Carbon-climate feedback higher when assuming Michaelis-Menten kinetics of respiration

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<u>Referee # 1, William Wieder</u>

Beer uses a reduced complexity model to look at different formulations of a land ecosystem respiration term that uses first order vs. Michaelis-Menten kinetics (FOK and MMK, respectively). The paper reports a stronger land C uptake with the Michaelis-Menten parameterization. The manuscript is a nice, albeit unsurprising, illustration of structural uncertainty in land models and how they impact the magnitude of the terrestrial C sink and potential carbon-cycle climate sensitivities.

I like the work, but feel some additional information and clarification is needed to make the findings more straight forward to understand / interpret.

I would like to thank you for reading carefully this manuscript and for your helpful and constructive questions and suggestions that helped to improve the manuscript.

Mainly. I'm a little fuzzy about the use of the term carbon-climate feedback here, which seems analogous to the gamma term in the C4MIP literature (e.g. Arora et al 2020; typically expressed as PgC per degree Celsius). With this convention, gamma_land is typically negative (from the atmosphere perspective), reflecting less land carbon storage under warmer conditions.

The carbon–climate feedback (γ) quantifies the response of the carbon cycle to changes in physical climate and is expressed in units of carbon uptake or release per unit change in global mean temperature (PgC ℃−1).

Conceptually, this looks similar to the left side of Fig 1, which focuses on positive feedbacks between temperature, ecosystem respiration and atmospheric CO2 burden. The rest of the results, however, don't share this perspective, which makes the conclusion (and title) confusing.

Thank you very much for this comment which shows that I need to explain the definition of the metrics used to quantify the carbon-climate feedback in more detail. I will add equations to the text in section 2.3 and hope this increases the clarity. Note, there was a clear mistake in the calculation of the feedback and the feedback factor before as has been noted by the other reviewer.

Confusion can occur because sometimes terms are used in short in the literature. According to the IPCC definition, a climate feedback is an interaction in which a perturbation in one climate quantity (here atmospheric CO2 content) causes a change in a second and the change in the second quantity ultimately leads to an *additional* change in the first due to mechanisms internal to the system. In our case of biogeochemical feedbacks, the feedback is the *additional* change in CO2 after its perturbation due to internal system mechanisms. We start with pre-industrial CO2 content and add anthropogenic CO2 until 2100. Then, we can measure the temporal difference as Delta_CO2. Due to feedbacks, this difference is not pre-industrial CO2 plus the sum of emissions ("ΔCO2 off" in the revised manuscript), but there is a difference which we call feedback f in units of mass of C (Hansen et al., 1984; Lade et al., 2018; Zickfeld et al., 2011) In addition, one can compute the ratio of both temporal CO2 changes, with and without feedback, which is called the feedback factor F (Zickfeld et al., 2011). This factor shows if the feedback is positive (F>1) or negative (F<1) and can be used to compare several biogeochemical feedbacks.

Another question that has been discussing in the literature is the response of land and ocean carbon pools to changes in CO2 or air temperature and assuming a linear relationship $\Delta C_{land}=\beta_{land} * \Delta CO2+\gamma_{land} * \Delta T$ (Friedlingstein et al., 2003, 2006, Arora et al., 2020). The feedback parameters beta and gamma are sensitivities: How much is land carbon changing due to either CO2 or T effects? Units are mass C per atmospheric concentration or mass C per temperature.

In this paper, I would like to use concentrate on the quantification of the feedback (change in atmospheric CO2) without assuming a linear relationship of the gamma-beta approach. Therefore, the feedback factor is applied. However, because the gamma-beta approach seems to be so manifested in the literature and also is asked for by two reviewers, I have extended the manuscript and added radiatively and biogeochemically coupled simulation experiments in order to estimate these sensitivities following (Friedlingstein et al., 2006; Friedlingstein et al., 2003).

