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To
Dr. Daniel Kirk-Davidoff
Handling Editor of
Earth System Dynamics

14 March 2019
Subject: Resubmission of manuscript #esd-2018-88

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Dear Dr. Kirk-Davidoff,

We wish to resubmit our manuscript entitled **'Including the efficacy of land ice changes in deriving climate sensitivity from paleodata'**, co-authored by L.B. Stap, P. Köhler and G. Lohmann, for consideration of publication in *Earth System Dynamics*. The manuscript represents a significant revision of our earlier submitted manuscript of the same name (MS No.: esd-2018-88) along the constructive reviewer comments.

Following the reviewers and your suggestions and to improve the readability of the manuscript, we have made the following major changes:

- We have removed Section 3.3 from the manuscript, because this section only served as a further illustration of the importance of the effect of land ice changes that is already found in Sect. 3.2. As such, it is not essential to the main storyline of our manuscript.
- We have included a brief introduction to the method and results sections, in which we explain the aim of each section. The results sections end with a statement and discussion of the gained insights.
- We have split Sect. 2.1 (the method section) into three parts, describing 1) the PALAEOSENS approach used so far in earlier studies, 2) our main refinement: the inclusion of the efficacy of land ice changes, and 3) a small refinement that unifies the dependent variable in cross-plots of radiative forcing and global temperature anomalies.
- We have relocated Sects. 2.2.1 and 2.2.2, so that first the modelling results are introduced and analyzed straight away, and thereafter the proxy-inferred dataset is introduced and analyzed.
- We have renamed the variable 'CO_2-equivalent temperature change' ($\Delta T_{[CO2\text{-}equiv]}$). In the revised manuscript, we have more accurately named it 'the global temperature change (with respect to PI) stripped of the influence of land ice changes ($\Delta T_{[-LI]}$)'.

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- In the last paragraph of Sect. 2.2, we discuss the alternative formulation of the efficacy factor suggested by reviewer #1, and why we opt for our formulation. At your suggestion, this includes a significance test for the (linear vs. non-linear) relation between ΔR_{CO2} and ΔR_{LI}.
- We have added an appendix, in which we analyze the same proxy-data inferred dataset, but using a constant polar amplification factor of 2.7 over the past 800 kyr.

We submit a color-coded revised manuscript, as well as a detailed point-by-point response to the comments of the reviewers. If you have any further questions, please do not hesitate to contact us.

Yours sincerely,

Lennert Stap

'Including the efficacy of land ice changes in deriving climate sensitivity from paleodata'
by L.B. Stap, P. Köhler and G. Lohmann.
Submitted for potential publication by Earth System Dynamics

REPLY TO THE COMMENTS BY THE REVIEWERS

Color coding:
Black – comments by reviewers
Green – reply by authors

Reviewer #1

In this paper the authors try to address a matter of importance — that concerning the efficacy of the different radiative forcing — and which is directly relevant to the ongoing efforts by various modelling and proxy analysis groups to estimate the planet's Equilibrium Climate Sensitivity (ECS). I like the idea of the paper and I am quite sure the paper will be accepted, but I feel there is need for clarity and additional analysis before the paper is in publishable form.

We thank the reviewer for a careful examination of our work. We are pleased that the reviewer likes the idea of the paper. In the revised manuscript, we have largely followed the provided comments to improve the clarity of the paper, and we have included additional analysis, as described below.

Points of broadest significance

Definition of the efficacy factor: This paper builds upon the work by Hansen et al. 2005 and by PALEOSENS members (2012), but the way the authors introduce the efficacy factor in equations (8) and (9) is different from those employed in these other works. For example, according to the PALEOSENS approach, equation (9) should be expressed as (See sample calculation in PALEOSENS supplementary materials section B.2):

$$S^{\varepsilon}_{[CO2,LI]} = \frac{\Delta T_g}{\Delta \mathrm{R}_{CO2} + \Delta \mathrm{R}_{LI}} = \frac{\Delta T_g}{\Delta \mathrm{R}_{CO2} + \varepsilon_{LI} \Delta \mathrm{R}_{CO2}}$$

This says that the efficacy of the radiative forcing from land ice changes, $\Delta R_{[LI]}$ is related to the equivalent radiative forcing from changes in CO_2 through is a fractional parameter $\varepsilon_{[LI]}$. This is what the efficacy is meant to serve: to help assess the radiative forcing from non-greenhouse gas sources by relating it to the better constrained forcing from CO_2. But the way the authors are using $\varepsilon_{[X]}$ is quite strange and it doesn't make sense to me. It doesn't appear to be a typographical mistake. The climate sensitivity world is already overflowing with numerous different formulations and I think there should be a very good reason (and which should be made extremely clear in the paper) to define an existing concept differently.

We would like to argue that the way we have implemented the efficacy factor in our approach is the most natural extension to (our) earlier studies. Indeed, the PALAEOSENS approach, which we have used so far, employs:

$$S_{[CO2,LI]} = \frac{\Delta T_g}{\Delta \mathrm{R}_{[CO2]} + \Delta \mathrm{R}_{[LI]}}.$$

Mind though: no superscript ε here, because efficacy differences are not considered.

In Köhler et al. (2010), radiative forcing records over the past 800 kyr of many different processes including CO_2 and land ice changes, were analyzed. This is not the issue we consider in this manuscript. Instead, we try to overcome the problem that the strength of the response of global-average temperature to global-average radiative forcing can be different, depending on the generating process (in this case land ice changes or CO_2 changes), so in general:

$$\frac{\Delta T_{[CO2]}}{\Delta \mathrm{R}_{[CO2]}} \neq \frac{\Delta T_{[LI]}}{\Delta \mathrm{R}_{[LI]}}.$$

In our opinion, the most logical approach to include this difference in efficacy is to multiply the radiative forcing of land ice changes by an appropriate factor so that the strength of the temperature response is the same as when CO_2 would be the generating process. Indeed, Hansen et al. (2005) compared the effects of several different processes, expressing the efficacy of these processes X as:

$$\varepsilon_{[X]} = \frac{\Delta T_{[X]}/\Delta \mathrm{R}_{[X]}}{\Delta T_{[CO2]}/\Delta \mathrm{R}_{[CO2]}}, \text{ so in our case: } \varepsilon_{[LI]} = \frac{\Delta T_{[LI]}/\Delta \mathrm{R}_{[LI]}}{\Delta T_{[CO2]}/\Delta \mathrm{R}_{[CO2]}}.$$

Our implementation,

$$\frac{\Delta T_{[LI]}}{\Delta R_{[LI]}} = \varepsilon_{[LI]} \frac{\Delta T_g - \Delta T_{[LI]}}{\Delta R_{[CO2]}},$$

follows this approach very closely. The only difference is that we relate the effect of land ice changes (left hand side) to the effect of all processes except land ice changes (right hand side), because we calculate specific climate sensitivity $S^{\varepsilon}_{[CO2,LI]}$, which does not account for the effect of these other processes.

In principal, it is also possible to relate the impact of land ice changes on global temperature directly to $\Delta R_{[CO2]}$, as the reviewer proposes:

$$S^{\varepsilon}_{[CO2,LI],\mathrm{alt}} = \frac{\Delta T_g}{\Delta \mathrm{R}_{[CO2]} + \varepsilon_{[LI],\mathrm{alt}} \Delta \mathrm{R}_{[CO2]}},$$

where the efficacy factor in this alternative case ($\varepsilon_{[LI],alt}$) relates to the one used in our approach ($\varepsilon_{[LI]}$) as:

$$\varepsilon_{[LI],\mathrm{alt}} = \varepsilon_{[LI]} \frac{\Delta R_{[LI]}}{\Delta R_{[CO2]}}.$$

However, from the records of $\Delta R_{[CO2]}$ and $\Delta R_{[LI]}$ of our dataset, we infer a non-linear relationship between these two quantities (see the figure below, included as the new Fig. 2 in the revised manuscript). This would introduce a cumbersome state dependency of $\varepsilon_{[LI]}$, which is avoided by our approach. This has now been elaborated upon in the revised manuscript.

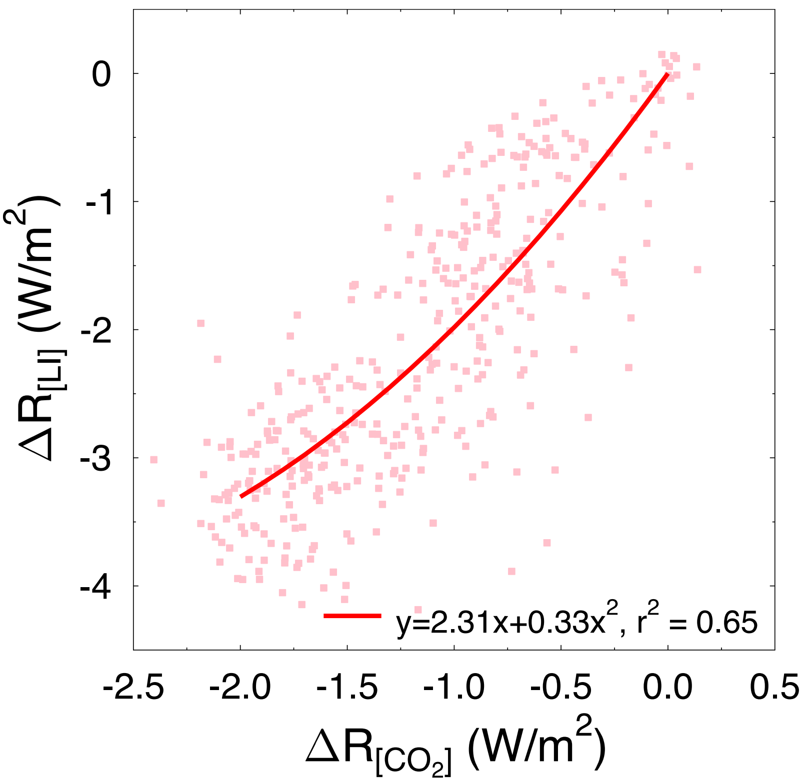

Figure: Relation between radiative forcing anomalies caused by CO_2 changes ($\Delta R_{[CO2]}$) and land ice changes ($\Delta R_{[LI]}$) from the proxy-inferred dataset (pink dots). The red line represents a second order polynomial least-squares regression through the scattered data.

Furthermore, for clarification we have split the method section (Section 2.1) into three parts in the revised manuscript, describing 1) the PALAEOSENS approach used in earlier studies, 2) our main refinement: the inclusion of the efficacy of land ice changes, and 3) a small refinement that unifies the dependent variable in cross-plots of radiative forcing and global temperature anomalies.

Regarding the sample calculations from CLIMBER experiment: The authors try to apply their new formulation to compute $S^{\varepsilon}_{[CO2,LI]}$ from their CLIMBER data and compare it to $S_{[CO2,LI]}$ that they have previously found. Using

$$S_{[CO2,LI]} = \frac{\Delta T_g}{\Delta R_{[CO2]} + \Delta R_{[LI]}}$$

the authors found $S_{[CO2,LI]}$ to be 0.54. This formulation uses ΔT_g, $\Delta R_{[CO2]}$ and $\Delta R_{[LI]}$ all of which are available from their CLIMBER models (and shown in Fig 1). Their new formulation $S^{\varepsilon}_{[CO2,LI]}$, after substituting for $\varepsilon_{[LI]}\Delta R_{[LI]}$ from equation (11) into equation (9) reduces to

$$S^{\varepsilon}_{[CO2,LI]} = \frac{\Delta T_g - \Delta T_{LI}}{\Delta R_{CO2}}$$

in which all the terms are again derived from their CLIMBER models, the only difference from the original expression is that instead of $\Delta R_{[LI]}$ the new expression uses $\Delta T_{[LI]}$. I am quite confused why the new approach using temperature from land ice changes, instead of radiative forcing due to land ice changes, (both from the same set of models), and leading to a higher inferences of S is to be favoured (a sentiment expressed at the start of page 8)?

