Our responses are in black, marked as **[Response]**, and the comments of the Reviewers are in purple, marked as **[Comment]**. In our responses, we mark the changes in the manuscript with shading and separate comments using “***********”.

Reviewer #2 (Remarks to the Author):

This study compares the climate and carbon cycle response to equivalent CO2 and non-CO2 forcings using a set of idealized concentration-driven simulations. The authors find that the climate-carbon feedback is dominant under non-CO2 forcing whereas both the carbon-concentration and climate-carbon feedbacks are important under the CO2 forcing. Under both CO2 and non-CO2 forcings, the land and ocean carbon uptake due to both feedbacks is quantified along with a cross term i.e., a term that quantifies the response to climate change in the presence of CO2 concentration.

The manuscript reads well – the introduction and methods are written clearly and are easy to follow. My main concern is that the paper does not provide enough background to help the reader understand the results, particularly with regards to the meaning and calculation of the cross term, which is discussed at length in the results section. I suggest an expansion of the introduction section to include: (1) more background on previous non-linearity studies (2) and studies that previously quantified the cross term (if any). Furthermore, an addition to the methods section of: (1) the carbon cycle feedback framework (β, γ) and (2) the meaning of the cross term and how it is calculated under CO2 and non-CO2 forcing.

[Response]

We thank the Reviewer for taking the time to read the manuscript and provide detailed and insightful comments that helped to improve the manuscript.

In response to the concern of the Reviewer as to the lack of background of the study, we expanded the Introduction to have a paragraph on the feedback nonlinearity and existing studies that investigate and quantify nonlinearity.

The weakening of land and ocean carbon sinks due to non-CO_2 GHGs underscores the importance of understanding the differences in carbon cycle feedbacks between CO_2 and non-CO_2 GHGs. Only the changes in CO_2 concentrations are associated with the carbon-concentration (β) feedback, that is the response of the land and ocean carbon uptake to the changes in CO_2 concentration, mainly via the stimulation of photosynthesis through CO_2 fertilisation effect over land and the solubility pump over the ocean. The changes in both CO_2 and non-CO_2 concentrations are associated with the carbon-climate feedback (γ), that is the response of the land and ocean carbon uptake to climate change, mainly via the increased plant and soil respiration over land and reduction of the CO_2 solubility in the ocean with warming (Arora et al., 2013; Schwinger et al., 2014; Zickfeld et al., 2011). Under changing CO_2 concentrations, land and ocean carbon storages are simultaneously exposed to the carbon-concentration and carbon-climate feedbacks. However, the interaction between these feedbacks can introduce a non-linearity in the system, whereby the combined effect is not simply the sum of individual feedbacks. Thus, temperature-mediated feedback can differ under changing versus constant CO_2 levels, an important distinction when comparing CO_2 and non-CO_2 GHG feedback mechanisms. Here, it is also important to acknowledge that other factors, such as time lags and potential irreversibilities in the climate system, may also contribute to these differences (Boucher et al., 2012; Chimuka et al., 2023; Schwinger et al., 2014).

Previous studies investigated the nonlinearity in the carbon cycle feedback and revealed that the nonlinearity, or the cross term, may be comparable in size with γ (Schwinger et al., 2014; Zickfeld et al., 2011). They attributed the nonlinearity to the different responses of the land biosphere to the temperature changes, depending on the presence or absence of the CO_2 fertilisation effect, as well as the weakening of ocean circulation and mixing between water masses of different temperatures. However, these studies did not consider non-CO_2 GHGs.

We also expanded the subsection “2.3 Carbon cycle feedback attribution” of the Methods to have more detailed and clear information about the carbon cycle feedback framework and the cross term.

