Reply to comments by reviewer 2: Exploring Holocene temperature trends and a potential summer bias in simulations and reconstructions (egusphere-2023-86)

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Summary of Changes

We thank the reviewer for taking the time to assess our work and providing valuable and detailed feedback. In response, we revise and expand the analysis by

- further exploring the role of seasonality in the temp12k dataset by,
- expanding on the role and benefits of TransEBM. To this end, we carry out revisions in the text and appendix and add sensitivity experiments,
- discussing the presence/ absence of the late Holocene cooling mode in different MPI-ESM simulations.

Below, we provide a detailed response to the reviewer's comments and describe the actions we plan to take in response. We are grateful for the reviewer's comments and suggested improvements, which will help improve our study as outlined below.

Detailed response

(Original report cited in italics)

Reviewer's comment:

Wirths et al. summarise a comparison of simulations and reconstructions of temperature trends over three phases of the Holocene. They confirm important differences between the warming seen in models and the cooling reconstructed in temp12k. They conclude that a simple seasonal bias in the temp12k proxy records is unlikely to be able to explain the differences with the model runs.

Authors' reply:

We thank the reviewer for the positive evaluation of our work.

Reviewer's comment:

A main assumption within this work is that the seasonal and annual reconstructions extracted from temp12k are able to separately resolve the seasons. I am no expert in this dataset, but this seems unlikely to be the case. In fact if we can take the separate seasonal records at face value then we can immediately conclude that the seasonal bias is not the answer to the 'Holocene *temperature conundrum'. My best guess would be that the annual and summer reconstructions are probably both somewhat a mixture of several seasons, consistent with line 144: "reconstructions tend to show similar patterns in annual and summer temperature trends over all periods".*

Authors' reply:

We agree with the reviewer that the uncertainties attached to the seasonal reconstructions of the Temp12k dataset imply that they might not represent the season they are labelled as. Since the different proxies and reconstructions have a broad range of specific seasonality, the authors of the dataset (Kaufmann et. al. 2020b Scientific Data) used a "Season General" category to classify the reconstructions. They classify them in three general categories, annual, summer and winter, which we use in this study. Records representing spring or autumn were grouped with summer or winter, respectively (Kaufmann et. al. 2020b, Scientific Data). Additionally, Kaufmann et al. categorized proxy reconstructions supposed to represent a signal longer than six months, including June, as "annual" (Kaufmann et. al. 2020b, Scientific Data). A more detailed explanation of the seasonal labelling in the Temp12k dataset can be found in Kaufmann et. al. (2020b). We agree with the reviewer, that those decisions made by the original authors need to be addressed in more detail in our manuscript. We will therefore discuss this and the resulting implications in more detail in the revised version of the manuscript.

In our manuscript, we assume that the captured signal is dominated by the climatic conditions of the labelled season as it represents the best approximation of the recorded season according to the authors of the Temp12k database. However, we agree with the reviewer that proxy reconstructions labelled as summer do not necessarily represent the climate signal of the summer months. Instead they might be a convolution of the climate signal with a "productivity function". The use of proxy system models would be best able to account for this. As this is out of the scope of this study, we will add several tests to address these issues: First, in addition to checking for a summer bias in proxies, we will check whether certain proxy seasons might fit other model data better, e.g. compare trends in summer proxies with simulated winter temperatures. Second, we will compare model timeseries at proxy locations with each other, e.g. compare simulated winter and summer temperature trends. Since different proxies will exhibit different seasonal biases, this will establish upper bounds for possible effects of mislabelled seasons. Finally, we will test the effect of labelling proxy timeseries covering parts of the year (signals longer than six months, including June) as "annual", by analysing the effect of doing so in the simulations, e.g. comparing data from April to September with the annual timeseries.

Those additional analyses will allow us to provide upper limits on the influence of mislabelled seasons and allow us to quantify potential uncertainties in the classification.

Action:

- We will enhance the discussion of the Temp12k dataset, its labelling of different seasons and the underlying assumptions throughout the manuscript.

- We will carry out additional analyses to test and provide upper limits for the uncertainties attached to the seasonal labels.
- These additional results will be added to the manuscript and discussed.

Reviewer's comment:

In the abstract it is stated that: "our study shows that a trivial summer bias in proxies is not sufficient to explain the conundrum". I believe this is based on the comparison of summer simulations with annual records but it's not clear because, apart from the caveat around the records mentioned above, the modelled summer signal would be unlikely to resemble a summer-biased annual record. It seems more likely that it might look like a weighted combination of two seasons. Given this, I think the main finding around seasonality could benefit from further elaboration.

