Response to Reviewer #2

GENERAL COMMENTS

In this study, a set of extended simulations under forcings equivalent to reduced and then net zero carbon emissions is generated for the CESM2 model and then these are analysed. Substantial long-term climate change signals are identified in terms of temperature and precipitation, climate variability, carbon fluxes, and ocean nutrients.

The study is comprehensive and a useful addition to the literature. I don't have any major concerns, although I have quite a few comments and suggestions below. Most of the comments are around the framing of the analysis and some overly strong inferences in my opinion.

I did think that even though a selling point of the analysis is the ensemble of simulations, much of the analysis doesn't really make the most of the large sample sizes available. This is a minor comment though and I would be keen to see follow up analyses where these simulations are used to look at climate extremes for example.

A: We sincerely thank the reviewer for evaluating our manuscript and providing a valuable number of comments and suggestions. In this study, we mainly focused on the forced changes (i.e., 10-ensemble mean) resulting from anthropogenic forcings with somewhat less emphasis on the ensemble spread and probability distribution (e.g., Fig. 2, Fig. 4, and Fig. 6). Nevertheless, we wish to emphasize that we did include analyses and interpretations on forced changes in the variability of the system, including not only ENSO timescales but also seasonal cycles of precipitation and marine sea surface pCO_2, as well as with the MJO.

To further advance our understanding of the probability distribution of the long-term mean state changes under greenhouse warming, additional analysis will be conducted and presented in future studies. Given the priorities of a scientific overview with the current study, we opted to emphasize the scientific novelty of forced changes in variability, where we have leveraged the wealth of ensemble information in the simulations. In fact, a more comprehensive analysis of climate extremes and attribution of their mean-state drivers under sustained warming is underway as a complementary publication. Additionally, we are conducting parallel research on forced changes in monsoonal behavior over multi-centennial timescales, where the probability information from the ensembles will be more exhaustively considered.

We have carefully revised the manuscript to incorporate the reviewer's comments and suggestions. Below, we present our detailed point-by-point responses (in black) to the reviewer's comments (in blue).

SPECIFIC COMMENTS

1. Line 11: The first sentence could be clearer. Maybe just "Changes in the climate system are anticipated well beyond the 21st century due to human influences." Or something similar?

A: We thank the reviewer for their comments here. We have modified the sentence as follows:

"Changes in the climate due to human influences are expected to extend well beyond the 21st century."

2. L18-19: I don't think this sentence is very helpful without more clarification on the baseline and given likely influence of high climate sensitivity on these numbers. I'd suggest a more qualitative sentence about global mean temperature and precipitation remaining elevated under net zero emissions would be more useful.

A: Following the reviewer's suggestion, we have modified the text:

"Global mean surface temperature and precipitation are projected to continue rising even after CO_2 emissions cease."

3. L23: Please define PO_4.

A: PO_4 refers to dissolved inorganic phosphate. We have revised the text to explicitly clarify this.

4. L24-26: This is a very confusing sentence that appears to try and summarise quite different findings in one. Some editing of this would be helpful.

A: We have rephrased this sentence as follows:

"The extended simulations predict substantial changes in the amplitude and timing of precipitation seasonality at the urban scale, with variations across different locations. Similarly, seasonal variations in the partial pressure of CO_2 in seawater along different latitudinal bands are projected to experience distinct changes. These findings suggest that post-2100 changes will not simply be an extension of the trends projected for the 21st century.

5. L29-30: You might want to note CMIP7 plans (van Vuuren et al., 2025) which have standard scenario runs out to 2125 and more emphasis on extensions partly in response to the issue you raise.

A: We thank the reviewer for the comment. We have added this study to the revised manuscript:

"…… protocols have been developed to extend Coupled Model Intercomparison Project (CMIP) simulations to 2500 Meinshausen et al. (2020). Very recently, scenarios for long-term extensions up to 2500 have been newly proposed for the ScenarioMIP experiments of CMIP phase 7 (ScenarioMIP-CMIP7) (van Vuuren et al., 2025). The growing interest in these extended timescales can be seen….."

6. L45-54: Santana-Falcón et al., (2023) may also be a relevant paper to use for this point, albeit with stronger mitigation than studied in this paper.