The goal of this section is to validate our refined approach by applying it to the idealized CLIMBER-2 simulations. Here, the effect of CO_2 is a-priori known from the results of experiment OC:

$$S^{\varepsilon}_{[CO2,LI]} = \frac{\Delta T_{OC}}{\Delta R_{[CO2]}}.$$

This result functions as the target for our approach of obtaining the sole effect of CO_2 changes on global temperature from the results of experiment OIC, where land ice cover and CO_2 levels are both varied over time. Our refined approach considers the efficacy of land ice changes:

$$S^{\varepsilon}_{[CO2,LI]} = \frac{\Delta T_g}{\Delta \mathrm{R}_{[CO2]} + \varepsilon_{[LI]}\Delta \mathrm{R}_{[LI]}}.$$

We calculate the efficacy factor $\varepsilon_{[LI]}$ as:

$$\varepsilon_{[LI]} = \frac{\omega}{1-\omega}\frac{\Delta \mathrm{R}_{[CO2]}}{\Delta \mathrm{R}_{[LI]}},$$

where

$$\omega = \left.\frac{\Delta T_{[LI]}}{\Delta T_g}\right|_{\text{spec. time}}.$$

Note here that the parameter ω is obtained from temperatures at a specific time (for instance, the LGM), constituting the assumption that $\varepsilon_{[LI]}$ is constant in time. Therefore, the simplification that the reviewer makes by substituting equation (11) into equation (9) is not generally valid. Otherwise, the refined approach would indeed by construction always yield the target value for $S^{\varepsilon}_{[CO2,LI]}$ (apart from a negligible contribution by the synergy of CO_2 and land ice changes). Instead, $S^{\varepsilon}_{[CO2,LI]}$ is only matched by construction at the LGM. The comparison we make between our approach and the target, provides a quantification of the error yielded by assuming a time-invariant $\varepsilon_{[LI]}$, which has been clarified in the revised manuscript (see also our answer to the next general comment).

We do not favour a higher or lower value for $S^{\varepsilon}_{[CO2,LI]}$, but the fact that our refined approach gives a quantification of $S^{\varepsilon}_{[CO2,LI]}$ that is much closer to the target, stresses the importance of including efficacy differences.

Constant $\varepsilon_{[LI]}$: The authors have talked a lot about the state dependency of $S^{\varepsilon}_{[CO2,LI]}$, but they have barely discussed the state dependency of $\varepsilon_{[LI]}$, which is the bread and butter of this paper. After all, $\varepsilon_{[LI]}$ will likely depend on state and it can be readily computed for either their numerical model or the paleo data using their equation (11) and therefore the variability can be assessed in the manuscript. The conclusion says "the assumption that the efficacy factor is indeed constant in time could be tested more rigorously using more sophisticated climate models", but it can be tested in this manuscript using the models and data they are already employing. Furthermore, in the absence of this analysis, the usage of LGM specific $\varepsilon_{[LI]}$ in calculations, and which is applied as a constant value to the entirety of the Pleistocene time series makes the analysis look very contrived. The reader does not know, if the results change a lot if $\varepsilon_{[LI]}$ is derived, from say MIS5 and then kept constant for the entire interval of analysis? So the range of changes in $\varepsilon_{[LI]}$ and the dependence of principle results on that should be included in the manuscript.

As explained in the answer to the previous general comment of the reviewer, the analysis of the CLIMBER-2 results gives a quantification of the error made by assuming the efficacy factor to be constant in time. This is now explained more clearly in the revised manuscript. CLIMBER-2 is, however, not the most advanced model around; the results are very linear (small synergy of the effects of land ice and CO_2 changes), and important long-term feedbacks such as dust and non-CO_2 greenhouse gas changes are ignored in the simulations we analyze. We therefore maintain the sentence stating that the assumption of a time-constant efficacy factor can be investigated more rigorously using results of more sophisticated models. We have moved this sentence to the section where we present and discuss the CLIMBER-2 results.

So far, we derived $\varepsilon_{[LI]}$ using data from the LGM, because this is a well-studied time slice, that we also use in the analysis of our proxy-inferred dataset. In principal, however, $\varepsilon_{[LI]}$ can be obtained using data from any moment in time. Preferably, the radiative forcing anomalies should be large to prevent outliers resulting from divisions by small numbers, making MIS5 a less suited candidate. Instead, we now include an extra analysis of the CLIMBER-2 results, where we obtain $\varepsilon_{[LI]}$ from the mean value of all glacial marine isotope stages of the past 810 kyr (MIS 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20). We find an $\varepsilon_{[LI]}$ of 0.56 ± 0.09 and a corresponding PI $S^{\varepsilon}_{[CO2,LI]}$ of $0.73^{+0.06}_{-0.05}$ K W^{-1} m^2.

Section 3.3: A big shortcoming of this manuscript is section 3.3 which is extremely convoluted and difficult to follow. For an otherwise relatively clearly written paper, this section seems to have been put together haphazardly without the attention to detail that makes the rest of the paper readily readable. Though I have made a couple of specific comments for this section further down in my review, in general I have not been able to follow this section at all and therefore have not been able to provided the quality of feedback that I would have liked. A careful re-writing of this section by the authors is required.

We understand from the comments of this reviewer and reviewer #2, that Sect. 3.3 was not as easily understandable as we had hoped upon submission of the manuscript. During the process of revising the manuscript, we have come to the realization that this section only served as a further illustration of the importance of the effect of land ice changes that is already found in Sect. 3.2. As such, it is not essential to the main storyline of our manuscript. To improve the clarity of the paper as a whole, we have therefore decided to remove it from the manuscript.

Scientific comments

1. The various sensitivities are quotes in two different units throughout the paper: K per doubling of CO_2 and K W^{-1} m^2. While the authors have been generally very clear about the units and about converting between them, as is the case on page 8, I do encourage them to use only one unit throughout the paper. This helps a reader to quickly compare various numbers from across the paper without having to convert the units. Alternatively, the authors could quote all sensitivities in both units, example: "so and so sensitivity was found to be 1.66 K W^{-1} m^2 or equivalently 5.6 K per doubling of CO_2" (similar to the last sentence in the conclusions section).

As we now explain in the method section, we express S^a in K W^{-1} m^2 and ECS in K per doubling. We now convert $S^{\varepsilon}_{[CO2,LI]}$ to both quantities, and quote them conjointly.

2. Sentence spanning lines 9–10 on page 3: I don't understand what is meant by this sentence, specifically by the part "it has been shown that simulations of models that have been integrated over a few centuries are not yet in equilibrium". Perhaps rephrasing this sentence could make it clearer.

We have removed this sentence from the manuscript, since it was not essential to - and therefore distracting from - the storyline.

3. Line 10 page 3: Regarding ECS the authors say "Another way to express" but no other way has been previously mentioned until that point in the article. The ECS has only been defined up to that point. I think it makes more sense to rephrase it as "One way to express".

This sentence has been rephrased. ECS is expressed in K per doubling, and S^a in K W^{-1} m^2. They relate to each other as: ECS = S^a * 3.7 W m^{-2}. This has now been made clear in the revised manuscript.

4. Since the form of "f" is important for the rest of the paper, the authors should clearly articulate the motivations for f as given in equation 5.

Equation 5 is part of the PALAEOSENS approach that has been used so far in numerous publications, and as such is not an equation we propose here. This has been made clear in the revised manuscript by splitting the method section into three parts (see our answer to the first general comment of the reviewer). The idea of the PALAEOSENS approach was that the influence of long-term processes on global temperature is directly proportional to the radiative forcing perturbation they induce, as is now mentioned in the revised manuscript.

5. Last para, page 4: So is $S_{[CO2,LI]}$ to be considered as an estimate of S^a? Maybe the authors should clarify this explicitly. In the process of making this clarification the starting sentence of that paragraph will likely need to be modified to make the argument fit in seamlessly.

No, we obtain an estimate for S^a by multiplying $S^{\varepsilon}_{[CO2,LI]}$ by 0.64. This has now been clarified in the method section.

6. In the first paragraph on page 5 the authors say that they take a "further simplifying step" to more easily compare "$S^{\varepsilon}_{[CO2,LI]}$ to other specific paleoclimates sensitivities $S^{\varepsilon}_{[CO2,X]}$ by unifying the dependent variable". But all they have done is move the specific dependent variable $\Delta R_{[X]}$ into the newly defined CO_2-equivalent temperature and which doesn't in any way free someone of the need to compute that forcing or to compute the efficacy factor. So I fail to see the simplification here (besides a notational one) but more importantly I fail to see the practical usefulness. For any given $S_{[CO2,LI]}$ by the time one has computed the CO_2-equivalent temperature, they might as well have just used equation 9.

We realize now that calling this step 'simplifying' was somewhat confusing. In the revised manuscript, we have made a separate subsection describing this small refinement, which serves to unify the dependent variable in cross-plots of radiative forcing and global temperature anomalies. This makes our calculated $S^{\varepsilon}_{[CO2,LI]}$ more readily comparable to other specific paleoclimate sensitivities, where more and/or different long-term processes are considered. We describe the newly introduced variable now more accurately as the global temperature change (with respect to PI) stripped of the inferred influence of processes X ($\Delta T_{[-X]}$), in our case land ice changes ($\Delta T_{[-LI]}$).

7. First para, page 6: In the experiments OC, and OI, which as I understand are meant to assess the effects of land ice and CO_2 respectively, why are the orbital conditions also varied in conjunction? It seems that the authors answer this later on in the manuscript, at the beginning of section 3.1: “since the influence of orbital variations is very small”. That comment should be moved closer to where these experiments OC and OI are discussed.

This comment has been moved to the description of the model data, as suggested by the reviewer.

8. Line 21, page 6: “ANICE was forced by northern hemisphere temperatures obtained…” Northern hemispheres temperature or temperature anomaly? I think it should be the anomaly.

ANICE was indeed forced by the anomaly. We thank the reviewer for this careful observation.

9. Page 6: regarding the discussion of the amplification factor for the Pliocene, new results coming from the revised paleo-geographic boundary conditions for PlioMIP2 (Kamae et al. 2016; Chandan and Peltier 2017; Hunter et al. 2019) that suggest that the amplification factor could have been larger. Models that were used in the previous PlioMIP and whose results were synthesized in Haywood et al. 2013 were consistently failing to produce the polar amplification that has been inferred from proxies. With the new results the polar amplification factor in the warm interval of the Pliocene is nearly the same as the amplification factor during the cold LGM. The authors should and cite the new papers add a comment/analysis regarding how the revised amplification factor for the warm interval affects their results.

In the revised manuscript, we have included an appendix, in which we analyze the same proxy-data inferred dataset, but using a constant polar amplification factor of 2.7 over the past 800 kyr (ΔT_{g2} in Köhler et al. 2015). This is in our opinion a very interesting addition to our manuscript, but it does not affect the main results qualitatively.

10. Lines 15-17 page 7: the authors say they are inferring $S^{\varepsilon}_{[CO2,LI]}$ or $S^{\varepsilon}_{[CO2]}$ here but I think a bit of additional comment is required to clarify the appearance of ε in these sensitivities. These are after all inferred from experiment OC in which $\Delta R_{[LI]}$ is zero, so the meaning of land-ice radiative efficacy ε is not strictly defined. This is probably hair-splitting over notation but I think it is best to be as clear as possible since the climate sensitivity literature is already overflowing with (sometimes sloppily used) notation.

As the reviewer rightly points out, in the case of $\Delta R_{[LI]}=0$, $\Delta R_{[LI]}$ and $\varepsilon_{[LI]}$ have no effect on $S^{\varepsilon}_{[CO2,LI]}$, so $S^{\varepsilon}_{[CO2,LI]} = S^{\varepsilon}_{[CO2]} = S_{[CO2,LI]} = S_{[CO2]}$, which is now indicated in the revised manuscript.

