycle, and 1.3 PgC yr^{-1} in the models without. The analysis indicates that part of the spread in CO2-fe emissions pathways can potentially be attributed to whether models include a terrestrial nitrogen cycle. However, the model spread in CO2-fe emissions also emerges due to other model differences, such as in ocean carbon uptake (e.g., Terhaar et al. 2022) or climate sensitivity (Cox et al. 2018)."

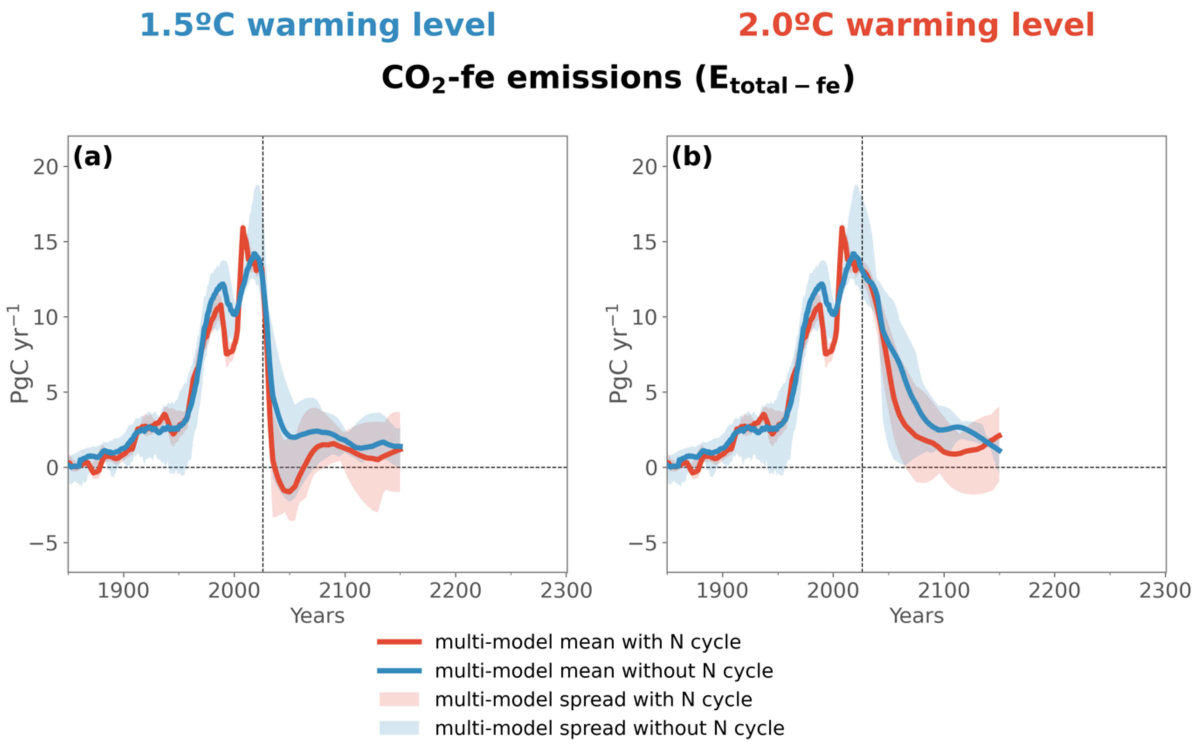

Figure A4: Simulated multi-model mean CO_2-fe emissions for the 1.5°C and 2.0°C warming levels for the models that include a terrestrial nitrogen cycle (red; CESM2, EC-Earth, MIROC, MPI, NorESM2, Bern) and for the models that do not include a terrestrial nitrogen cycle (blue; NASA-GISS, GFDL-ESM2M, GFDL-ESM4, IPSL, UVic). ACCESS is not included.

Specific Comments:
Line 19: I suspect that only a handful of your models had a representation of the permafrost carbon feedback (UVic, CESM2, maybe Bern?), so this statement needs a caveat.

We have excluded the northern high-latitude land sink from the abstract. The sentence now reads: "*On the other hand, the Southern Ocean remains a carbon sink over centuries after temperatures stabilize.*" We also included a new caveat paragraph in the discussion section that addresses permafrost carbon: "*Additionally, most models in our study either neglect or poorly represent permafrost dynamics (Burke et al. 2020) and often underestimate soil carbon stocks in the northern high latitudes. Permafrost thaw due to global warming has the potential to release a substantial amount of carbon stored in soil for millennia into the atmosphere over a relatively short period (e.g., Schuur et al. 2015). Therefore, CO2-fe emissions pathways that account for the release of permafrost soil carbon may differ from those shown here, potentially requiring more stringent emissions reduction to achieve the prescribed global warming levels. Future model studies incorporating permafrost soil carbon are necessary to quantify this effect and fully capture the uncertainty in land and ocean carbon-warming feedbacks.*"

Line 41: Delete 'Damon'.