Authors' reply:

We thank the reviewer for raising this and will elaborate on our findings, especially the potential summer bias, in more detail in the revised version of the manuscript. In our study, we compare the modelled summer signal with the reconstructed annual signal as well as the modelled annual signal with the reconstructed annual signal. Under the assumption that the reconstructed annual signal is biased towards the summer months, we would assume that it shows a higher agreement with the modelled summer signal than with the modelled annual signal. As stated above, we aim to discuss the seasonal definitions of the Temp12k dataset in more detailed in a revised version of the manuscript. Together with the above proposed additional tests we are convinced this will substantially improve the manuscript.

Action:

- We will add additional analyses as stated above and expand the discussion of seasonality as suggested by the reviewer.

Reviewer's comment:

It's not always clear how the present study's use of the EBM adds to the existing debate. Instead the results seem to highlight where the EBM is significantly different from the other models and these already span a fairly large gradient of complexity. Perhaps one conclusion that could be strengthened is that a model like TransEBM is not greatly informative for this type of problem where seasonal differences are large?

Authors' reply:

We are convinced that simple models like TransEBM are useful tools for testing the sensitivity to individual forcings (e.g. as in Ellerhoff et al., 2022). We will add an analysis of such sensitivity experiments to the revised version, especially testing the role of volcanic forcing as outlined also in respone to reviewer 1. As the reviewer described, TransEBM shows the lowest agreement in temperature trend with the proxy reconstructions from all investigated models. Considering the linear nature of TransEBM, this highlights the fact that the observed temperature trends in the proxy reconstructions cannot be explained by the forcings themselves, but rather that internal, non-linear feedbacks of the climate system are vital. We will discuss the linear response of TransEBM and how its inclusion benefits our study in more detail in the revised version as described in response to reviewer 1 as well.

Action:

- We will include additional sensitivity experiments with TransEBM in the manuscript, analyse and discuss them.

Reviewer's comment:

The MPI-ESM simulations by Bader et al (2020) show a cooling mode as discussed in your introduction. It would be good to clarify here whether the simulation with MPI-ESM analysed here shows a similar result as it does not look to be the case from figure 1 or B3. If this is not the case, does this support your hypothesis about ocean spin up temperature being important or is there some other reason that can be identified?

Authors' reply:

Our study provides a comparison of early, mid-, and late Holocene climate trends. However, the simulation by Bader et al. (2020) covers only mid-Holocene to present-day. In our study, we therefore used the MPI-ESM simulation by Kleinen et al. (2020). The simulations differ in resolution, considered forcings and overall simulated time span. While the simulation by Bader et al. (2020) covers the mid-Holocene (6000 BCE) to 1850 CE, the simulation by Kleinen et al. (2020) runs from LGM to present-day and covers the full period of our study. The simulations also differ in applied ice sheet forcings. While the simulation by Kleinen et al. (2020) uses prescribed transient ice sheets from GLAC-1D (Tarasov et al., 2012; Briggs et al., 2014; Ivanovic et al., 2016), the simulations performed by Bader et al. keep ice sheet topography and extent constant.

The late Holocene cooling pattern, which correlates with the sea-ice extent in the simulation by Bader et al. (2020) is not observable in the MPI-ESM simulation by Kleinen et al. (2020) used in this study. Although there are the differences in the model setup and forcing, the lack of cooling mode may be related to the initialization of the simulations at different times and thus might support a stronger imprint of the ocean's initial state on the Holocene trend. We note that the Kleinen et al. simulation was initialized during the LGM and does not show the same cooling trend as the Bader et al. simulation initialized in the early to mid-Holocene, which shows some cooling. Considering that TransEBM does not show this cooling mode while being in perpetual equilibrium, this observation might be due to the MPI-ESM simulation by Bader et al. being in dis-equilibrium. At the same time, other simulations initialized during that time seem to not show the same cooling trend (c.f. Askær et al. 2022 Fig. 3), although a definite statement on this would require applying the methodology from Bader et al.

More, and more faithful, multi-proxy reconstructions of temperature variables on land, surface and deep ocean would help to further constrain the temperature trends. For example, observations of mean ocean temperature (MOT) showed that MOT peaked at the onset of the early Holocene around 12 thousand years ago and were rather constant afterwards (Bereiter et al., 2018; Haeberli et al., 2021). Yet, for the period of the Holocene climate maximum in global reconstructions around 6 thousand years ago MOT reconstructions are only sparsely available (Bereiter et al., 2018; Baggenstoss et al. 2019; Haeberli et al. 2021) due to clathrate formation in the ice core. To investigate this further, looking into differences of the energy uptake of the ocean during the Deglaciation and the Holocene would be an option if such model output were widely available. Additionally, mid-Holocene ice core data would potentially allow to fill the gap in the reconstructed MOT to clarify if there was a thermal maximum in MOT as well.

Action:

- We will enhance discussion regarding the presence/absence of the cooling mode in the two MPI-ESM simulations.

Reviewer's comment:

It seems like a major difference between TransEBM and the other 3D models arises in the polar regions. Could you elaborate on this?