11. Line 1, page 8: “the new approach considering efficacies clearly leads to a more satisfactory result that the old approach.” In the present form this sentence implies that for some reason the numerical value 0.74 is more satisfactory than the older value of 0.54. I am

not sure if that is defensible or even that the authors themselves meant to imply that. I think the authors meant to say something like “the new approach is more flexible/accommodating/physically accurate than the old approach”. Please re-phrase this accordingly.

This has been rephrased, because calling the results ‘more satisfactory’ could let readers believe we have a certain preference for a lower or higher result, which we of course do not have. We meant to say the new result (0.72 K W^{-1} m^2) is much closer to the target value of 0.74 K W^{-1} m^2 than the result of the old approach, stressing the importance of including efficacy. This has been clarified in the revised manuscript.

12. Lines 13–15, page 8: The authors have presented two results which lead to opposite conclusions. This needs to be addressed here directly instead of referring the reader to another publication. While the issue may have been more thoroughly assessed in Köhler et al. 2018, a brief comment should also be provided here so that the reader grasps the discordance in the author’s results at a bare-minimum level without having to read up another paper.

A brief explanation of this result has been included in the revised manuscript.

13. Line 9, page 8: For the calculation of $\varepsilon_{[LI]}$ using equation 11 please provide the values of $\Delta R_{[CO2]}$ and $\Delta R_{[LI]}$ at LGM that were used.

The LGM values ($\Delta R_{[CO2]}$ = -2.04 W m^{-2} and $\Delta R_{[LI]}$ = -3.88 W m^{-2}) are now provided. Upon including them and redoing the calculations, we realized we made a small mistake in the calculation of ε in the former section 3.2, and the corresponding $S^{\varepsilon}_{[CO2,LI]}$. This has been corrected in the revised manuscript. We thank the reviewer for letting us double-check our calculations.

14. Line 15, page 8: is the mean the value “of” years 20 and 22 kya or “between” those years?

The temporal resolution of this dataset is 2,000 years, so we have values for 20 and 22 kyr ago. In that sense, it is indeed the mean ‘of’ these times. This has now been clarified.

15. Line 16, page 8: “The specific paleo climate sensitivities we find here are generally higher than calculated by the old approach” But the new sensitivity calculated is 1.39 which is lower than that by the old approach which was 1.66.

The new sensitivity of 1.39 K W^{-1} m^2 (revised to 1.45 K W^{-1} m^2, see our answer to scientific comment #13) holds for the LGM, and should be compared to 0.93 K W^{-1} m^2 obtained by the old approach. The PI sensitivity of 1.66 K W^{-1} m^2 of the old approach should be compared to our new PI sensitivity of 2.45 K W^{-1} m^2. This has now been clarified in the revised manuscript.

16. Line 12 page 9: "We correct the induced $\Delta T_{[CO2]}$ of all individual models for this ratio” I don’t follow.

17. Line 15 page 9: At this point I am lost. Why are you doing that regression? What it the motivation? And are you subtracting the global value $\Delta T_{[CO2]}$ from ΔT_{NH}?

18. The ECS given in Table 1 for the CCSM4 model is different from that usually cited. Bitz et al. 2012 using the NCAR-CCSM4 and recently Chandan and Peltier, 2018 using a related UofT-CCSM4 have deduced the ECS to be 3.2. The value in Table 1 is lower than that. Where did the authors get this from? Haywood et al. 2013 also use CCSM4 ECS (from Bitz et al) of 3.2. Do the numbers for the other models need to be checked as well?

19. The authors should cite all the original experiment design papers for the PMIP3 experiments listed in Table 1. This can be done readily by adding a new column to the table called "References".

Answer to points 16 to 19: Section 3.3 has been removed from the manuscript, see our answer to the fourth general comment of the reviewer.

20. The figure description for Figure 3 is completely wrong. It is talking about things that are not on the figure.

Figure 3 and its caption have been corrected.

Technical comments

We are very grateful for these technical comments by the reviewer. We have implemented all the suggestions, except where indicated.

1. Line 2 page 1:"~~with~~ to equilibrium"

This sentence has been rewritten completely.

2. Line 29 page 2: "are obtained from ~~different~~ various model setups"

This sentence has been rewritten completely.

3. Line 16 page 3: "In this case, the average global paleo temperature anomaly with respect to the pre-industrial (PI) ~~average~~ (ΔT_g) is"
4. Line 17 page 3: "that are typically neglected in ~~the~~ climate simulations".
5. Lines 3-4 on page 4 incorporating the phrase "the calculated paleoclimate sensitivity" in the current form refers to some specific and as yet undefined sensitivity. It's best to rephrase it as "If, for instance, only the most important slow feedback in the climate system, namely radiative forcing anomalies induced by albedo changes due to land ice (LI) variability are taken into account, then one can correct S^p to derive the following specific paleoclimate sensitivity."
6. The sentence on line 5, page 4, appears as a sharp interruption to the logic train before and after that sentence. It should instead be placed at the end of that paragraph and rephrased as "~~An overview~~ A synthesis of ~~different values~~ estimates of $S_{[CO_2,LI]}$ ~~for~~ from both ...."
7. Line 15 page 4: "~~e.g. because~~ because, e.g."
8. Line 18 page 4: "through efficacy factors ($\varepsilon_{[LI]}$), ~~which demands~~. This requires a reformulation"
9. Line 20 page 4: "to clearly distinguish ~~them~~ the sensitivities from ~~the former ones~~ those of the PALAEOSENS project~~,~~ in which the radiative forcing of the different processes ~~had identical weights~~ were assigned identical efficacies."

This sentence has been rephrased to:
'This serves to clearly distinguish these newly-derived sensitivities from those of the PALAEOSENS project in which efficacy was not taken into account, implying that identical radiative forcing of different processes leads to identical temperature changes.'

10. Line 25 page 4: "by land ice changes ($\varepsilon_{[LI]}$), using ~~a slightly different definition than~~ the following formulation which is based on, but modified from Hansen et al. (2005)"
11. Line 22 page 5: The sentence "CLIMBER-2 combined a 2.5 statistical-dynamical…" seems something is missing after 2.5. Did the authors mean "2.5 degree"?

Corrected to '… 2.5-dimensional …'

12. Line 5 page 5: Add comma after "Similarly"

Corrected to 'As before, …'

13. Line 3 page 5: "leaving 217 data points as indicated in Fig 1c,d."
14. Sentence beginning on line 18 page 7: change it to something like "For our first attempt at compensating paleoclimates sensitivity for slow processes other than CO_2 changes we strive to deduce the same $S^{\varepsilon}_{[CO2,LI]}$, inferred above, from experiment OIC in which both CO_2 and land ice cover vary over time".

This sentence has been rewritten as:
'Now, we apply our approach to the results of experiment OIC, in which both CO_2 and land ice cover vary over time, with the aim of deducing the sole effect of CO_2 changes on global temperature.'

15. Line 23 page 7: "Between …. ~~there are~~ some ~~outlying values caused by~~ outliers resulted from division ~~of~~ by small numbers (not shown on Fig. 2b)."
16. Line 29 page 7: "….is more linear than that ~~of~~ between …"
17. Line 31 page 7 "~~in the simulated domain~~ through the entire 5 million year interval."
18. Line 11 page 8: "~~Similarly as before (Köhler et al., 2018), we detect~~ Similar to Köhler et al., 2018, we too detect"
19. Line 15 page 8: the value of $\Delta R_{[CO2]}$ should be -2.04
20. Line 15 page 8: "the LGM value (~~here taken~~ taken here as the mean…)"
21. Line 21 page 8: "we first scale ~~them~~ it by a factor"

This sentence has been removed.

22. Line 23 page 8: "Note that this scaling still assumes unit efficacy for ~~all other~~ process other than land ice changes"

This sentence has been corrected as suggested by the reviewer, and replaced to the method section.

23. Line 24 page 8: "Then, after ~~After~~ multiplying by"

This sentence has been removed.

24. Line 24 page 8: Units should be Wm^{-2}

This sentence has been removed.

25. Line 11 page 9: "that the ratio of the radiative forcing change ~~$\Delta R_{[CO2]}$~~ between the LGM (185 ppm CO_2) and the PI (280 ppm CO_2), to the change between the PI and ~~2 x CO_2~~ a 2 X PI case is
26. Line 16 page 9: "significant ~~on~~ at the 95% level"

Answer to points 25 and 26: Section 3.3 has been removed from the manuscript, see our answer to the fourth general comment of the reviewer.

27. Conclusions section, Lines 26, 28, 30: $\varepsilon_{[CO2,LI]}$ is a new symbol not previously defined. It seems like a mistake and the authors likely meant $\varepsilon_{[LI]}$
28. The yellow star in Fig 4 is barely visible against the cyan background. Please change it to something dark, maybe black.

All the colors in Fig. 4 have been changed for better visibility.

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Reviewer #2

My initial thoughts on seeing this paper were very positive in the sense that, given the uncertainty of information in the paleorecord, and the difficulty of using state of the art models to make very long runs, all progress in the area of better defining climate sensitivity as it relates to past climates is worthwhile.

My optimism remained through the first parts of the paper, but by the end I have to admit that I am lost and really do not understand what the authors are trying to do and what they have discovered.

We thank the reviewer for considering our work. We are pleased the reviewer sees merit in the aim of our study. Along the helpful comments provided, we have thoroughly rewritten and restructured the manuscript to get our message across more clearly.

Most importantly we have improved the readability of the manuscript in the following manners:

- We have removed Section 3.3 from the manuscript, because this section only served as a further illustration of the importance of the effect of land ice changes that is already found in Sect. 3.2. As such, it is not essential to the main storyline of our manuscript.
- We have included a brief introduction to the method and results sections, in which we explain the aim of the section. The results sections end with a statement and discussion of the gained insights.
- We have split Sect. 2.1 (the method section) into three parts, describing 1) the PALAEOSENS approach used so far in earlier studies, 2) our main refinement: the inclusion of the efficacy of land ice changes, and 3) a small refinement that unifies the dependent variable in cross-plots of radiative forcing and global temperature anomalies.
- We have relocated Sects. 2.2.1 and 2.2.2, so that first the modelling results are introduced and analyzed straight away, and thereafter the proxy-inferred dataset is introduced and analyzed.
- We have renamed the variable 'CO2-equivalent temperature change' ($\Delta T_{[CO2\text{-}equiv]}$). In the revised manuscript, we have more accurately named it 'the global temperature change (with respect to PI) stripped of the influence of land ice changes ($\Delta T_{[-LI]}$)'.

The authors introduce a variable, DTe[CO2 - equiv] but do not explain why this is useful or interesting.

The introduction of this variable, named $\Delta T_{[-LI]}$ in the revised manuscript (see below), serves to unify the dependent variable in cross-plots of radiative forcing and global temperature anomalies. This makes our calculated $S^{\varepsilon}_{[CO2,LI]}$ more readily comparable to other specific paleoclimate sensitivities, where more and/or different long-term processes are considered. This step is a small refinement compared to our main refinement of including the efficacy of land ice changes. This has been clarified in the revised manuscript by splitting the method section into three parts.

What I would have done is take equation (9), replace X with LI and then explore all the elements of that equation. This would show us how S varies with DRLI and DRCO2, as well a DTg and one could consider how much of the state+forcing+efficacy dependence of S[CO2] is accounted for by considering land ice with and without considering efficacy.

This has been done in detail in Köhler et al. (2010) for the old approach (equivalent to $\varepsilon_{[LI]} = 1$ in the refined approach). The inclusion of an efficacy factor for land ice changes does not qualitatively change this analysis, it just linearly amplifies (when $\varepsilon_{[LI]} > 1$) or diminishes (when $\varepsilon_{[LI]} < 1$) the effect of radiative forcing by land ice changes. We therefore focus directly on the effect of $\varepsilon_{[LI]}$ on $S^{\varepsilon}_{[CO2,LI]}$.

I can see that Figures 2 and 3 represent some kind of sensitivity-like variable, but I cannot grasp its meaning.

Indeed, in Figures 2 and 3 we showed the main results of our manuscript: the influence of the deduced $\varepsilon_{[LI]}$ on $S^{\varepsilon}_{[CO2,LI]}$.