A: We thank the reviewer for bringing this study to our attention. We have included it in the relevant text of the revised manuscript (line 148 in the submitted version):

"By the end of the 25th century, the projections indicate a cumulative increase of ~17,000 ZJ, which is approximately seven times higher than the projected heat content perturbation by the end of the 21st century in the CESM2-LE (Rodgers et al., 2021). Based on the idealized and comprehensive overshoot simulations, it is noted that human-induced ocean warming and deoxygenation are altering marine ecosystems, potentially resulting in a centuries-long, irreversible loss of habitable ocean volume in the upper 1000 m (Santana-Falcón et al., 2023). A rapid growth in ocean heat content leads to considerable changes in sea ice melting, …"

7. L74-76: I think it's worth noting that there are some single model sets of simulations in existence either under constant concentrations (Dittus et al., 2024; Fabiano et al., 2023) or net zero emissions (King et al., 2024) but these are with a single simulation for a given forcing. This study is unusual

in having an initial conditions ensemble for a given scenario under net zero emissions which is a nice selling point of your paper.

A: We thank the reviewer for sharing this comment. We have added the following sentences in the revised manuscript:

"Regarding multi-centennial timescales, several stabilization experiments have been conducted, including those with constant atmospheric greenhouse gas concentrations (Dittus et al., 2024; Fabiano et al., 2024) or net-zero CO_2 emission simulations (King et al., 2024), to study climate projections under stabilized warming and the dependence on different levels of forcing. However, these experiments are based on single simulations. For this study, we have chosen to investigate forced changes in the climate system out to the year 2500 by extending 10 members of the 100-member Community Earth System Model 2 large ensemble….."

8. L104-105: Could you clarify whether the simulations are run in emissions or concentration-driven mode? I'm assuming the extensions beyond 2100 are emissions driven but it's not as clear as it could be. It's also not clear if the SSP3-7.0 simulations are emissions or concentration driven. You might interested in Sanderson et al., (2024) that discusses the merits of emissions-driven simulations.

A: We thank the reviewer for pointing this out. Our simulations are concentration-driven, meaning the greenhouse gas concentrations (defined as dry air mole fractions) from historical observations and the SSP3-7.0 scenario were prescribed throughout the entire simulation period (e.g., for CO_2, atmospheric CO_2 mole fraction is specified directly from 1850 to 2500). We have clarified this point in Section 2. We also added the study that the reviewer pointed out:

"Meinshausen et al. (2020) provided greenhouse gas concentrations, defined as dry air mole fractions, for both standard and extended SSP scenarios. They used the reduced-complexity climate-carbon-cycle model MAGICC7.0 ('Model for the Assessment of Greenhouse Gas Induced Climate Change') to produce future greenhouse gas concentrations driven by harmonized SSP greenhouse gas emissions (Gidden et al., 2019) and extended emissions beyond 2100. To extend the CESM2-LE from 2101 to 2500, we followed the extended SSP3-7.0 protocol, a concentration-driven configuration. In this extended scenario, fossil and industrial CO_2 emissions are effectively ramped down to zero by 2250 (Meinshausen et al., 2020), as shown in Fig. 1a. Figure 1b presents the time evolution of global mean greenhouse gas mole fractions (CO_2, CH_4, N_2O, and CFCs) which are prescribed in these simulations under the historical (1850-2014), standard SSP3-7.0 (2015-2100) and extended SSP3-7.0 (2101-2500) scenario forcings. The global mean atmospheric CO_2 mole fraction at the end of the 25^{th} century, as provided by the extended SSP3-7.0 scenario, is approximately 1371 ppm."

9. Figure 1c,d: I assume the red lines are observations? In c it doesn't look like you're plotting anomalies from the observational period but the caption suggests you are.

A: We have modified the caption of Fig. 1 as follows:

"Figure 1: Time series of global mean (a) fossil fuel and industrial CO_2 emissions and (b) greenhouse gas mole fractions over 1850-2500 for the CESM2-LE extension simulations. Values are taken from Meinshausen et al. (2020). Time series of global fields over 1850-2500 for 10 ensemble members for (c) top-of-atmosphere radiative imbalance (W m^{-2}) along with the CERES-EBAF product (red) (Loeb et al., 2018; Loeb et al., 2009) and (d) anomalies of global mean surface air temperature (°C) along with HadCRUT4 (red) (Morice et al., 2012). In (c) and (d), bold lines represent ensemble means, and dark and light shading represent 1 standard deviation (SD) and 2 SD variability. In (d), observed and simulated temperature anomalies are calculated with respect to the period spanned by the observations (period 1950-2019).

10. L149-153: Could you clarify if this is annual-average sea ice extent? Of course, there are strong seasonal cycles and you are likely reaching "ice free" conditions at some times of the year. I'm wondering if this might be contributing to the decreased ensemble spread shown in Figure 2.