Traditionally, carbon cycle feedback analysis relies on [CO_2], [CO_2bgc] and [CO_2rad] simulations (Arora et al., 2013, 2020; Friedlingstein et al., 2006; Gregory et al., 2009; Schwinger et al., 2014; Schwinger and Tjiputra, 2018; Williams et al., 2019; Zickfeld et al., 2011). The carbon uptake (ΔU) can then be estimated using the well-established carbon cycle feedback framework as a sum of carbon-concentration β parameter (GtC ppm^{-1}) multiplied by the changes in the atmospheric CO_2 concentration ΔC_{CO2} (ppm) and carbon-climate γ feedback parameter (GtC K^{-1}) multiplied by the changes in surface temperature ΔT (K), using Eq. (1):

$$\Delta U = \beta \times \Delta C_{CO2} + \gamma \times \Delta T + \varepsilon\ . \tag{1}$$

Here, term ε refers to a residual term.

The β parameter can be estimated from the [CO_2bgc] - [piControl], using Eq. (2):

$$\beta = \frac{\Delta U_{BGC}}{\Delta C_{CO2}}, \tag{2}$$

where ΔU_{BGC} is the carbon uptake in the biogeochemically-coupled experiment [CO_2bgc]. The β feedback is associated with strengthening of the land and ocean carbon sink (positive to the land and ocean). Thus, it acts as negative climate feedback (decreasing CO_2 content and dampening climate change).

Existing studies derived the γ feedback from the [CO_2rad] - [piControl] combination of experiments, using Eq. (3), as well as from the difference between the [CO_2] and [CO_2bgc] experiments, hereafter referred to as [CO_2] – [CO_2bgc], using Eq. (4) (Arora et al., 2013, 2020; Asaadi et al., 2024; Friedlingstein et al., 2003, 2006; Melnikova et al., 2021):

$$\gamma = \frac{\Delta U_{RAD}}{\Delta T}, \tag{3}$$

$$\gamma = \frac{\Delta U_{COU-BGC}}{\Delta T}, \tag{4}$$

where ΔU_{RAD} and $\Delta U_{COU\text{-}BGC}$ are the carbon uptake in the radiatively-coupled experiment [CO_2rad] and the difference between the COU and BGC experiments [CO_2] – [CO_2bgc]. The γ feedback is associated with a weakening of the land and ocean carbon sinks globally, albeit with regional variability (negative to the land and ocean). Thus, it acts as positive climate feedback (increasing CO_2 content and accelerating climate change).

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Minor comments

A few minor comments are included below:

[Comment 1]

L19: I suggest using the term ‘climate-carbon cycle feedback’ instead of temperature-driven feedback, since that is the terminology most used in the field.

[Response]

We agree and changed the term to “carbon-climate feedback” to be consistent with existing studies (e.g., Arora et al., 2013; Schwinger et al., 2014).

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[Comment 2]

L20: Is this sentence correct? From my understanding, the CO2 forcing drives both carbon cycle feedbacks through changes in CO2 concentration and temperature, whereas the non-CO2 forcing drives the climate carbon cycle feedback only through changes in temperature. Please clarify.

[Response]

This indeed was erroneous (should be the other way round), now corrected.

CO_2 forcing affects both carbon-climate and carbon-concentration feedbacks, whereas non-CO_2 gases influence only the carbon-climate feedback.

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[Comment 4]

L38: Acronym ‘GHG’ not introduced - I suggest writing greenhouse gas in full here.

[Response]

Added.

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[Comment 5]

L50: Please specify which forcing components were included in the Richardson et al. (2019) study. If the study included the response to CO2 and non-CO2 forcing, I suggest briefly discussing the results from this study in your introduction section, and if possible, comparing these results to your results in your discussion section.

[Response]

We add clarification, now the text reads as follows.

Richardson et al. (2019) revealed spatial and temporal differences in the surface temperature response to different forcings, such as CO_2 and CH_4, in part due to the physiological CO_2 warming over the densely vegetated regions that is absent under non-CO_2 forcing.

Our findings are consistent with Richardson et al. (2019), which we briefly acknowledge in the revised manuscript.

When comparing CO_2- and non-CO_2-induced forcing ([CO_2] and [nonCO_2] experiments) at a global scale, our results are consistent with Richardson et al. (2019) who show the higher surface temperature response of CO_2 when compared to CH_4.