Basically, DTe[CO2 - equiv] is not, as you suggest in equation 14 simply a function of DRCO2 but also depends on Tg and DRLI.

What we meant here is that we make a regression to the scattered data of $\Delta R_{[CO2]}$ and the variable DTe[CO2 - equiv] (now called $\Delta T_{[-LI]}$). $\Delta T_{[-LI]}$ comprises the influences of $\Delta R_{[LI]}$, $\Delta R_{[CO2]}$ and ΔT_g. To clarify this, in the revised manuscript we have named this function *regfunc* (instead of *g*).

I hope that the remedy is a better explanation of the reasons behind the derivations in section 1 and also better explanation of the insight that you gain from the results.

Other points.

P1L10 "Recently, it has been shown that simulations of models that have been integrated over a few centuries are not yet in equilibrium, and from longer climate simulations a higher ECS can be deduced (Knutti et al., 2017)."

This needs rephrasing. It has been well known since before dynamical oceans were included in climate models that the equilibrium time of the ocean is of the order of thousands of years. Since the invention of the AOGCM, ad-hoc methods have been introduced to try to estimate equilibrium climate sensitivity without running the models to equilibrium. What recent work has been doing is assessing the accuracy of such approximations.

We have removed this sentence from the manuscript, since it was not essential to - and therefore distracting from - the storyline.

P2L23 "likewise as several earlier studies"
-> "as in several earlier studies"

This sentence has been removed.

Eq(10) This equation suggests to me that DTg-DT[LI]=DT[CO2]. Maybe I misunderstand, but it seems to me that DTg=DT[LI]+DT[CO2]+DT[X]+Z, where DT[X] is the influence of all the other forcings and Z represents cross terms (ie nonlinearities).

In this manuscript, we aim to calculate specific climate sensitivity $S^{\varepsilon}_{[CO2,LI]}$, which only compensates paleoclimate sensitivity (S^{p}) for the influence of land ice cover changes. To deduce the efficacy of land ice changes, we relate its effect on global temperature changes to that of all other processes combined. This is in line with our calculation of S^{a} from $S^{\varepsilon}_{[CO2,LI]}$ by multiplying by a factor of 0.64, which implies unit efficacy for all other processes than land ice changes. As stated in the text, this is a source of uncertainty to be investigated in future research.

P3L5 "Similarly as in the old approach," Not English

Corrected to: 'As before, …'

Eq(13) Looks like a minus sign between "CO2" and "equiv".

We realize that calling this variable 'CO2-equivalent temperature change' ($\Delta T_{[CO2\text{-}equiv]}$) was confusing. In the revised manuscript we have therefore more accurately named it 'the global temperature change (with respect to PI) stripped of the influence of land ice changes ($\Delta T_{[-LI]}$)'.

P5L12 "A functional relationship between TE[CO2−equiv] and R[CO2] (T[CO2−equiv]= g(R[CO2])) can be obtained by least squares regressions of higher-order polynomial to the scattered data of these variables."

It is not clear which variables are "these variables".

This sentence has been rephrased as:
'Now, we quantify $S^{\varepsilon}_{[CO2,LI]}$ by performing a least-squares regression (regfunc) through scattered data from $\Delta T^{\varepsilon}_{[-LI]}$ and $\Delta R_{[CO2]}$.'

Sections 2 and 3

I think the paper order should be 2.2.1, 3.1 then 2.2.2, 3.2. The way it is presented is just confusing. Present the whole of the simple modelling case and then move on to the data-based case.

We have followed the suggestion of the reviewer.

P7L22 "and again fit a second order polynomial to the scattered data of T"
[CO2−equiv]"

Which experiment?

Here, we analyse the results of experiment OIC. We have clarified this in the revised manuscript.

P8L12 "Similarly as before" Not English

This sentence has been corrected.

Table 1 State which paper each "published ECS" comes from.

Section 3.3 has been removed from the manuscript, see our answer to the comment of the reviewer below.

I prefer to write reviews before reading what other reviewers have posted, as I feel I will be too easily influenced, so I did not read the other reviewer's comment until now. I am encouraged to see that the other reviewer also found the paper very difficult to follow. This increases my optimism that there is hope that with better explanation in critical areas, and reorganisation to improve the storyline, that the paper may become both comprehensible and publishable.

Reviewer #1 was mostly concerned about Sect. 3.3. During the process of revising the manuscript, we have come to the realization that this section only served as a further illustration of the importance of the effect of land ice changes that is already found in Sect. 3.2. As such, it is not essential to the main storyline of our manuscript. To improve the clarity of the paper as a whole, we have therefore decided to remove it from the manuscript.

Including the efficacy of land ice changes in deriving climate sensitivity from paleodata

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In red, newly added or significantly revised text

In blue, relocated text

Abstract. The equilibrium climate sensitivity (ECS) of climate models is calculated as the equilibrium global mean surface warming resulting from a simulated doubling of the atmospheric CO_2 concentration. In these simulations, long-term processes in the climate system, such as land ice changes, are not incorporated. Hence, they have to be compensated for when comparing climate sensitivity derived from paleodata to the ECS of climate models. Several recent studies found that the impact these long-term processes have on global temperature cannot be quantified directly through the global radiative forcing they induce. This renders the approach of deconvoluting paleotemperatures through a partitioning based on radiative forcings inaccurate. Here, we therefore implement an efficacy factor $\varepsilon_{[LI]}$, that relates the impact of land ice changes on global temperature to that of CO_2 changes, in our calculation of climate sensitivity from paleodata. We apply our new approach to a proxy-inferred paleoclimate dataset, and base the range in $\varepsilon_{[LI]}$ we use on a multi-model assemblage of simulated relative influences of land ice changes on the Last Glacial Maximum temperature anomaly. We find that $\varepsilon_{[LI]}$ is smaller than unity, meaning that per unit of radiative forcing the impact on global temperature is less strong for land ice changes than for CO_2 changes. Consequently, our obtained ECS estimate of $5.8 \pm 1.3\,\mathrm{K}$, where the uncertainty reflects the implemented range in $\varepsilon_{[LI]}$, is $\sim$50% higher than the result of the old approach that does not consider efficacy.

1 Introduction

Equilibrium climate sensitivity (ECS) expresses the simulated equilibrated surface air temperature response to an instantaneous doubling of the atmospheric CO_2 concentration. The simulated effect of the applied CO_2 radiative forcing anomaly includes the Planck response, as well as the fast feedbacks e.g. through snow, sea ice, lapse rate, clouds and water vapour changes. ECS varies significantly between different state-of-the-art climate models, as for instance the CMIP5 ensemble shows a range of 1.9 to 4.4 K (Vial et al., 2013). Several ways have been put forward to constrain ECS, for example through the usage of paleoclimate data (e.g. Covey et al., 1996; Edwards et al., 2007), which is also the focus of this study. However, unlike results of models, which can be run ceteris paribus, temperature reconstructions based on paleoclimate proxy data always contain a mixed signal of all processes active in the climate system. Among these are long-term processes (or slow feedbacks) such as changes in vegetation, dust, and, arguably most importantly, land ice changes, which are not taken into account in the quantification of ECS. Therefore, it is necessary to correct paleotemperature records for the influence of these processes, in order to make a meaningful comparison to ECS calculated by climate models.

In a co-ordinated community effort, the PALAEOSENS project proposed to relate the temperature response caused by these long-term processes to the global averaged radiative forcing they induce (PALAEOSENS Project Members, 2012). Consequently, the paleotemperature record can be disentangled on the basis of the separate radiative forcings of these long-term processes (e.g. von der Heydt et al., 2014; Martínez-Botí et al., 2015; Köhler et al., 2015, 2017b, 2018; Friedrich et al., 2016). If all processes are accounted for in this manner, the sole effect of CO_2 changes, as is asserted by the ECS, can be quantified. However, several studies have shown that, depending on the type of radiative forcing, the same global average radiative forcing can lead to different global temperature changes (e.g. Stuber et al., 2005; Hansen et al., 2005; Yoshimori et al., 2011). For instance, in a previous article (Stap et al., 2018) we simulated the separate and combined effects of CO_2 changes and land ice changes on global surface air temperature using the intermediate complexity climate model CLIMBER-2 and showed that the specific global temperature change per unit radiative forcing change depends on which process is involved. As a possible solution to this problem, Hansen et al. (2005) formulated the concept of 'efficacy' factors, which express the impact of radiative forcing by a certain process in comparison to the effect of radiative forcing by CO_2 changes.

Based on the concept of Hansen et al. (2005), here we introduce an efficacy factor for radiative forcing by albedo changes due to land ice variability, in our method of deriving climate sensitivity from paleodata. We first validate our refined approach by applying it to transient simulations over the past 5 Myr using CLIMBER-2 (Stap et al., 2018). We compare the results of our approach of obtaining the sole effect of CO_2 changes on global temperature from a simulation forced by land ice and CO_2 changes, to a simulation where CO_2 changes are the only operating long-term process. Hence, we can assess the error resulting from using a constant efficacy factor. Thereafter, we refine a previous estimate of climate sensitivity based on a paleoclimate dataset of the past 800 kyr (Köhler et al., 2015, 2018). In this dataset, the sole effect of CO_2 is not a-priori known. We therefore investigate the influence of the introduced efficacy factor on the calculated climate sensitivity. To do so, we appraise the influence of land ice changes and the associated efficacy using a range that is given by different modelling efforts of the Last

Glacial Maximum (LGM; ∼21 kyr ago) (Shakun, 2017). The climate sensitivity resulting from applying this range provides a quantification of the consequence of the uncertain efficacy of land ice changes.

2 Material and methods

In this section, we recapitulate the approach to obtain climate sensitivity from paleodata, used in numerous earlier studies (e.g. PALAEOSENS Project Members, 2012; von der Heydt et al., 2014; Martínez-Botí et al., 2015; Köhler et al., 2015, 2017b, 2018; Friedrich et al., 2016). We also discuss the main refinement we make in this study, which is the inclusion of the efficacy of land ice changes, and a further small refinement that unifies the dependent variable in cross-plots of radiative forcing and global temperature anomalies.

2.1 Approach to obtain climate sensitivity from paleodata

Equilibrium climate sensitivity (ECS) is the long-term global average surface air temperature change resulting from a CO_2 doubling, and is usually obtained from climate model simulations. In these simulations, fast feedbacks, i.e. processes in the climate system with timescales of less than ∼100 yrs, are accounted for. However, slower processes, such as ice sheet, vegetation and dust changes, are commonly kept constant. The resulting response is also sometimes called 'Charney' sensitivity (Charney et al., 1979). Following the notation of PALAEOSENS Project Members (2012), taking the ratio of the temperature change ($\Delta T_{[CO_2]}$) over the radiative forcing due to the CO_2 change ($\Delta R_{[CO_2]}$), leads to S^a (in $\mathrm{K\,W^{-1}\,m^2}$, and where a stands for *actuo*):

$$S^a = \frac{\Delta T_{[CO_2]}}{\Delta R_{[CO_2]}}. \quad (1)$$

The subscript denotes that CO_2 is the only long-term process involved. Analogously, paleoclimate sensitivity (S^p) can be deduced from paleo-temperature reconstructions and paleo-CO_2 records as

$$S^p = \frac{\Delta T_g}{\Delta R_{[CO_2]}}. \quad (2)$$

In this case, the average global paleotemperature anomaly with respect to the pre-industrial (PI) (ΔT_g) is, however, also affected by the long-term processes that are typically neglected in climate simulations. Therefore, a correction to the paleotemperature perturbation is needed to obtain $\Delta T_{[CO_2]}$ from ΔT_g:

$$\Delta T_{[CO_2]} = \Delta T_g (1 - f), \quad (3)$$

or equivalently S^a from S^p:

$$S^a = S^p(1 - f) = \frac{\Delta T_g}{\Delta R_{[CO_2]}}(1 - f). \quad (4)$$

Here, f represents the effect of the slow feedbacks on paleotemperature (e.g. van de Wal et al., 2011). To obtain f, PALAEOSENS Project Members (2012) proposed an approach, which has subsequently been used in numerous studies aiming to constrain climate sensitivity from paleodata (e.g. von der Heydt et al., 2014; Martínez-Botí et al., 2015; Köhler et al., 2015, 2017b, 2018; Friedrich et al., 2016). Their idea was that the influence of long-term processes (X) on global temperature, is directly proportional to the radiative forcing perturbation they induce ($\Delta R_{[X]}$), hence:

$$f = \frac{\Delta R_{[X]}}{\Delta R_{[CO_2]} + \Delta R_{[X]}} = 1 - \frac{\Delta R_{[CO_2]}}{\Delta R_{[CO_2]} + \Delta R_{[X]}} \tag{5}$$