I'll try to walk though some sources of this confusion and offer suggestions on how to clarify:

- *Results (Fig 3) shows higher land C uptake and lower atmospheric burden of CO2 with the MMK. To me this implies a reduction in strength of the temperature-respiration feedback with MMK, which allows for more land C uptake. Is this accurate?*

This is a very important question to understand the study. Fig 3 shows changes in state variables of the two model versions when assuming all feedbacks. This is to show how the system of equations work in general and how model results compare to observation-based estimates during the historical period, and how they evolve in future. This shows us the behaviour of the model, e.g. inter-annual variability is not captured, but trends do. The higher land uptake by the MMK model is due to internal carbon dynamics: the CO2 fertilization of GPP leads to more substrate availability for respiration which leads to proportionally more respiration in the case of the linear model (FOK) while the Menten kinetics model assumes a less pronounced impact of more substrate availability and hence reduced respiration relative to the input.

- *The "terrestrial carbon-climate feedback", Table 2, it's unclear if this is basically the size of the cumulative land sink, which is positive (i.e.; from the land perspective) and expressed as Pg C, (not Pg C/degC). Or if this is the difference in atmospheric CO2 accumulation from the "feedback on", (Q10=2) vs. "feedbacks off" (Q10=1). If it's the later, this suggests a larger atmospheric CO2 burden from warming with the MMK approach, which is difficult to square with the results in Fig 3. Maybe the heading for this figure can be clarified?*

I hope that Tab 2 becomes clear with the advanced definition of what is the carbon-climate feedback in section 2.3 of the revised manuscript. Indeed, Tab 2 shows that the feedback is stronger for the MMK model.

- *Finally the "feedback factor" seems to be some kind of a ratio (see additional question below), maybe comparing the runs with Q10=2 ("feedbacks on") vs. Q10=1* *(feedbacks off)? this may allow diagnoses of the inferred temperatures sensitivity of FOK vs. MMK respiration schemes, but it's not really clear what this metric is communicating, or where the results from the "feedbacks off" simulations come into play here?*

Yes, the feedback factor is explained in detail in (Lade et al., 2018; Zickfeld et al., 2011) but I will extend the methods section using equations to make it more clear here. There is a new definition in the revised manuscript because reviewer #2 identified a mistake. The feedback factor is the ration of two changes in atmospheric CO2 content, including specifically this feedback and without any feedback. Please, have a look in the revised methods section. This dimensionless factor can be used to compare the strength of different feedbacks and different models, and it shows whether the feedback is positive (>1) or negative (<1).

The simplest solution here may be to remove the use of "carbon-climate feedbacks" here, unless results can be presented in a way that similar to the C4MIP conventions (commonly a reduction in land C uptake per deg warming). If taking this approach, the manuscript can focus on land C sink or land C uptake from the title and throughout the manuscript to be more consistent with results presented. If taking this approach Fig 1 may not be necessary. Clarification on the 'feedback factor' (Table 3, Fig 5) would also be necessary. This may not be accurate, however, if Table 2 is actually showing the difference in atmospheric CO2 burden from Q10=2 vs. Q10=1 experiments.

I hope to have clarified the term carbon-climate feedback (not the feedback parameter) and how it is calculated, and that I could convince you about its usefulness to understand the uncertainty of model structure for such feedback estimation. In addition, feedback parameters (sensitivities) beta and gamma has been added, too.

<u>Minor and technical questions</u>

Abstract (and elsewhere?) for a single author paper use "I" not "we".

Yes I can change the manuscript accordingly.

I'm not really clear how the "carbon climate feedbacks" were calculated (Table 2), or what the carbon-climate feedback factor represents (Table 3 and Fig 5)? It's the ratio of temporal changes in the land C stocks (end of 21st century pools / end of 19th century pools) Line 134? This doesn't add up when if I do the math on numbers reported in Tables 1 & 2, please clarify in methods. Maybe it's the ratio of the temporal changes in the runs with Q10=2 (feedbacks on) vs. Q10=1 (feedbacks off)? Some addition text in the method and results would help clarify these results.

See above. Methods section revised.

References

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