Review of "Asymmetry in carbon cycle feedbacks and transient climate response under positive and negative CO$_2$ emissions" by Chimuka and Zickfeld

The authors present novel simulations with an Earth system model of intermediate complexity, that allow to determine the asymmetry of carbon cycle feedbacks and TCRE/TCRR under positive and negative emissions. They investigate the rate and state-dependency of their results with additional simulations. They find large asymmetries in all of the metrics investigated and a clear rate-dependance. The manuscript is well written, the experimental design is novel and very relevant to address some of the knowledge gaps surrounding carbon dioxide removal (CDR). I did not find any major problems with the manuscript, and I would recommend publication in Biogeosciences after a few comments and suggestions have been addressed by the authors.

We thank the reviewer for their positive comments.

General comments:

I was a bit disappointed about the discussion related to a comparison of results to the previous study by Chimuka et al. (2023). The authors use only two short sentences on this, stating that the results are inconsistent. Given that the same model was used by the same authors, I would have been curious to learn more. Particularly, since I believe that the setup of Chimuka et al. 2023, i.e. running a zero-emission simulation as a reference to single out the committed changes from previous positive emissions, is much better suited for multi-model studies with full ESMs. I agree that the set-up with a 2x-CO2 reference state used in the present study is a very clean experimental design, but I doubt that CMIP modelling groups will be willing to do a full >1000 year spinup at 2xCO2 as a prerequisite for these experiments. Therefore, it would be extremely valuable to learn more about the reason why the results from these two kinds of experiments are different, and I would encourage the authors to add a more details on this in the Discussions section.

We thank the reviewer for this key point. We can see the importance of building on previous frameworks, especially when the framework (Chimuka et al. 2023) is easier to reproduce in ESMs. We have, therefore, included additional discourse in the discussion comparing this framework to that from Chimuka et al. (2023) to highlight the differences between the two frameworks and included the text below:

4 Discussion

Carbon cycle feedbacks under negative emissions have previously been quantified from CDR reversibility simulations (CDR-MIP: Keller et al., 2014), in which a phase of CO$_2$ decline (negative emissions) immediately follows a phase of CO$_2$ increase (positive emissions). In these studies, the magnitudes of both feedbacks are smaller under negative emissions because of climate system inertia (Schwinger et al., 2018; Chimuka et al., 2023). Although other studies using preindustrial as the reference year for quantifying feedbacks under negative emissions

show that both feedbacks become larger under negative emissions, they also show the same lagged carbon pool response (Melnikova et al., 2021; Asaadi et al., 2024). Chimuka et al. (2023) proposed an approach to correct for climate system inertia using zero emissions simulations. Compared to the framework used here, there is a difference in the initial state, the range of CO_2 concentration, configuration of simulations, and linearity assumptions, and these differences have various implications. First, feedbacks are smaller under positive emissions here than in Chimuka et al. (2023) because the initial state here is higher. At a higher initial state, the sinks are more saturated, and therefore, the sink sensitivity to changes in CO_2 concentration and the temperature response to a given CO_2 concentration are both smaller. Second, although the CO_2 concentration change in both frameworks is the same (~280ppm), carbon fluxes and pools exhibit different magnitudes of asymmetry due to different ranges of CO_2 concentration in the two frameworks. In this study, the two symmetric simulations span CO_2 concentrations between $2xCO_2$ to $1xCO_2$ and $2xCO_2$ to $3xCO_2$, whereas, in Chimuka et al. (2023), the range of CO_2 concentrations is between $1xCO_2$ and $2xCO_2$. As a result, the two frameworks exhibit different magnitudes of temperature asymmetry and non-linearities in net primary productivity, soil respiration, buffer capacity and the solubility pump resulting in differences carbon cycle asymmetries.

After correcting for inertia, Chimuka et al. (2023) found a larger climate-carbon feedback and smaller concentration-carbon feedback under negative emissions, whereas we find a smaller climate-carbon feedback and larger concentration-carbon feedbacks under negative emissions. The two studies point to opposite signs of asymmetry due to comparison to different magnitudes of feedbacks under positive emissions as aforementioned. Furthermore, when feedbacks here are compared to those from the ramp-up phase of the CDR-reversibility simulation (we have added a new Section 3.4 on this), results are slightly more consistent with Chimuka et al. (2023): we find larger land feedbacks parameters and smaller ocean feedback parameters under negative emissions. Despite discrepancies in sign of asymmetry, our results are qualitatively consistent with Chimuka et al. (2023): feedbacks under negative emissions are larger in our approach than in the standard CDR-reversibility approach. The difference is, however, the extent to which feedbacks are larger. The inertia-corrected feedbacks from Chimuka et al. (2023) are larger than our feedbacks under negative emissions due to limitations in the correction approach, such as unsatisfied linearity assumptions, irreversible vegetation shifts and different simulation configurations (concentration-driven CDR-reversibility simulations and emissions-driven zero emissions simulations), which result in over- or underestimation of the carbon cycle inertia. The benefit of the novel approach used in this study is that it eliminates climate system inertia by prescribing both CO_2 trajectories from the same equilibrium state, allowing for a more accurate quantification of carbon cycle feedbacks under positive and negative emissions.