Combining Eqs. 4 and 5 and following the PALAEOSENS nomenclature, we can then derive the 'specific' paleoclimate sensitivity $S_{[CO_2,X]}$, where X represents the processes that are accounted for in the calculation of f:

$$S_{[CO_2,X]} = \frac{\Delta T_g}{\Delta R_{[CO_2]}}(1 - \frac{\Delta R_{[X]}}{\Delta R_{[CO_2]} + \Delta R_{[X]}}) = \frac{\Delta T_g}{\Delta R_{[CO_2]} + \Delta R_{[X]}} = \frac{\Delta T_g}{\Delta R_{[CO_2,X]}}. \tag{6}$$

If, for instance, only the most important slow feedback in the climate system, namely radiative forcing anomalies induced by albedo changes due to land ice (LI) variability are taken into account, then one can correct S^p to derive the following specific climate sensitivity:

$$S_{[CO_2,LI]} = \frac{\Delta T_g}{\Delta R_{[CO_2]} + \Delta R_{[LI]}} = \frac{\Delta T_g}{\Delta R_{[CO_2,LI]}}. \tag{7}$$

Using this approach, several studies performed a least-squares regression through scattered data from paleotemperature and radiative forcing records (Martínez-Botí et al., 2015; Friedrich et al., 2016; Köhler et al., 2015, 2017b, 2018) relating ΔT_g to $\Delta R_{[CO_2,LI]}$ in a time-independent manner, from which $S_{[CO_2,LI]}$ could be determined. In this way, a state dependency of $S_{[CO_2,LI]}$ as function of background climate has been deduced for those data which are best approximated by a non-linear function. Furthermore, the quantification of $S_{[CO_2,LI]}$ for those state-dependent cases has been formalized in Köhler et al. (2017b). A synthesis of estimates of $S_{[CO_2,LI]}$ from both colder- and warmer-than-present climates has been compiled by von der Heydt et al. (2016).

To obtain S^a, one needs to multiply $S_{[CO_2,LI]}$ by a factor of 0.64 that accounts for the influence of other long-term processes, namely vegetation, aerosol and non-CO_2 greenhouse gas changes (PALAEOSENS Project Members, 2012). Finally, we obtain the equivalent ECS by multiplying S^a by 3.7 $\mathrm{W\,m^{-2}}$, the radiative forcing perturbation representing a CO_2 doubling (Myhre et al., 1998).

2.2 Refinement 1: Taking the efficacy of land ice changes into account

The validity of the PALAEOSENS approach to calculate f is contingent on the notion that identical global-average radiative forcing changes leads to identical global temperature responses, regardless of the processes involved. However, it has been demonstrated that the horizontal and vertical distribution of the radiative forcing affects the resulting temperature response (e.g. Stuber et al., 2005; Hansen et al., 2005; Yoshimori et al., 2011; Stap et al., 2018) because, e.g. different fast feedbacks are triggered depending on the location of the forcing. To address this issue, Hansen et al. (2005) introduced the concept of 'efficacy' factors, which we will explore further in this study. These factors ($\varepsilon_{[X]}$) relate the strength of the temperature response to radiative forcing caused by a certain process X ($\Delta T_{[X]}/\Delta R_{[X]}$), to a similar ratio caused by CO_2 radiative forcing

$(\Delta T_{[CO_2]}/\Delta R_{[CO_2]})$. This introduction of efficacy requires a reformulation of f as f_ε:

$$f_\varepsilon = \frac{\varepsilon_{[X]}\Delta R_{[X]}}{\Delta R_{[CO_2]} + \varepsilon_{[X]}\Delta R_{[X]}} = 1 - \frac{\Delta R_{[CO_2]}}{\Delta R_{[CO_2]} + \varepsilon_{[X]}\Delta R_{[X]}}, \tag{8}$$

and hence also of $S_{[CO_2,X]}$ as $S^{\varepsilon}_{[CO_2,X]}$:

$$S^{\varepsilon}_{[CO_2,X]} = \frac{\Delta T_g}{\Delta R_{[CO_2]} + \varepsilon_{[X]}\Delta R_{[X]}}. \tag{9}$$

In these reformulations, where in principal $\varepsilon_{[X]}$ can take any value, we introduce the superscript ε. This serves to clearly distinguish these newly-derived sensitivities from those of the PALAEOSENS project in which efficacy was not taken into account, implying that identical radiative forcing of different processes leads to identical temperature changes.

To calculate $S^{\varepsilon}_{[CO_2,LI]}$, we constrain the efficacy factor for radiative forcing by land ice changes ($\varepsilon_{[LI]}$), using the following formulation, which is based on, but slightly modified from Hansen et al. (2005):

$$\frac{\Delta T_{[LI]}}{\Delta R_{[LI]}} = \varepsilon_{[LI]}\frac{\Delta T_g - \Delta T_{[LI]}}{\Delta R_{[CO_2]}}. \tag{10}$$

This leads to:

$$\varepsilon_{[LI]} = \frac{\omega}{1-\omega}\frac{\Delta R_{[CO_2]}}{\Delta R_{[LI]}}, \tag{11}$$

where ω represents the fractional relative influence of land ice changes on the global temperature change ($\omega = \Delta T_{[LI]}/\Delta T_g$). If $\varepsilon_{[LI]}$ is assumed to be constant in time (see Sect. 3.2 and 5), it can be calculated using Eq. 11 from data of any specific moment in time, and consequently applied to the whole record of $\Delta R_{[CO_2]}$ and $\Delta R_{[LI]}$ (Fig. 1a,c). As before, with this $\varepsilon_{[LI]}$ a quantification of $S^{\varepsilon}_{[CO_2,LI]}$ can be obtained by performing a least-squares regression through scattered data from paleotemperature and radiative forcing records, now relating ΔT_g to $(\Delta R_{[CO_2]} + \varepsilon_{[LI]}\Delta R_{[LI]})$ in a time-independent manner.

Note that apart from the formulation based on Hansen et al. (2005) followed here, other formulations of the efficacy factor are possible. For instance, one can define an alternative efficacy factor ($\varepsilon_{[LI],alt}$) such that it relates the effect of land ice changes on global temperature directly to the radiative forcing anomaly caused by CO_2 changes, leading to:

$$S^{\varepsilon}_{[CO_2,X],alt} = \frac{\Delta T_g}{\Delta R_{[CO_2]} + \varepsilon_{[LI],alt}\Delta R_{[CO_2]}}. \tag{12}$$

In this alternative case, the efficacy factor $\varepsilon_{[LI],alt}$ relates to our original $\varepsilon_{[LI]}$ as:

$$\varepsilon_{[LI],alt} = \varepsilon_{[LI]}\frac{\Delta R_{[LI]}}{\Delta R_{[CO_2]}}. \tag{13}$$

This implies that if $\varepsilon_{[LI]}$ is indeed constant, any non-linearity in the relation between $\Delta R_{[CO_2]}$ and $\Delta R_{[LI]}$ would demand a more complex formulation of the alternative efficacy factor $\varepsilon_{[LI],alt}$ (e.g. via a higher-order polynomial). Since we find such a non-linearity in our data (Fig. 2), using an F test to determine that a second order polynomial is a significantly (p value < 0.0001) better fit to the data than a linear function, we refrain from following this alternative formulation further.

2.3 Refinement 2: Unifying the dependent variable

In the cross-plots of radiative forcing and global temperature anomalies used to calculate $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$, the radiative forcing on the x-axis is caused by a combination of CO_2 and land-ice changes. To more readily compare $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$ to other specific paleoclimate sensitivities $S^{\varepsilon}_{[\mathrm{CO_2,X}]}$, where more and/or different long-term processes are considered, the dependent variable has to be unified. Here, we therefore reformulate our equation to get $\Delta R_{[\mathrm{CO_2}]}$ in the nominator, enabling the use of cross-plots that now have $\Delta R_{[\mathrm{CO_2}]}$ on the x-axis.

$$S^{\varepsilon}_{[\mathrm{CO_2,X}]} = \frac{\Delta T_{\mathrm{g}}}{\Delta R_{[\mathrm{CO_2}]} + \varepsilon_{[\mathrm{X}]}\Delta R_{[\mathrm{X}]}} = \frac{\Delta T_{\mathrm{g}}}{\Delta R_{[\mathrm{CO_2}]}} \frac{\Delta R_{[\mathrm{CO_2}]}}{\Delta R_{[\mathrm{CO_2}]} + \varepsilon_{[\mathrm{X}]}\Delta R_{[\mathrm{X}]}} = \frac{\Delta T^{\varepsilon}_{[-\mathrm{X}]}}{\Delta R_{[\mathrm{CO_2}]}}. \tag{14}$$

Here, $\Delta T^{\varepsilon}_{[-\mathrm{X}]}$ is the global temperature change (with respect to PI) stripped of the inferred influence of processes X, defined as:

$$\Delta T^{\varepsilon}_{[-\mathrm{X}]} := \Delta T_{\mathrm{g}} \frac{\Delta R_{[\mathrm{CO_2}]}}{\Delta R_{[\mathrm{CO_2}]} + \varepsilon_{[\mathrm{X}]}\Delta R_{[\mathrm{X}]}}. \tag{15}$$

Hence, for the calculation of $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$ we use:

$$\Delta T^{\varepsilon}_{[-\mathrm{LI}]} := \Delta T_{\mathrm{g}} \frac{\Delta R_{[\mathrm{CO_2}]}}{\Delta R_{[\mathrm{CO_2}]} + \varepsilon_{[\mathrm{LI}]}\Delta R_{[\mathrm{LI}]}}. \tag{16}$$

Now, we quantify $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$ by performing a least-squares regression (regfunc) through scattered data from $\Delta T^{\varepsilon}_{[-\mathrm{LI}]}$ and $\Delta R_{[\mathrm{CO_2}]}$. We use the precondition that no change in CO_2 is related to no change in $\Delta T^{\varepsilon}_{[-\mathrm{LI}]}$, meaning the regression intersects the y-axis at the origin ($(x,y) = (0,0)$). Following Köhler et al. (2017b), for any non-zero $\Delta R_{[\mathrm{CO_2}]}$, we calculate $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$ as:

$$S^{\varepsilon}_{[\mathrm{CO_2,LI}]}\Big|_{\Delta R_{[\mathrm{CO_2}]}} = \frac{\mathrm{regfunc}}{\Delta R_{[\mathrm{CO_2}]}}\Big|_{\Delta R_{[\mathrm{CO_2}]}}. \tag{17}$$

If $\Delta R_{[\mathrm{CO_2}]} = 0\,\mathrm{W\,m^{-2}}$, as is among others the case for pre-industrial conditions, $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$ is quantified as:

$$S^{\varepsilon}_{[\mathrm{CO_2,LI}]}\Big|_{\Delta R_{[\mathrm{CO_2}]}=0} = \frac{\delta(\mathrm{regfunc})}{\delta(\Delta R_{[\mathrm{CO_2}]})}\Big|_{\Delta R_{[\mathrm{CO_2}]}=0}. \tag{18}$$

Equations 17 and 18 yield a quantification of $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$, which can be compared to the value obtained for $S_{[\mathrm{CO_2,LI}]}$ using the approach without considering efficacy (equivalent to using $\varepsilon_{[\mathrm{LI}]} = 1$) (Köhler et al., 2018).

