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Interactive comment on "The middle-to-late Eocene greenhouse climate, modelled using the CESM 1.0.5" *by* Michiel Baatsen et al.

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RC: This modelling study targets the middle to late Eocene, a time interval important to understand as it represents the close of the Cenozoic greenhouse. This is a great paper, good clear accessible explanations of model aspects, a variety of useful figures and addressing an important and outstanding issue in modelling the warmth of the early Cenozoic, i.e. how to get Antarctica as warm as proxies suggest without cranking CO2 up to levels above most proxy constraints. Modellers will likely have technical questions about the methods but my general feeling is that this paper is backed by sound theory, it uses appropriate methods and is appro- priately careful in producing the data model comparison, considering different proxy C1 calibrations, seasonal bi- ases etc. If anything, I think the abstract falls short of com- municating some of the key

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Discussion paper

findings of this paper, and its transferability to other warm climate phases, i.e. warming the poles without warming the equator too much. My overall recommendation is publish after minor revision.

AR: The authors would like to thank the referee for the detailed review. The reviewer is overall positive and seems to agree with the main findings. Several constructive remarks are made to improve mostly on consistency and clarity, which we feel can be incorporated with mostly minor changes.

RC: Abstract: This could better highlight some of the important tangible climate signals. It's a bit mechanical as is. e.g. - Highlight the gap in knowledge: i.e. What has been missing in other models, identify gap, need for different models. Remaining proxy-model mismatch at high latitudes especially. This is there in the introduction but not in the abstract. - Emphasize that you have come some way to addressing the long-standing problem of warm poles at 2 x CO2. This is a big step forward. - and connected . . . ..emphasize that by optimizing treatment of clouds etc, and having a carefully considered and time-appropriate paleogeography you manage to warm the poles, especially Antarctica, in a way that is consistent with proxies. This has important implications for the future. . . - Emphasize your finding of strong seasonality in the precipitation and the importance of monsoons in this warm Eocene climate - You find variable/reduced climate sensitivity compared to today – summarize why. Introduction and implications The paleogeography used in this model is very similar to Hutchinson et al., 2018. But you use a different model. This is thus a really good experiment opportunity to see what effects are model dependent and what are robust features. This could be emphasized better throughout. Kennedy-Asser et al., 2019 explored this idea.

AR: As the manuscript is quite long, it is challenging to keep the abstract focused while still complete. Both reviewers suggest that the abstract does not stress enough on some of the main results, so we will make the necessary changes to improve this.

RC: Introduction and implications The paleogeography used in this model is very similar to Hutchinson et al., 2018. But you use a different model. This is thus a really good experiment opportunity to see what effects are model dependent and what are robust features. This could be emphasized better throughout. Kennedy-Asser et al., 2019 explored this idea. Good description of the general conditions. Experiments at 4 x and 2 x modern CO2 are appropriate for the time interval.

AR: Considering the current length of the manuscript, it was chosen not to add a complete model inter-comparison study. Indeed, the very similar boundary conditions used by Hutchinson et al. 2018 provide a great opportunity to look at model-dependent responses. This will be stressed more when introducing the models and discussing the results, but leaving a more elaborate comparison to potential future work.

RC: Line 45: Add the Goldner et al., 2014 ref here. Lines 65: add Hutchinson et al., 2018; 2019 here. Also Kennedy-Asser et al., 2019; 2020;

AR: These references will be added.

RC: Line 75: The considered period is suitable to investigate both the warm greenhouse climate as the conditions leading up to the EOT. Should be and, not as?

AR: Indeed, this will be corrected.

RC: Elsworth et al., 2017 also specifically explored the late Eocene in a model, so that's another one.

AR: We can add this reference in the introduction as well.

RC: Justify why there's a need for a customized middle Eocene paleogeography between say the early Eocene (warm optimum) and late Eocene. What changes and what could make a difference?

AR: The palaeogeogrpahy reconstruction used here is an updated version, using more recent plate tectonic models. In addition, the reconstruction is quite detailed, which is needed to make it suitable for the model resolution used here. The timing uncertainty in these reconstructions is considerable, so the middle Eocene time frame was chosen such that it was before most of the changes occurring around the EOT. This will be better explained and referred to in the introduction.

RC: Explain that its crucial to have different models doing the same thing to explore what features are robust between models. Kennedy-Asser et al., 2019.

AR: In line with the above comment regarding the results of Hutchinson et al. 2018, we will emphasise and consider this more throughout.