A: In Fig. 2, we considered the annually averaged fields, as clarified in the figure caption in the revised manuscript. Figure R1 shows the sea ice extent for the Arctic and Southern Ocean. The Arctic sea ice extent in March (maximum) is projected to decline sharply after 2100, with reduced ensemble spread after the mid-22^{nd} century. This indicates that the sea ice decline will be pronounced across all ensemble members, contributing to the decrease in ensemble spread of the annual mean sea ice extent after the mid-22^{nd} century. Additionally, the Arctic sea ice extent in September (minimum) shows little variation after the mid-21^{st} century, with nearly all ensemble members predicting ice-free conditions, further reducing the ensemble spread. Similarly, in the Southern Ocean, the transition to ice-free conditions in March across all ensembles after 2100 may also contribute to the reduced ensemble spread in the annual mean sea ice extent after the 21st century, relative to the period 1850-2100.

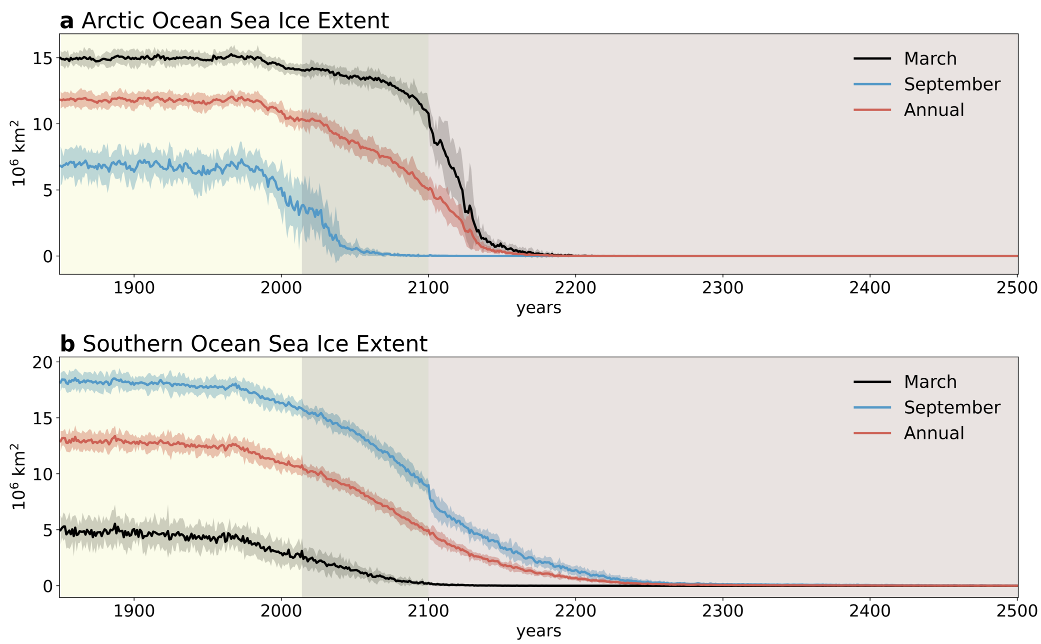

Figure R1: Sea ice extent (10^6 km^2) for the (a) Arctic and (b) Southern Ocean. Bold lines represent ensemble means, and shadings represent 2 standard deviation variability.

11. L153-156: Could note that in ZECMIP the AMOC projections are highly model dependent and diverse (MacDougall et al., 2022).

A: We have added the following sentence following the reviewer's suggestion:

"However, it is noted that in the idealized experiments of the Zero Emission Commitment Model Intercomparison Project (ZECMIP), some models indicate AMOC strengthening, while others predict a continued decline after 50 years of CO_2 emissions cessation, illustrating the model dependency of future AMOC projections (MacDougall et al., 2022)."

12. L208-210: These are certainly alarming amounts of global and local warming which should be highlighted. I think it is worth noting though that CESM2 has quite a high ECS (Gettelman et al., 2019).

A: We thank the reviewer for the suggestion. We have addressed this point and added the suggested reference (line 113 in the submitted version of the manuscript).

13. L222-239: It could be noted that the precipitation changes are likely to be quite model dependent but increases at high latitudes in Southern Hemisphere are likely also associated with the warming in the region (Grose & King, 2023).

A: We have added the text as follows:

"The projected precipitation changes over the southern mid-latitudes and the Southern Ocean are expected to be linked to both Southern Ocean warming and the resulting meridional temperature gradient reduction between the tropics and the Southern Ocean (Grose and King, 2023)."