Deleted.

Figure 1: Delete 'or Concentration'. This panel of the figure is clearly only represents an emissions pathway. The 'or Concentration' is just confusing.

Agree and deleted.

Line 53: 'climate-carbon feedbacks' are either part of TCRE if they are included in the ESM or are part of the 'unrepresented feedbacks' if not represented in the ESM. Delete 'climate-carbon feedbacks'.

Deleted.

Section 2.2. Should note here that the two models with the largest positive ZEC values in ZECMIP, UKESM and CNRM, did not participate in AERA-MIP.

We did not include this sentence because 4 out of the 10 ESMs participating in AERA-MIP did not participate in ZECMIP (i.e., EC-Earth3-CC, GFDL-ESM4, IPSL-CM6-LR-ESMCO2, NASA-GISS-E2-1-G-C). These models may have similarly large positive ZEC values. Adding such a statement thus appears speculative.

Line 128 to 129: Fix grammar.

Changed to: "*Ideally, more ensemble members are necessary to properly quantify the internal variability (Lehner et al. 2020).*"

Line 132 to 136: Is this due to the way non-CO2 is simulated in the radiative transfer code of ACCESS, or due to something like dynamic CH4 emissions?

We do not know the exact cause of this mismatch. This would need to be explored in future studies.

In response to Referee 3, we have now included a figure in the Appendix (Figure A3) that incorporates the ACCESS model in the multi-model mean. The new figure demonstrates that our study's results are qualitatively robust and do not depend on whether the ACCESS model is included in the ensemble statistics or not.

Line 180: Fix grammar.

Changed to: "*Further details on the configuration of the AERA simulations are provided in Appendix A*".

Line 205: I suggest not using abbreviations as variables. For consistency with your other variables C$_{AF}$, C$_{OF}$, and C$_{LF}$ would be preferable.

Changed as suggested.

Line 210: Operationally these are actually sums not integrals (just adding up the yearly or monthly values from the model output). Would be sensible just to use sum notation to not make this seem more complicated than it really is.

Following reviewer #2 suggestion, we added 'dt' to the integrals instead of using sums as suggested here.

Line 218 to 220: Fix grammar.

Changed to: "*The IPSL model temporarily leaves the 1.5°C uncertainty range, and MIROC briefly leaves the 2.0°C uncertainty range. In the 1.5°C simulation, the multi-model mean GSAT anomaly enters the target uncertainty range in 2026, i.e., the year when the first AERA period begins (black thick line in Fig. 2a)*."

Line 317 to 324: Be clear which numbers are calendar years in this paragraph.

We now write: "*..of 53 ppm in year 2025..*", "*..After year 2025..*", " *..by year 2050..*", "*..by year 2100..*", and "*..by year 2150..*".

Line 334 to 335: 'already' should go before 'exhibits'.

We removed the word 'already'.

Line 379 to 380: Be clear that you are referring to either effective-TCRE or TCRE-fe. By definition true-TCRE only includes the effect of CO2 emissions.

We clarified that we mean TCRE-fe.

Line 392: Cannot make a strong statement of significance for your collection of ESMs. Climate models are not independent, and mathematically closer to phylogenetically related (Knutti et al. 2013). Independence is a foundational assumption underlying all tests of significance. Can replace 'significant' with 'strong' or 'substantial'.

Changed to 'strong' as suggested.

Figure 6: Would be good to include a panel with the land-use change emissions used. Maybe as its own figure as land-use change is a forcing not an output of the model experiment.

The land-use change emissions are now shown in Figure 3 (previously in Appendix Figure A2a). Although, each model simulates its own land-use change emissions based on the prescribed land-use change, these emissions are not available for all models so that land use change emissions are prescribed in the AERA based on estimates from the global carbon budget (see Methods or Terhaar et al. (2022)).

Line 443 to 445: Re-write this sentence for clarity.

Changed to "*From 1850 to 2020, 294 PgC (ranging from 236 to 354 PgC) of the total cumulative CO2 emissions from fossil fuels (462 PgC) and land use change (170 PgC) remained in the atmosphere. During the same period, the ocean has taken up 173 PgC (ranging from 128 to 208 PgC), and the land absorbed 168 PgC (ranging from 79 to 254 PgC)(Table 4).*"

References:

Knutti R, Masson D, Gettelman A. Climate model genealogy: Generation CMIP5 and how we got there. Geophysical Research Letters. 2013 Mar 28;40(6):1194-9.

Sincerely:

-Andrew MacDougall