In this study, we continue to use a multiplication factor of 0.64 to obtain S^a from $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$. Note that this scaling still assumes unit efficacy for processes other than land ice changes. Therefore, it is a source of uncertainty to be investigated in future research. The equivalent ECS (in K per CO_2 doubling) can again be calculated by multiplying S^a by 3.7 $\mathrm{W\,m^{-2}}$.

3 Validation of the approach using model simulations

In this section, we validate our refined approach by applying it to transient simulations over the past 5 Myr using CLIMBER-2 (Stap et al., 2018). We compare the results of our approach of obtaining the sole effect of CO_2 changes on global temperature from a simulation forced by land ice and CO_2 changes, to a simulation where CO_2 changes are the only operating long-term process. By doing so, we assess the error resulting from using a constant efficacy factor.

3.1 CLIMBER-2 model simulations

Using the intermediate complexity climate model CLIMBER-2 (Petoukhov et al., 2000; Ganopolski et al., 2001), climate simulations over the past 5 Myr were performed and analysed in Stap et al. (2018). CLIMBER-2 combines a 2.5-dimensional statistical-dynamical atmosphere model, with a 3-basin zonally averaged ocean model (Stocker et al., 1992), and a model that calculates dynamic vegetation cover based on the temperature and precipitation (Brovkin et al., 1997). In brief, the simulations are forced by solar insolation which changes due to orbital (O) variations (Laskar et al., 2004), and further by land ice (I) changes on both hemispheres (based on de Boer et al., 2013), and CO_2 (C) changes (based on van de Wal et al., 2011). In the reference experiment (OIC) all input data are varied, while in other model integrations the land ice (experiment OC) or the CO_2 concentration (experiment OI) is kept fixed at PI level. The synergy of land ice and CO_2 changes is negligibly small, meaning their induced temperature changes add approximately linearly when both forcings are applied. Furthermore, the influence of orbital variations is also very small, so that experiment OC approximately yields the sole effect of CO_2 changes on global temperature ($\Delta T_{[\mathrm{OC}]}$). As in Stap et al. (2018), we use the simple energy balance model of Köhler et al. (2010) to analyse the applied radiative forcing of land ice albedo and CO_2 changes and simulated global temperature changes, after averaging to 1,000 year temporal resolution (Fig. 1a,b).

3.2 Analysis

First, we analyse experiment OC, which will serve as a target for our refined approach as deployed later in this section. We use a least-squares regression through scattered data of $\Delta R_{[\mathrm{CO_2}]}$ and $\Delta T_{[\mathrm{OC}]}$ to fit a second order polynomial (Fig. 3a). Using a higher order polynomial rather than a linear function allows us to capture state dependency of paleoclimate sensitivity. Fitting even higher order polynomials leads to negligible coefficients for the higher powers, and is not pursued further. From the fit, we calculate a specific paleoclimate sensitivity $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$ of 0.74 $\mathrm{K\,W^{-1}\,m^2}$ for PI conditions ($\Delta R_{[\mathrm{CO_2}]} = 0\ \mathrm{W\,m^{-2}}$) using Eq. 18. Note that, in this case, $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$ is equal to $S^{\varepsilon}_{[\mathrm{CO_2}]}$, $S_{[\mathrm{CO_2,LI}]}$ and $S_{[\mathrm{CO_2}]}$ as there are no land ice changes and therefore also no efficacy differences. The fit further shows decreasing $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$ for rising $\Delta R_{[\mathrm{CO_2}]}$.

Now, we apply our approach to the results of experiment OIC, in which both CO_2 and land ice cover vary over time, with the aim of deducing the sole effect of CO_2 changes on global temperature. We calculate the efficacy of land ice changes for the Last Glacial Maximum (21 kyr ago; LGM) from experiment OI, in which the CO_2 concentration is kept constant. We obtain $\omega = \Delta T_{[\mathrm{LI}]}/\Delta T_{\mathrm{g}} = \Delta T_{[\mathrm{OI}]}/\Delta T_{[\mathrm{OIC}]} = 0.54$. Consequently, we find $\varepsilon_{[\mathrm{LI}]} = 0.58$ from Eq. 11, and apply this value to the whole record of $\Delta R_{[\mathrm{CO_2}]}$ and $\Delta R_{[\mathrm{LI}]}$. In this manner, we calculate $\Delta T^{\varepsilon}_{[-\mathrm{LI}]}$ using Eq. 16. We then fit a second order polynomial to the scattered data of the thusly obtained $\Delta T^{\varepsilon}_{[-\mathrm{LI}]}$ from the results of experiment OIC, and $\Delta R_{[\mathrm{CO_2}]}$ (Fig. 3b). Between $\Delta R_{[\mathrm{CO_2}]} = -0.5\,\mathrm{W\,m^{-2}}$ and $\Delta R_{[\mathrm{CO_2}]} = 0.5\,\mathrm{W\,m^{-2}}$, outliers resulted from division by small numbers (not shown in Fig. 3b). To remove these outliers, we first calculate the root mean square error (RMSE) between the fit and the data in the remainder of the domain. We then exclude all 144 values from the range $\Delta R_{[\mathrm{CO_2}]} = -0.5\,\mathrm{W\,m^{-2}}$ to $\Delta R_{[\mathrm{CO_2}]} = 0.5\,\mathrm{W\,m^{-2}}$ where the fit differs from the data by more than 3 × RMSE, and perform the regression again. This yields an $S^{\varepsilon}_{[CO_2,LI]}$ of $0.72\,\mathrm{K\,W^{-1}\,m^2}$ for PI (Fig. 3b), which supports our approach since it is only slightly lower than the $S^{\varepsilon}_{[CO_2,LI]}$ of $0.74\,\mathrm{K\,W^{-1}\,m^2}$ obtained from experiment OC, which it should approximate. The relationship between $\Delta T^{\varepsilon}_{[-LI]}$ and $\Delta R_{[CO_2]}$ (Fig. 3b) is more linear than that between $\Delta T_{[OC]}$ and $\Delta R_{[CO_2]}$ (Fig. 3a), hence the state dependency of $S^{\varepsilon}_{[CO_2,LI]}$ is reduced. However, the difference between the $S^{\varepsilon}_{[CO_2,LI]}$ obtained from both experiments remains smaller than $0.07\,\mathrm{K\,W^{-1}\,m^2}$ through the entire 5-Myr interval, indicating that a constant efficacy is an acceptable assumption which only introduces a negligible additional uncertainty. However, the possible time-dependency of efficacy could be investigated more rigorously in future research using more sophisticated climate models.

In principal, $\varepsilon_{[LI]}$ can be obtained using data from any moment in time, preferably when the radiative forcing anomalies are large to prevent outliers resulting from divisions by small numbers. For example, using the results from all glacial marine isotope stages of the past 810 kyr (MIS 2, 6, 8, 10, 12, 14, 16, 18, and 20), instead of just the LGM, leads to a mean ($\pm 1\sigma$) $\varepsilon_{[LI]}$ of 0.56 ± 0.09. The resulting PI $S^{\varepsilon}_{[CO_2,LI]}$ is $0.73^{+0.06}_{-0.05}\,\mathrm{K\,W^{-1}\,m^2}$ (Fig. 3c).

The old approach, which is equal to using $\varepsilon_{[LI]} = 1$ in the refined approach, yields a PI $S_{[CO_2,LI]}$ of $0.54\,\mathrm{K\,W^{-1}\,m^2}$ (Fig. 3d). This is clearly much more off-target than the results of our refined approach, signifying the importance of considering efficacy.

4 Application to proxy-inferred paleoclimate data

In this section, we compare our refined approach to calculate $S^{\varepsilon}_{[CO_2,LI]}$ incorporating efficacy, to our previous quantification of $S_{[CO_2,LI]}$ (Köhler et al., 2018), by reanalysing the same paleoclimate dataset (introduced in Köhler et al., 2015). Other than for climate model simulations, the influence of land ice changes on global temperature perturbations cannot be directly obtained from proxy-based datasets, and is hence a-priori unknown. We therefore base the value of $\varepsilon_{[LI]}$ we implement here on a multi-model assemblage of simulated relative influences of land ice changes on the Last Glacial Maximum (LGM) temperature anomaly (Shakun, 2017).

4.1 Proxy-inferred paleoclimate dataset

The investigated dataset contains reconstructions of ΔT_g, $\Delta R_{[CO_2]}$, and $\Delta R_{[LI]}$. Although it covers the past 5 Myr, here we focus on the past 800 kyr (Fig. 1c,d) because over this period $\Delta R_{[CO_2]}$ is constrained by high-fidelity ice core CO_2 data, whereas Pliocene and Early Pleistocene CO_2 levels are still heavily debated (e.g. Badger et al., 2013; Martínez-Botí et al., 2015; Willeit et al., 2015; Stap et al., 2016, 2017; Chalk et al., 2017; Dyez et al., 2018). Radiative forcing by CO_2 is obtained from Antarctic ice core data compiled by Bereiter et al. (2015), using $\Delta R_{[CO_2]} = 5.35\,\mathrm{W\,m^{-2}} \cdot \ln(CO_2/(278\,\mathrm{ppm}))$ (Myhre et al., 1998). Revised formulations of $\Delta R_{[CO_2]}$ following Etminan et al. (2016) lead to very similar results with less than 0.01 $\mathrm{W\,m^{-2}}$ differences between the approaches for typical late Pleistocene CO_2 values (Köhler et al., 2017a). Radiative forcing caused by land ice albedo changes, as well as the global surface air temperature record (ΔT_g), are based on results of the 3D ice-sheet model ANICE (de Boer et al., 2014). ANICE was forced by northern hemispheric temperature anomalies with respect to a reference PI climate, obtained from a benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005) using an inverse technique.

This provided geographically specific land ice distributions, and hence radiative forcing due to albedo changes with respect to PI on both hemispheres. In Köhler et al. (2015), the northern hemispheric (NH) temperature anomalies ($\Delta T_{\rm NH}$) are translated into global temperature perturbations (ΔT_{g1} in Köhler et al. (2015)) using polar amplification factors ($f_{\rm PA} = \Delta T_{\rm NH}/\Delta T_{\rm g}$) as follows: at the LGM, $f_{\rm PA} = 2.7$ is taken from the average of PMIP3 model data (Braconnot et al., 2012), while at the mid-Pliocene Warm Period (mPWP, about 3.2 Myr ago), $f_{\rm PA} = 1.6$ is calculated from the average of PlioMIP results (Haywood et al., 2013). At all other times, $f_{\rm PA}$ is linearly varied as a function of NH temperature. In Appendix A, we investigate the influence of the chosen polar amplification factor (Köhler et al., 2015) on our results. The temperature dynamics follow from a benthic δ^{18}O stack and are unconstrained by climatic boundary conditions such as insolation and greenhouse gases, since ANICE only simulates land ice dynamics. Therefore, these results are here considered to be more similar to those of proxy-based reconstructions than of climate-model-based simulations. The temporal resolution of the dataset is 2,000 years.

Analysing this dataset, Köhler et al. (2018) found a temperature-CO_2 divergence appearing mainly during, or in connection with, periods of decreasing obliquity related to land ice growth or sea level fall. For these periods, a significantly different $S_{\rm [CO2,LI]}$ was obtained than for the remainder of the time frame. However, in the future we expect sea level to rise, hence these intervals of strong temperature-CO_2 divergence should not be considered for the interpretation of paleodata in the context of future warming, e.g. by using paleodata to constrain ECS. In the following analysis, we therefore exclude these times with strong temperature-CO_2 divergence, leaving 217 data points as indicated in Fig. 1c,d.