****

[Comment 6]

L58: This may be a good point to link non-CO2 forcing to the climate-carbon cycle feedback.

Non-CO2 forcing induces warming => capacity of the land and ocean sinks reduces => atmospheric CO2 concentration and temperature affected. It may also help to explain why the non-CO2 concentration-carbon feedback is not relevant.

[Response]

We are grateful for this suggestion. Following the Reviewer's comment, we added a linkage of non-CO_2 forcing to the climate-carbon cycle feedback to the Introduction as described in our response to the main comment.

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[Comment 7]

L60: It may help readers to preface this paragraph with a brief description of how the two carbon cycle feedbacks work under increasing and decreasing CO2 concentrations. This will make it easier to understand L62 where you state the results from your Melnikova et al. (2021) study.

[Response]

We agree and added a brief description as follows.

Previous studies have also examined the impact of declining atmospheric CO_2 concentrations on the climate and carbon cycle (Boucher et al., 2012; Chimuka et al., 2023; Jones et al., 2016; Koven et al., 2023; Melnikova et al., 2021; Schwinger and Tjiputra, 2018). During the period of decreasing atmospheric CO_2 concentrations and temperature (ramp-down), the β and γ feedbacks are influenced by both the reduction of CO_2 levels and temperature and the inertia of the carbon cycle—specifically, the altered land and ocean carbon pools resulting from prior increases in the CO_2 concentrations and temperature (Chimuka et al., 2023; Zickfeld et al., 2016).

****

[Comment 8]

L69-71: This sentence is too long. For clarity, please separate the two research questions using (1) and (2) or a semi-colon.

[Response]

We followed the Reviewer's suggestion by moving "carbon cycle responses" to the first question and focusing on the nonlinearity feedback in the second research question.

The purpose of this study is twofold:

- to clarify whether the climate and carbon cycle responses to declining CO_2 and non-CO_2 GHGs differ globally and regionally
- to investigate the carbon cycle nonlinearity feedback under CO_2 and non-CO_2 GHG decrease, and the different implications for climate change mitigation.

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[Comment 9]

L81: Please clarify which climate factors you are referring to here.

[Response]

Following specific comment 5 of Reviewer #1, we removed this paragraph on the study's approach limitations, just keeping part of it in the discussion section. Thus, this sentence has now been deleted. We keep justification of the use of IPSL-CM6A-LR with the following text.

However for this study, the use of the model is justified because current changes in CH_4 and N_2O concentrations are primarily driven by anthropogenic sources, suggesting that the absence of interactive modules of natural sink/source processes does not significantly affect the representation of natural variability trends for the CH_4 and N_2O concentration (Nakazawa, 2020; Palazzo Corner et al., 2023; Zhu et al., 2013).

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[Comment 10]

L120: From my understanding of the table format, experiments are above the horizontal line, while combinations of experiments are below the horizontal line. This is why I am surprised that the [CO2bgc+non-CO2] experiment is above the line. Is this an experiment or an addition of two separately run experiments? If it is indeed an experiment, then I assume you prescribed both CO2 forcing and non-CO2 forcings, then specified the piControl CO2 concentration in the radiation code? If so, that would mean that the only warming seen in that experiment would be CO2 physiological warming, so how then can non-CO2 γ be included in this experiment? Please clarify.

[Response]

This understanding is correct, this was indeed an experiment. We prescribed the piControl CO_2 concentration and varying non-CO_2 (CH_4 and N_2O) concentrations in the radiation code. Thus, the non-CO_2 radiative and CO_2 physiological (negligible) forcings caused the warming. This is consistent with our original description in the table. We added a clarifying sentence to the section on Experiment design.

Additionally, an experiment that combines nonCO_2 radiative forcing with CO_2 physiological forcing [CO_2bgc + nonCO_2] allows for the comparison of nonlinearities arising from combined carbon-concentration feedback and CO_2- and non-CO_2-driven carbon-climate feedback ([CO_2bgc + nonCO_2]). It serves as the nonCO_2 counterpart of the [CO_2] experiment.