I was also a bit confused about the definition of the sign of asymmetry. I would suggest to help the reader by including a definition in terms of an Equation. Also, currently, the definition is

somewhat hidden in section 3.2.1. I would suggest to move the definition to the beginning of section 3.2 (also since it applies to both land and ocean).

We have now added a definition of asymmetry in equation form in the Methods in Section 2.3.4 and included it below. We also include a reminder at the beginning of the land and ocean carbon asymmetry sections.

2.3.4 Determining the sign of asymmetry

As aforementioned, all metrics were computed under positive and negative emissions and compared to determine the magnitude and sign of asymmetry. The sign of the asymmetry was determined as follows:

Where 'X' denotes β_L, β_O, γ_L, γ_O, TCRE or TCRR under positive ('pos') or negative ('neg') emissions:

[13]
$$asymmetry = \ X_{neg} - X_{pos}$$

Therefore, the asymmetry is positive (negative) when a given metric is larger (smaller) under negative emissions.

Specific comments:

line 129-130: "that cannot yet be achieved in the real world" This sounds as if the authors would be confident that these levels of negative emission could be achieved in the future. I'm not sure this is intended, and I would suggest to reword this sentence.

We agree – that was not the intended meaning. We have clarified this in the text by removing the word "yet".

line 160 and 164: "twice the preindustrial CO_2 concentration for both simulations" This doesn't hold for the 3xCO_2 and 4xCO_2 simulations, so maybe better "the CO_2 concentration of the respective equilibrium state from which the simulations were branched off" or similar?

Corrected as suggested.

line 203-204: "However, this warming is considered negligible in this feedback framework". Arora et al. 2020 and Asaadi et al. 2024 (both cited) have looked at the assumption $\Delta T_{BGC}=0$ and found that the effect is indeed relatively small.

These citations have now been added.

Equations 7 and 8: I guess $\Delta T_{BGC}=0$ is assumed also here, too (as in Equations 3 and 4)? I would suggest to adjust Equations 7 and 8 accordingly to not confuse the reader.

We have included a note to clarify that $\Delta T_{BGC} = 0$.

lines 238-239: "All changes in variables were calculated relative to the $2xCO_2$ (twice the preindustrial CO_2 concentration) equilibrium state." See my comment above, this doesn't hold for the 3x and $4xCO_2$.

Corrected.

line 261-262: The logarithmic relationship is not only used by UVic, but widely used in climate sciences (Myre et al. 1998; Etminan et al. 2016).

Cited. We thank the reviewer for these references.

line 345: Here you could in addition cite Schwinger et al. 2014 (which is already cited before, note that it is missing in the list of references)

We have added the citation and included the reference in the bibliography.

line 355-361: This paragraph is largely repetition of what has been said before for the FULL, because the difference between FULL and BGC is so small. I would suggest to shorten this.

We thank the reviewer for pointing this out. We have shortened this paragraph to the key differences between FULL and BGC.

line 373: Delete "land" before "climate-carbon feedback"

Deleted.

lines 388-389: I cannot follow this argument. A larger temperature change under negative emissions means that the land and ocean carbon cycle have actually seen these colder temperatures. A smaller gamma means that land and ocean have reacted less to this cooling per degree of cooling compared to warming. I do not see that the way of calculating would "favour a smaller gamma under negative emissions". Please double check this logic.

We thank the reviewer for this comment. The land (ocean) carbon changes in the positive and negative RAD emissions are small and comparable in magnitude, and therefore, the key differentiator in the magnitude of gamma for land (ocean) is the asymmetry in the temperature response. We have changed the wording to make this clearer.

line 396: The results on the rate dependency (for positive emissions) are consistent with the early results of Gregory et al. 2009 (cited), this could be mentioned.

We have now cited Gregory et al., 2009.

line 405: As far as I can see from Fig. S1.3 is at least the sign of the asymmetry the same for both land and ocean across all equilibrium states?

This is correct. We have now clarified this in the manuscript.

line 474: The correct reference is "Schwinger and Tjiputra (2018)"

Corrected.

line 504: Isn't the sign of the asymmetry robust, as seen from Fig. S1.3?

This is correct. We have now clarified this in the manuscript as well.

References:

Etminan, M., G. Myhre, E. J. Highwood, and K. P. Shine (2016), Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing, Geophys. Res. Lett., 43, 12,614–12,623, doi:10.1002/2016GL071930.

Myhre, G., E. Highwood, K. Shine, and F. Stordal (1998), New estimates of radiative forcing due to well mixed greenhouse gases, Geophys. Res.Lett., 25(14), 2715–2718, doi:10.1029/98GL01908.