14. Figure 4h: Title is a bit confusing because I think this is precipitation variability? In general figure 4 could be improved as some axis labels are missing and some colour bar labels may lead to misinterpretation.

A: The title in Fig. 4h is "Niño3.4 precipitation variability". Additionally, following the reviewer's comment, we have modified Fig. 4:

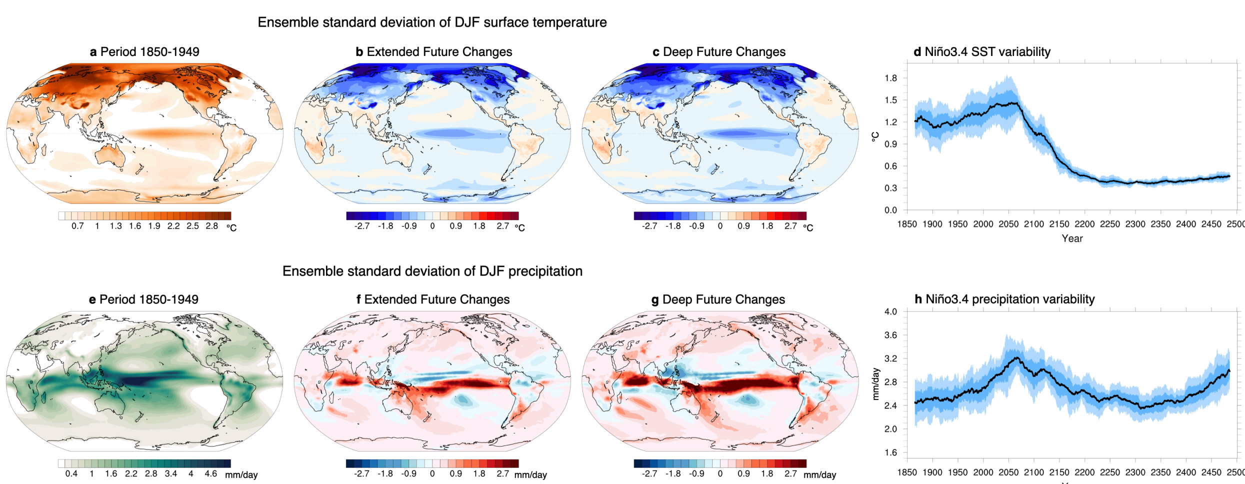

Figure 4: Time-averaged across-ensemble standard deviation of the boreal winter (DJF) mean (a) surface temperature (°C) and (e) precipitation (mm day^{-1}) over the period 1850-1949. Future changes of the standard deviation values of (b, c) surface temperature and (f, g) precipitation over the period 2150-2249 and over the period 2401-2500, respectively, relative to 1850-1949. These calculations involve first determining the standard deviation across all ensemble members for the same time period, followed by averaging across time. (d, h) 30-year running standard deviations of monthly Niño3.4 SST and precipitation, respectively.

15. L269-285: The projected changes in MJO are indeed very interesting. I would caution that the interpretation could be a bit more understated given this is a single model result. Certainly this finding should motivate related analysis with other models.

A: We thank the reviewer for their comment here. We understand the reviewer's concerns regarding the interpretation based on results from a single model. In response, we have added the following sentences at the end of Section 3.1 in the revised manuscript:

"Although our study provides valuable insights, the results should be interpreted with caution due to the limitations of using output from a single Earth system model to represent long-term changes in climate variability. Therefore, further investigations utilizing simulations from multiple Earth system models would be highly beneficial in identifying areas of general consistency across models, as well as potential areas of substantial disagreement."

16. L310-312: I can see why this sentence is included but it reads like a non-sequitur, and I think is unnecessary.

A: We have deleted the sentence in the revised manuscript.

17. L375: ZECMIP studies with a carbon cycle focus may be worth citing here too (e.g MacDougall et al., 2020).

A: We have added the appropriate reference to this study. We thank the reviewer for this suggestion.

18. L389-390: This answers my earlier question. This is a fairly large caveat to some of the analysis which should be noted earlier in the Data and Methods section.

A: As mentioned earlier, our simulations are concentration-driven. We have clarified this point in Section 2. We kindly suggest that the reviewer refer to our response to comment #8 for further clarification.

19. Figure 10: Given the same colour scale is used throughout it would look better to have a single larger colour bar.

A: Thank you for the suggestion. We have modified Fig. 10 in the revised manuscript.