****

[Comment 11]

On the same note, is the additional combination [CO2bgc+non-CO2]-[CO2bgc] necessary? It looks like we could get at non-CO2 γ by taking the difference between [CO2+non-CO2] and [CO2] and this would give the cross term as well. Is there a benefit to using [CO2bgc+non-CO2]-[CO2bgc] over [CO2+non-CO2]-[CO2]?

[Response]

The Reviewer is correct that non-CO2 γ may be derived either from [CO2bgc+non-CO2]-[CO2bgc] or from [CO2+non-CO2]-[CO2], with both combinations involving two experiments. However, there are at least two benefits of using [CO2bgc+non-CO2]-[CO2bgc]. Firstly, it is consistent with deriving γ_{CO2} and χ_{CO2} terms from [CO2]-[CO2bgc], because both combinations subtract the BGC component from an experiment that has β, γ and χ. Secondly, using [CO2+non-CO2]-[CO2] would lead to a using an experiment with nearly doubled warming level ([CO2+non-CO2]), that would affect the value of cross term χ (probably by overestimating it).

****

[Comment 12]

In the 4th column, the first two combinations of experiments seem to be missing the ΔU! components.

[Response]

Thank you, this is now corrected.

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[Comment 13]

Figure 1: I would like to commend the authors on this figure – it complements the methods section very nicely.

[Response]

We sincerely thank the Reviewer.

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[Comment 14]

L146: Section 3.1 assumes that readers have a solid grasp of the carbon cycle feedback framework and the feedback parameters (β, γ) used, which may not be the case. I suggest prefacing this section with a brief description of carbon cycle feedback parameters (equations for quantification, units and sign convention) before introducing ΔU.

[Response]

We added a paragraph with a brief explanation on the β, γ quantification, units and sign convention, as suggested (although not before but after introducing ΔU), as described in our response to the Reviewer's main comment.

****

[Comment 15]

L184: I suggest citing Zickfeld et al. (2011) here.

[Response]

Thank you for bringing up this study that we had missed. The refence has now be added together with some other relevant publications that we also missed in the original manuscript (Arora et al., 2013; Schwinger et al., 2014). We also added references to Zickfeld et al. (2011) in several other places in the revised manuscript (e.g., in the new paragraph in the Introduction about existing studies on nonlinearity of carbon cycle feedbacks).

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[Comment 16]

Figure 2: Is the last column of panels on Figure 2 necessary? I notice that these figures are hardly referenced.

[Response]

We agree and removed the last column of Figure 2.

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[Comment 17]

Also, I suggest using a different colour for either the CO2 or CO2bgc lines? The two are compared several times in the text but the colours are difficult to distinguish on the figure panels.

[Response]

We changed the colour of [CO_2] from orange to deep pink for a better distinction.

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[Comment 18]

L219: What is the reason for the higher sensitivity to non-CO2 forcing than CO2 forcing?

[Response]

We apologize for the confusion in text, as it should be opposite, i.e., higher sensitivity of CO_2 forcing compared to non-CO_2 forcing. We made the correction and added a clarification for the reason as follows.

Our results are consistent with Nordling et al. (2021) who show the higher effective temperature response for CO_2 forcing compared to non-CO_2 forcing, attributing it to the changes in clear-sky planetary emissivity.

****

[Comment 19]

L262: It appears that the figure in the paper referenced – Chimuka et al. (2023) – shows little hysteresis in autotrophic respiration and GPP, and not in heterotrophic respiration as mentioned in the text.

[Response]

This is indeed true, we misread the paper. We now removed the sentence.

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[Comment 20]

L283-284: Are there merits to attributing the cross term to γ rather than keeping it as a separate term?

Keeping the legacy of previous studies is probably the biggest merit. However, considering the implications of the carbon cycle framework for nonCO_2 scenarios, it is more accurate to keep the cross-term as a separate feedback term. Following encouragement from Reviewer #1, we introduced the new symbol χ for the cross-term and divided the original "Carbon-Climate Feedback" section into two parts, creating a new section titled "Nonlinearity in Carbon Cycle Feedback."

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