4.2 Analysis

Shakun (2017) compiled the simulated relative impact of land ice changes on the LGM temperature anomaly (ω in Eq. 11) using a 12-member climate model ensemble, and found a range of 0.46 ± 0.14 (mean $\pm 1\sigma$, full range $0.20 - 0.68$). Applying these values, in combination with the LGM values (taken here as the mean of the data at 20 and 22 kyr ago) $\Delta R_{\rm [CO_2]} = -2.04\,{\rm W\,m^{-2}}$ and $\Delta R_{\rm [LI]} = -3.88\,{\rm W\,m^{-2}}$, yields $\varepsilon_{\rm [LI]} = 0.45^{+0.34}_{-0.20}$. Implementing this range for $\varepsilon_{\rm [LI]}$ in Eq. 16, we calculate $\Delta T^{\varepsilon}_{\rm [-LI]}$ over the whole 800-kyr period. Fitting second order polynomials by least-squares regression to the scattered data of $\Delta T^{\varepsilon}_{\rm [-LI]}$ and $\Delta R_{\rm [CO_2]}$, we infer a PI $S^{\varepsilon}_{\rm [CO_2,LI]}$ of $2.45^{+0.53}_{-0.56}\,{\rm K\,W^{-1}\,m^2}$ (Fig. 4a). The substantial uncertainty given here only reflects the 1σ uncertainty in $\varepsilon_{\rm [LI]}$. Similar to Köhler et al. (2018), we also detect a state dependency with decreasing $S^{\varepsilon}_{\rm [CO_2,LI]}$ towards colder climates for this dataset, more strongly so in case of lower $\varepsilon_{\rm [LI]}$. This state dependency is opposite to the one found in the CLIMBER-2 results. The difference may be related to the fact that fast climate feedbacks are too linear, or that some slow feedbacks are underestimated in intermediate complexity climate models like CLIMBER-2 (see Köhler et al., 2018, for a detailed discussion). At $\Delta R_{\rm [CO_2]} = -2.04\,{\rm W\,m^{-2}}$, the LGM value, $S^{\varepsilon}_{\rm [CO_2,LI]}$ is only $1.45^{+0.33}_{-0.37}\,{\rm K\,W^{-1}\,m^2}$. The old approach, which does not consider efficacy and is therefore equivalent to the new approach using $\varepsilon_{\rm [LI]} = 1$, yields $S_{\rm [CO_2,LI]} = 1.66\,{\rm K\,W^{-1}\,m^2}$ for PI, and $S_{\rm [CO_2,LI]} = 0.93\,{\rm K\,W^{-1}\,m^2}$ for the LGM (Fig. 4b). The specific paleoclimate sensitivities we find using the refined approach are hence generally larger than those obtained by using the old approach. This is because, for the range of the impact of land ice changes on the LGM temperature anomaly implemented ($\omega = 0.46 \pm 0.14$), the efficacy factor $\varepsilon_{\rm [LI]}$ is smaller than unity. In other words, these land ice changes contribute comparatively less per unit radiative forcing to the global temperature anomalies than the CO_2 changes.

Our inferred PI $S^{\varepsilon}_{[CO_2,LI]}$ is equivalent to an S^a of $1.6^{+0.3}_{-0.4}\,\mathrm{K\,W^{-1}\,m^2}$, and an ECS of $5.8 \pm 1.3\,\mathrm{K}$ per CO_2 doubling. This is on the high end of the results of other approaches to obtain ECS (Knutti et al., 2017), e.g. the 2.0 to 4.3 K 95%-confidence range from a large model ensemble (Goodwin et al., 2018), and the 2.2 to 3.4 K 66% confidence range from an emerging constraint from global temperature variability and CMIP5 (Cox et al., 2018). Hence, the low end of our ECS estimate is in the best agreement with these other estimates. This could mean that the influence the relative influence of land ice changes on the LGM temperature anomaly is on the high side, or possibly higher than, the 0.46 ± 0.14 range we consider here. Alternatively, the factor of 0.64 we use to convert $S_{[CO_2,LI]}$ to S^a is an overestimation, which could be caused by a larger-than-unity efficacy of long-term processes besides CO_2 and land ice changes.

5 Conclusions

We have incorporated the concept of a constant efficacy factor (Hansen et al., 2005), that interrelates the global temperature responses to radiative forcing caused by land ice changes and CO_2 changes, into our framework of calculating specific paleoclimate sensitivity $S^{\varepsilon}_{[CO_2,LI]}$. The aim of this effort has been to overcome the problem that land ice and CO_2 changes can lead to significantly different global temperature responses, even when they induce the same global-average radiative forcing. Firstly, we have shown the importance of considering efficacy differences by applying our new approach to results of 5-Myr CLIMBER-2 simulations (Stap et al., 2018), where the separate effects of land ice changes and CO_2 changes can be isolated. In the results of these simulations, the error from assuming the efficacy factor to be constant in time is negligible. Thereafter, we have used our new approach to reanalyse an 800-kyr proxy-inferred paleoclimate dataset (Köhler et al., 2015). We have inferred a range in the land ice change efficacy factor $\varepsilon_{[LI]}$ from the 0.46 ± 0.14 (mean $\pm 1\sigma$) relative impact of land ice changes on the LGM temperature anomaly simulated by a 12-member climate model ensemble (Shakun, 2017). The thusly obtained efficacy factor $\varepsilon_{[LI]}$ is smaller than unity, implying that the impact on global temperature per unit of radiative forcing is less strong for land ice changes than for CO_2 changes. Consequently, our derived PI $S^{\varepsilon}_{[CO_2,LI]}$ of $2.45^{+0.53}_{-0.56}\,\mathrm{K\,W^{-1}\,m^2}$ is $\sim$50% larger than the result of the old approach. The uncertainty in this estimate is only caused by the implemented range in $\varepsilon_{[LI]}$. The equivalent S^a and ECS corresponding to this $S^{\varepsilon}_{[CO_2,LI]}$ are $1.6^{+0.3}_{-0.4}\,\mathrm{K\,W^{-1}\,m^2}$ and $5.8 \pm 1.3\,\mathrm{K}$ per CO_2 doubling respectively.

Data availability. The CLIMBER-2 dataset is available at https://doi.pangaea.de/10.1594/PANGAEA.887427, and the proxy-inferred paleoclimate dataset is available at https://doi.pangaea.de/10.1594/PANGAEA.855449, from the PANGAEA database. For more information or data, please contact the authors.

Appendix A: Influence of the polar amplification factor

In the analysis performed in Sect. 4.2, we have used a global temperature record that was obtained from northern high-latitude temperature anomalies using a polar amplification factor f_{PA} that varies from 2.7 at the coldest to 1.6 at the warmest conditions (Sect. 4.1). However, recent climate model simulations of the Pliocene using updated paleogeographic boundary conditions show that in warmer times polar amplification could have been nearly the same as in colder times (Kamae et al., 2016; Chandan and Peltier, 2017). We therefore repeat the analysis using the same range in $\varepsilon_{[\mathrm{LI}]}$ and the same dataset, but with an applied constant $f_{\mathrm{PA}} = 2.7$ over the entire past 800 kyr to generate ΔT_g (ΔT_{g2} in Köhler et al. (2015)).

The constant polar amplification used here counteracts increasing state dependency towards low temperatures, as the temperature differences are no longer amplified by changing polar amplification. Hence, $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$ is smaller at PI, $1.96^{+0.42}_{-0.44}\,\mathrm{K\,W^{-1}\,m^2}$ compared to $2.45^{+0.53}_{-0.56}\,\mathrm{K\,W^{-1}\,m^2}$ using the variable f_{PA}, but diminishes less strongly towards colder conditions (Fig. A1a cf. Fig. 4a). As before, the old approach (equivalent to the new approach using $\varepsilon_{[\mathrm{LI}]} = 1$), yields a lower PI $S_{[\mathrm{CO_2,LI}]}$ of $1.34\,\mathrm{K\,W^{-1}\,m^2}$ (Fig. A1b). The PI $S^{\varepsilon}_{[\mathrm{CO_2,LI}]}$ inferred here using the refined approach corresponds to an S^a of $1.3^{+0.2}_{-0.3}\,\mathrm{K\,W^{-1}\,m^2}$, and an ECS of $4.6^{+1.0}_{-1.3}\,\mathrm{K}$ per CO_2 doubling.

Author contributions. L.B.S. designed the research. L.B.S. and P.K. performed the analysis. L.B.S. drafted the paper, with input from all co-authors.

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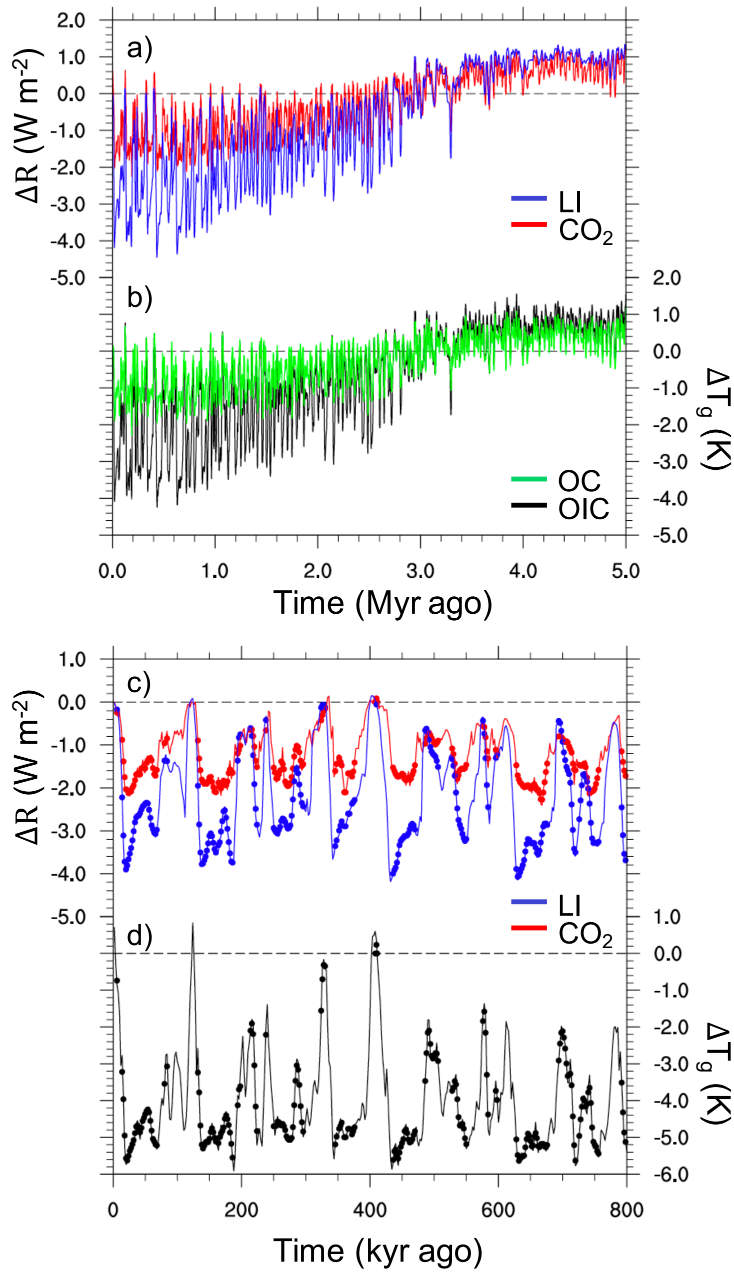

Figure 1. Timeseries of radiative forcing anomalies (ΔR) caused by CO_2 (red) changes and land ice changes (blue), and global temperature anomalies (ΔT_g) with respect to PI, from **a-b)** the CLIMBER-2 model dataset (Stap et al., 2018), with temperature data for experiment OIC in black and for experiment OC in green, and from **c-d)** the proxy-inferred dataset (Köhler et al., 2015), with solid lines for the whole dataset, and dots for the data used in this study which exclude times with strong temperature-CO_2 divergence (see Sect. 4.1). Note the differing axis scales.