RC: Methods Model resolution; How does the model resolution compare with other models, e.g. with the Hutchinson et al., 2018 DFDS model, which professes to have a relatively high-resolution ocean? Mention this upfront. If your ocean is 1âŮę, what kind of process should this improve upon compared to previous models?

AR: The ocean resolution is similar at ~1deg, the atmosphere has a slightly higher resolution compared to Hutchinson et al. 2018. This should lead to generally better resolved atmospheric eddies, oceanic boundary currents and gateway flows (see e.g. Bitz et al. 2012).

RC: Hutchinson et al., 2018 have proposed that the Arctic was important for some middle to EOT ocean changes. Therefore, can you add an Arctic-focused map view to fig. 1 (or SI section) to ensure its clear how this 38Ma geography treats the Arctic.

AR: To make this figure better focused on the model geography, we propose to add polar projections here and rather show the vegetation (for both Eocene and Pre-Industrial experiments) as a supplementary figure.

RC: Fig. 1 caption: and corresponding text. To the caption, add where the vegetation constraints come from i.e. proxies or modelled. Worth mentioning in the caption.

AR: This can indeed be added to the caption of the proposed supplementary figure.

RC: "note that neither desert nor land ice are implemented"?, later on in the text the word ‘incorporated’ is used. What does that mean? Do you mean that proxies and or models find no evidence for these biomes? Please clarify because this is important since any ice will have a strong albedo effect so we need be clear on this.

AR: This is based on proxy reconstructions (mostly Sewall et al. 2000) and will be mentioned here.

RC: Some would argue that there should be small amounts of Antarctic Eocene ice. Do you think this would make a difference in your model?

AR: Any ice in the modelled climate would exist solely on the highest Antarctic mountains, which is unlikely to have a significant impact on the results shown here. No model simulations were carried out to test this, so we can only argue but not show this.

RC: Why is the BDT biome (seen in the Fig. 1c) more extensive in the northern hemisphere than on Antarctica? Is it because Antarctica is warmer than the high northern latitudes?

AR: The biomes are based on proxy-reconstructions and are thus not necessarily consistent with the modelled climate. This will be better pointed out in the methods section. The most likely reason for a different biome on Antarctica is the much stronger seasonality compared to the Arctic.

RC: For the pre- industrial control – I’d like to see how the vegetation biomes are conceptu- alized for comparison with the 38 Ma version. Add as a supplementary figure?

AR: This will be shown alongside the Eocene vegetation in a supplementary figure.

RC: More on figures: Fig. 3 and Figs. S3 and S4, can you use the same scale increments/range and colours between the 38 Ma and PI controls -that way the differences are much clearer visually. Figure 3. Clarify in the Fig. caption that this is 38Ma. Figure 4. Explain MSLP in the caption.

AR: The colour scales and contours are consistent between the different figures as much as possible. Yet, the differences in temperature and circulation between Eocene and pre-industrial are to such an extent that this would make a significant part of the colour scale unused. It was chosen to have the 38Ma 2x and 4x figures all using the same scales and the pre-industrial ones deviating in just a few cases. We will adjust the captions as suggested and highlight more where different conventions are used.

RC: LINE 380: Describes extreme seasonality on Antarctica. This is key but we are not directed to a figure/result that shows this. A reference to the supplementary figures showing seasonality at the end of this sentence would fix this.

AR: We should indeed refer to the figure in the supplementary material here (S8 and S10).

RC: Please keep the matching x 2 CO_2 version (SI Fig S6) with the same axis temperature scale for comparison. This applies to other figure sets.

AR: Figure S6 uses the same scale as Figure 4, but deviates from Figure S5 as the latter again shows pre-industrial fields. Again, the argument here is that the latter differs so much from the Eocene cases that a consistency of scales would reduce the readability of the figures.

RC: Fig. 7. This is a very useful comparison figure! A difference between the H18 modelled 38 Ma ocean is that H18 gets Pacific overturning and you do not. This means that H18 has some northern hemisphere ocean heat transport, while you do not. Does this make a difference anywhere? Do you find compensation by the atmosphere?

AR: H18 indeed have North Pacific overturning while we do not, which is worth mentioning in the discussion. We did not make a direct comparison of oceanic heat transport, but there are no significant differences in zonally averaged temperatures. This indeed suggests that any differences in oceanic heat transport on a global change are probably compensated by the atmosphere.

RC: Fig. 8 There is surprisingly little continental proxy data. Is it worth including data even from a little wider time frame (early Eocene?) to get a sense of whether the temperatures on land are close to sensible for this epoch? This would be useful for the Antarctic and Arctic.

AR: Even stretching the considered period does not add any available terrestrial proxies to compare to either the low or high latitude regions.

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