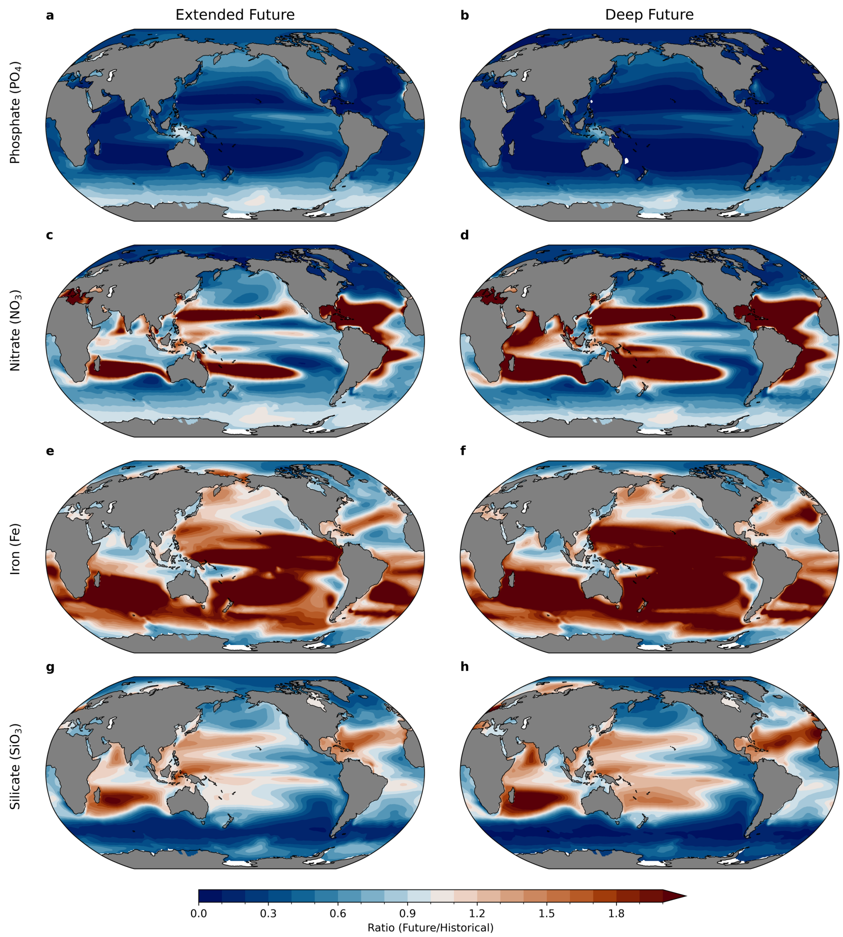

Figure 10: The changes in the future period 2150-2249 (first column) and period 2401-2500 (second column) relative to the historical period 1850-1949. (a, b) PO_4 (mmol m^{-3}), (c, d) NO_3 (mmol m^{-3}), (e, f) Fe (mmol m^{-3}), and (g, h) SiO_3 (mmol m^{-3}). The changes were calculated as the ratio of the future to historical period. Blue (<1.0) and red (>1.0) indicate future decreases and increases, respectively, relative to the historical period. All values are averaged over the upper 100 m depth.

20. L555-562: Similarly to a previous comment, the wording here is a bit over-confident given the results are derived from a single model.

A: We thank the reviewer for pointing this out. We have made efforts to avoid making overly strong or forceful statements throughout the text. Additionally, in the last paragraph of Section 4 Summary and Discussion, we have added the following sentences:

"The Earth System is currently on a Hothouse Earth trajectory driven by human-induced greenhouse gas emissions (Steffen et al., 2018). Our simulations project climate states that are well outside the range of what humans have thus far experienced, making it challenging to present the astonishingly broad range of large impacts under sustained anthropogenic perturbations. We emphasize that our study aims to provide a comprehensive overview of these important changes. Given the considerable uncertainty in future decisions regarding anthropogenic emissions, we do not intend to suggest that the climate changes projected in our simulations are likely pathways for the evolution of climate states. However, our simulations may serve as a crucial illustration of a potential future that we should strive to avoid. A novel aspect of our simulations lies in the presentation of not only mean state changes but also of shifts in the variability of the Earth system across diverse temporal and spatial scales under the influence of strong anthropogenic forcing. Furthermore, we anticipate that the ensemble framework analyses presented here can contribute a foundational step toward understanding the mechanisms that can impact multi-century climate-carbon feedbacks. Further complementary simulations, as well as emission-driven scenarios (Sanderson et al., 2024), are needed to explore these potential feedbacks more thoroughly. Although the future climate projections are……"

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