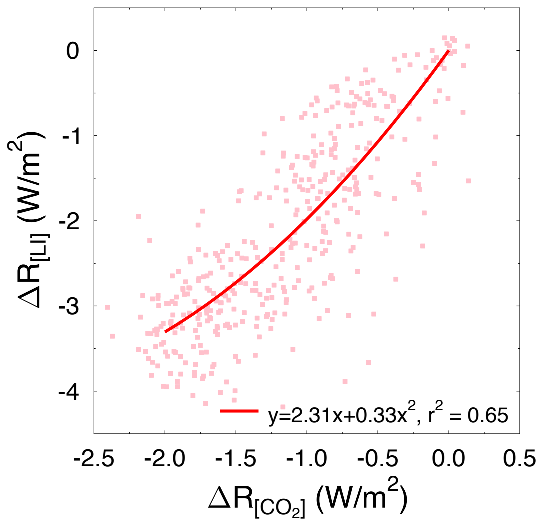

Figure 2. The relation between radiative forcing anomalies caused by CO_2 changes ($\Delta R_{[CO_2]}$) and land ice changes ($\Delta R_{[LI]}$) from the proxy-inferred dataset (Köhler et al., 2015) (pink dots). The red line represents a second order polynomial least-squares regression through the scattered data.

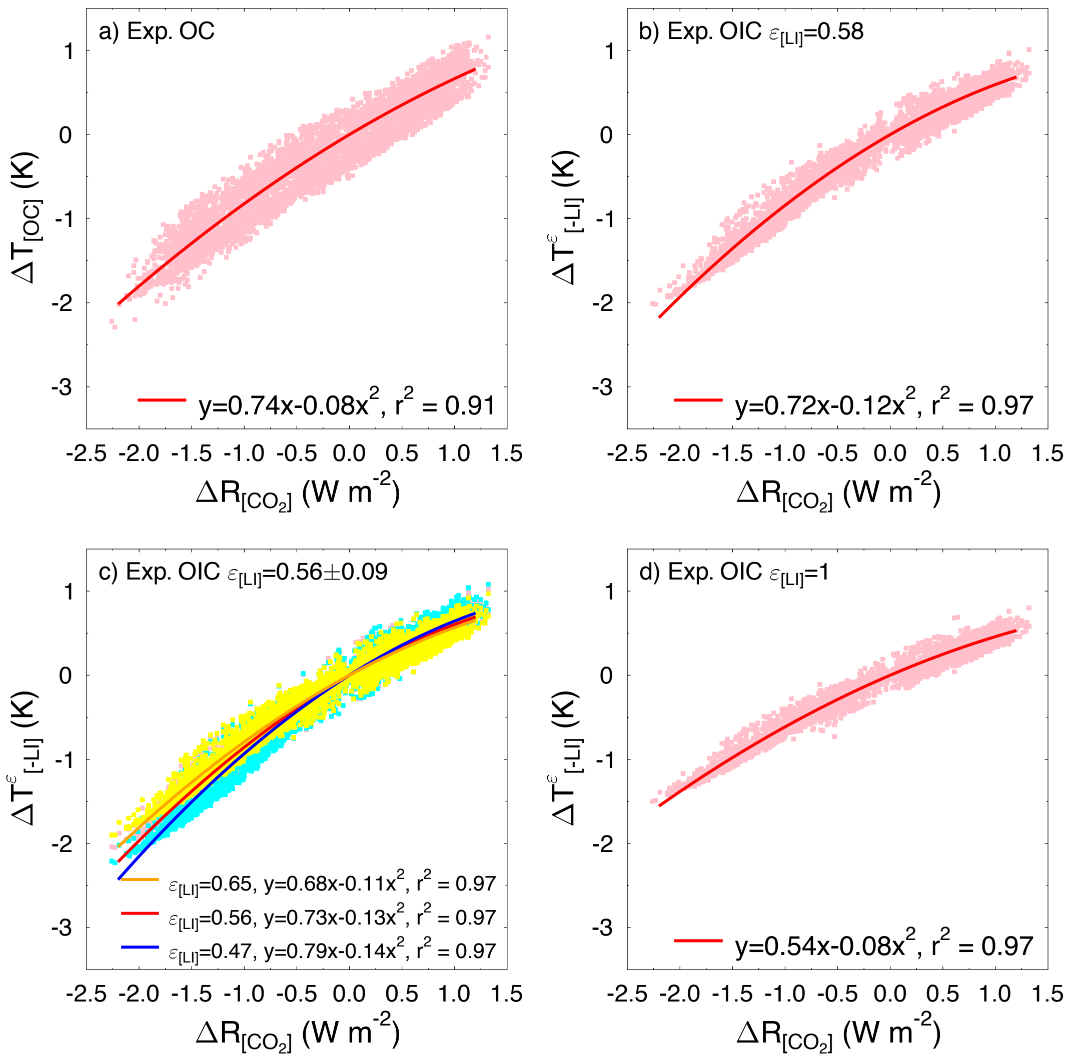

Figure 3. Temperature anomalies with respect to PI over the last 5 Myr from CLIMBER-2 (Stap et al., 2018) against imposed radiative forcing of CO_2. **a)** Simulation with fixed PI land ice distribution (experiment OC) ($\Delta T_{[OC]}$). **b)** Calculated global temperature perturbations from experiment OIC stripped of the inferred influence of land ice ($\Delta T^{\varepsilon}_{[-LI]}$) using Eq. 16 with $\varepsilon_{[LI]} = 0.58$. Here, $\varepsilon_{[LI]}$ is obtained from matching climate sensitivity with the target value at the LGM. **c)** Same as in (b), but using $\varepsilon_{[LI]} = 0.47$ (cyan dots), $\varepsilon_{[LI]} = 0.56$ (pink dots), and $\varepsilon_{[LI]} = 0.65$ (yellow dots), Here, $\varepsilon_{[LI]}$ is obtained from the mean ($\pm 1\sigma$) of matching climate sensitivity with the target value at all glacial marine isotope stages of the past 810 kyr (MIS 2, 6, 8, 10, 12, 14, 16, 18, and 20). **d)** Same as in (b), but using $\varepsilon_{[LI]} = 1$, which is equivalent to the old approach where efficacy differences were not considered. The red lines - and in **(c)** also the orange and blue lines - represent second order polynomial least-squares regressions through the scattered data.

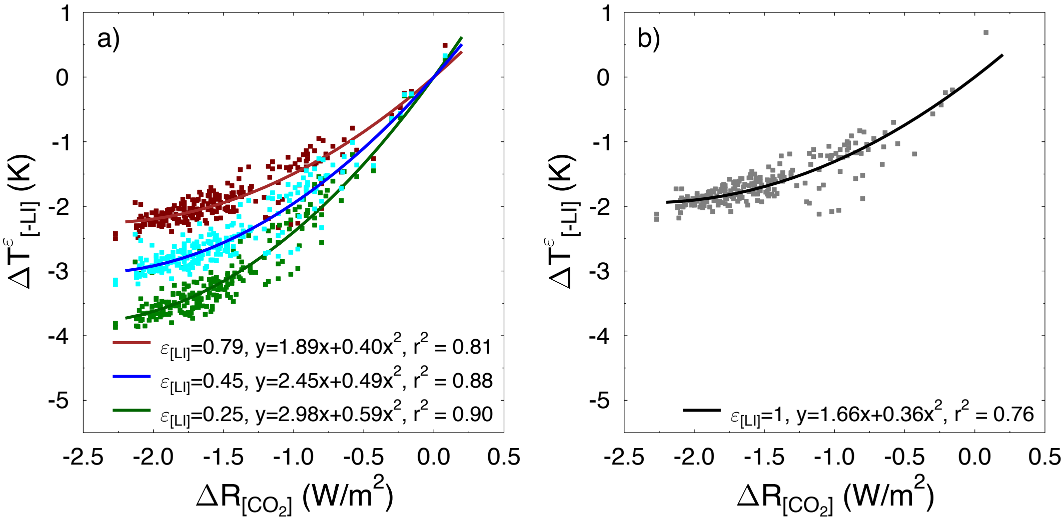

Figure 4. The global temperature perturbations stripped of the inferred influence of land ice ($\Delta T^{\varepsilon}_{[-\mathrm{LI}]}$) calculated using Eq. 16 against $\Delta R_{[\mathrm{CO_2}]}$ from the proxy-inferred paleoclimate dataset (Köhler et al., 2015), using: **a)** $\varepsilon_{[\mathrm{LI}]} = 0.79$ (maroon dots), $\varepsilon_{[\mathrm{LI}]} = 0.45$ (cyan dots), and $\varepsilon_{[\mathrm{LI}]} = 0.25$ (green dots). Here, $\varepsilon_{[\mathrm{LI}]}$ is obtained by converting the multi-model assemblage of simulated relative influences of land ice changes on the LGM temperature anomaly (0.46 ± 0.14) (Shakun, 2017). **b)** Same as in (a), but using $\varepsilon_{[\mathrm{LI}]} = 1$ (grey dots), which is equivalent to the old approach. The brown, blue, dark green (**a**), and black lines (**b**) represent second order polynomial least-squares regressions through the data.

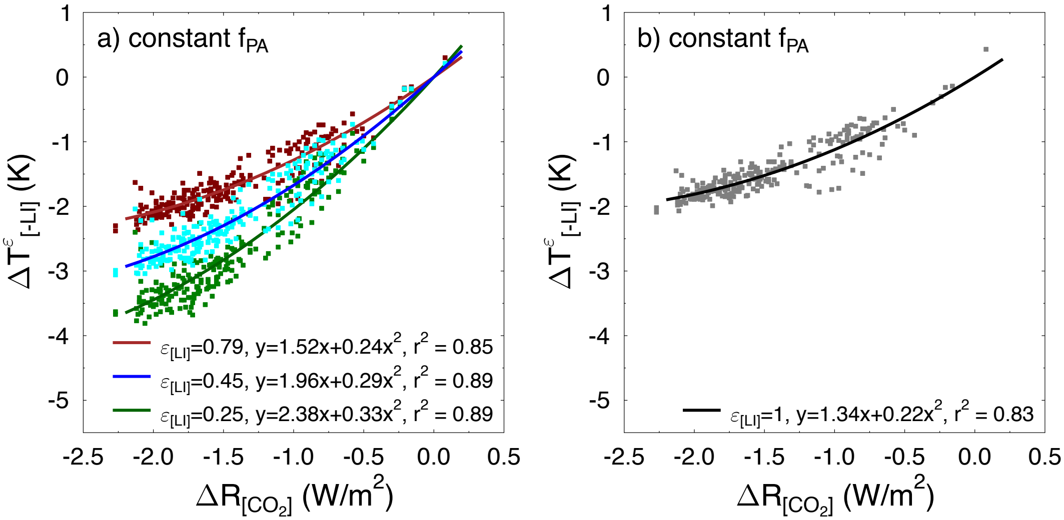

Figure A1. The global temperature perturbations stripped of the inferred influence of land ice ($\Delta T^{\varepsilon}_{[-\mathrm{LI}]}$) calculated using Eq. 16 against $\Delta R_{[\mathrm{CO_2}]}$ from the proxy-inferred paleoclimate dataset (Köhler et al., 2015), using: **a)** $\varepsilon_{[\mathrm{LI}]} = 0.79$ (maroon dots), $\varepsilon_{[\mathrm{LI}]} = 0.45$ (cyan dots), and $\varepsilon_{[\mathrm{LI}]} = 0.25$ (green dots). Here, $\varepsilon_{[\mathrm{LI}]}$ is obtained from converting the multi-model assemblage of simulated relative influences of land ice changes on the LGM temperature anomaly (0.46 ± 0.14) (Shakun, 2017). **b)** Same as in (a), but using $\varepsilon_{[\mathrm{LI}]} = 1$ (grey dots), which is equivalent to the old approach. The brown, blue, dark green (**a**), and black lines (**b**) represent second order polynomial least-squares regressions through the data. Here, the global temperature anomalies are derived from the northern high-latitude temperature anomaly reconstruction assuming a constant polar amplification factor (f_{PA}) of 2.7, as opposed to the variable f_{PA} used in Fig. 4.