Authors' reply:

TransEBM shows a more homogeneous response during the early Holocene and lacks dynamical features in areas of cooling shown in the other simulations, but overall shows a similar magnitude of warming. TransEBM further shows a later onset of cooling in the high latitudes and the cooling is smaller than in the other models.

The difference between the warming displayed by the different models (Fig. 3 in the original manuscript) during the early Holocene can be largely related to the prescribed land and sea-ice. For TransEBM, the areas of pronounced warming reflect those ice cover changes and linearly related feedbacks, and the prescribed sea-ice extent results in fairly zonal and smooth warming patterns. Regarding the more complex models, dynamic features around the ice sheets and sea-ice/ocean interactions produce cooling/warming features due to atmospheric dynamics. The smaller cooling during the mid- and late Holocene in TransEBM might possibly be related to smaller and linear feedbacks in response to orbital insolation changes, in comparison to the feedbacks in the more complex models.

Additionally, TransEBM does not model seasonality of sea-ice or apply any land model or land use forcing which would enable it to simulate and respond to changes in the biosphere during that period. Finally, since TransEBM only simulates diffusive heat transport it does not resolve ocean currents. The observed differences – and broad similarities -- between TransEBM and the other three models are a clear indication that it is of importance to take complex feedback mechanisms into account to understand the Holocene climate.

Action:

- We will further elaborate on the differences between TransEBM and the more complex models in the polar regions in the manuscript.

Reviewer's comment:

Line 67: "Sea-ice extent is linearly interpolated between the Last Glacial Maximum (LGM) and present-day states given in Zhuang et al. (2017)."

Line : "The sea-ice was interpolated using the same method. For sea-ice, the distributions given by Zhuang et al. (2017) were used as fix points for present-day and LGM conditions."

Related to the point above, the role that sea-ice plays in the EBM is not clear from the sentences above. I suggest you add a paragraph briefly summarising TransEBM itself (in addition to forcings) to the Appendix.

Authors' reply:

In TransEBM sea-ice is handled as a prescribed transient forcing to the model. As described above, this has the effect that there is no sea-ice feedback. Additionally, no seasonal sea-ice cycle is simulated or prescribed. A detailed description of how the sea-ice forcing was generated as well as a general description of TransEBM is given by Ziegler and Rehfeld (2021). However, we agree with the reviewer that our manuscript would benefit from extending our summary of TransEBM in the Appendix, and we are happy to do so in a revised version of the manuscript.

Action:

- We will further elaborate on TransEBM in the Appendix as suggested by the reviewer.

Reviewer's comment:

Line 91: Could you spell out in more detail how you extract a seasonal reconstruction from temp12k?

Authors' reply:

The Metadata of the Temp12k dataset contains the information "Seasonality" and "Season General" (Kaufmann et al. 2020b). The "Seasonality" information specifies the time of year a climate variable in the dataset represents and is given as a list of calendar months (Kaufmann et al. 2020b). Accounting for the variety of seasonalities, this is generalized by the "Season General" metadata. As prescribed above "Season General" classifies seasonality as either annual, summer or winter (Kaufmann et al. 2020b). In our study we used this classification made by Kaufmann et al. and directly extracted it from the Temp12k dataset. As discussed above, we will significantly revise and extend the discussion of this in the revised version of the manuscript.

Action:

- We will further elaborate on the assumptions and we will further test the effect of the assigned seasonalities on our results as described above.

Reviewer's comment:

Is JJA the best choice of season for the southern hemisphere? Related to this, can you replace summer with northern hemisphere summer (JJA) in the rest of the text.

Authors' reply:

We thank the reviewer for pointing out that our usage of "summer" and "JJA" was unclear in the manuscript. We clarify this in the revised manuscript.

Action:

- We will clarify the usage of "summer" and "JJA" in the manuscript.

Reviewer's comment:

Line 129: expect for TransEBM which shows a high latitude cooling and warming over the North Atlantic and the North American East Coast.
Can you discuss why TransEBM has hte opposite sign over the ice-sheet?

Authors' response:

While the Laurentide ice sheet is still retreating during the early Holocene in all simulations, the impact of the decreasing northern summer (c.f. Fig 1 k) insolation at high latitudes is largest in TransEBM. This signal is then superimposed on the retreat of the ice sheet leading to a net negative temperature trend for the Hudson Bay. However, we can partly observe a warming at the north American east coast where the warming in response to the glacial retreat is dominant. Overall, this points to a lack of dynamical features in TransEBM.

Action:

- Will discuss this difference between TransEBM and the other models.

Reviewer's comment:

Line 228: Another relevant reference here is Dallmeyer et al (2022): https://doi.org/10.1038/s41467-022-33646-6.

Authors' reply:

We agree with the reviewer that this is a valuable reference for our statement and will add this in the revised version.

Action:

- We will include the reference.

References:

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