Manuscript: egusphere-2023-1808

**Title:** Alternative climatic steady states for the Permian-Triassic paleogeography

**Reviewer #1:**

Ragon et al. spent lots of effort in finding all the possible steady states for the Permian-Triassic paleogeography using a relatively sophisticated Earth system model. The interesting finding, in my opinion, is that they found a 'warm' state in between the 'cold' and 'hot' states. This warm state cannot be reached from the either the cold or hot state by increasing or decreasing greenhouse gas forcings. The other findings are less interesting but worth being published on the journal EGUsphere.

We are thankful for this positive evaluation of our paper. We agree that the original part of our paper is the approach and the fact that multiple alternative steady states can be found for the same boundary conditions. We note however that we did not look for 'all the possible steady states', but that we restricted our analysis to those of relevance to the Early Triassic.

The major reason that the results may be less important than they seem to is that the multiple steady states found here could disappear when a fully coupled state-of-the-art climate model is used. To my own experience, the cold and hot climate states (even the cold state is still quite warm) presented in this manuscript could not coexist at the same forcing in the NCAR model family. Especially, the sea ice used in the model of this manuscript is thermodynamic only. When the NCAR model was run in such mode, a so-called Jormungand state could be found (Abbot et al., 2011; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2011JD015927) but never found in the fully coupled mode. Therefore, I think the authors should point out in the abstract or conclusion that the multiple steady states found in their study may depend on the specific configuration of their model, especially the neglect of sea-ice dynamics.

We agree that the number of steady states may depend on the configuration and the model setup. Indeed, feedback mechanisms acting on the same time scale could affect the balance between different processes and the number of steady states. A sentence on this aspect can be added in the Conclusions, mentioning the role of sea ice dynamics, and also ocean dynamics, and relevant references (at line 300):

*In particular, including sea ice dynamics or different numerical implementations of thermodynamic sea ice Lewis et al. (2007); Voigt & Abbot (2012); Hörner & Voigt (2023), as well as considering a mixed-layer ocean or a fully dynamical one Poulsen et al. (2001); Pohl et al. (2014), may change the number of steady states, and reveal the source of possible biases.*

This is also the reason why in the Conclusions (last paragraph, line 299) we call for the need of comparing different climate models. We can also specify that we use a *thermodynamic* sea ice in the abstract and the Conclusions (second paragraph, line 278) when we mention the MITgcm configuration.

Moreover, I think a snowball Earth branch should exist in their model if the initial condition is cold enough. They do not need to explore the full branch but just confirming their existence is necessary in this kind of study.

As mentioned above, we did not look for all the possible steady states. However, we indeed confirm that at least a colder climate exists: at the lower edge of the stable branches of both hot and cold states the system is attracted towards a colder state, as shown in Fig. B1 of the manuscript. A waterbelt state is present where the ice extends to ∼ 30° latitude and the global mean surface air temperature is approx. −10 °C (see Fig. 1 in this response). However, we have not investigated this state further since simulations require long CPU time while geological data exclude for the presence of snowball or waterbelt states in the Early Triassic Sun et al. (2012); Romano et al. (2013); Goudemand et al. (2019); Widmann et al. (2020).

We propose to include the following paragraph in the Introduction (at line 40) to describe the climatic oscillations in the aftermath of the Permian-Triassic Boundary mass extinction and to provide the general context for our numerical simulations.

*We are interested in the climatic oscillations observed at the Smithian-Spathian boundary in the Early Triassic, just after the Permian-Triassic boundary (PTB) mass extinction (∼252 Ma), the most severe of the Phanerozoic Raup (1979); MacLeod (2014); Stanley (2016). As a consequence of the volcanic activity of the Siberian Large Igneous Province Campbell et al. (1992); Renne et al. (1995); Reichow et al. (2009), the global carbon cycle entered a perturbed state which persisted for nearly 5.4 Myr in the Early Triassic, until a new equilibrium state was reached in the Anisian Sun et al. (2012); Romano et al. (2013); Goudemand et al. (2019); Leu et al. (2019); Widmann et al. (2020). The observed fluctuations in the carbon isotope record Payne et al. (2004); Galfetti et al. (2007); Retallack et al. (2011) with successive diversification-extinction cycles of the nekton Orchard (2007); Brühwiler et al. (2010); Leu et al. (2019)*

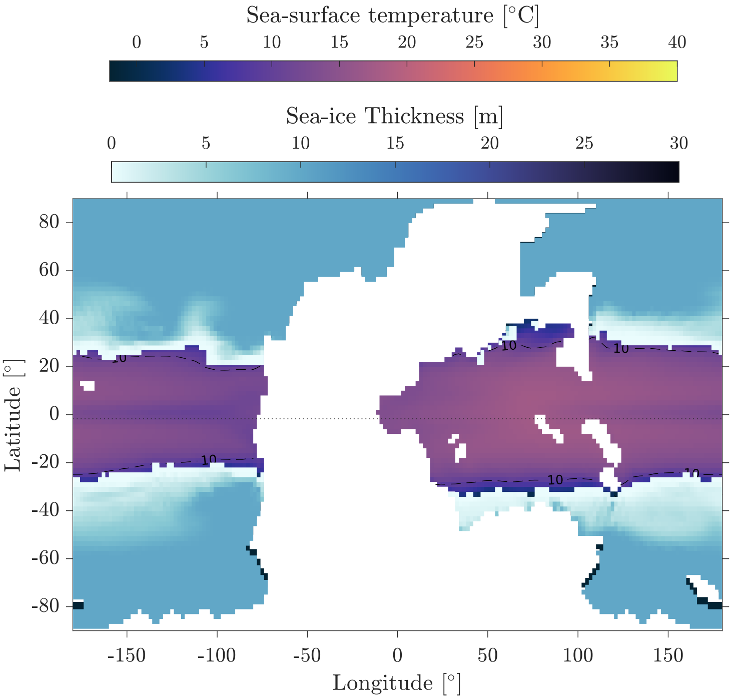

Figure 1: Sea-surface temperature and sea-ice extent in waterbelt.

*and ecological crises of terrestrial plants Hermann et al. (2011); Schneebeli-Hermann (2020), are all indicative of the climatic changes which occurred in the Early Triassic, with variations in the global temperature of the order of 7-8 °C from the thermal maximum in the late Smithian to cold climates in early Spathian times Widmann et al. (2020).*
*However, despite the great effort of the scientific community to reconstruct such climatic oscillations in the aftermath of the PTB, large uncertainties remain in timing and causal relationships, implying that numerical modelling needs to consider a wide range of initial and boundary conditions for the simulation of such geological interval. In this context, ...* [continuing at line 44]

L164: "stronger" than what? This makes the sentence hard to understand.

We meant 'stronger than the heat transport in a climate without sea ice'. We suggest to reformulate this sentence as follows:

*As reported in an aquaplanet configuration Ragon et al. (2022), the presence of sea ice increases the meridional surface air temperature gradient, defined as the temperature difference between polar (30° to 90°) and equatorial (-30° to 30°) regions, and thus makes the heat transport stronger than for an ice-free climate.*

Fig. 6: It has been pointed in the literature that the strength of annual mean Hadley circulation may not be meaningful, can the authors please confirm that the strength of seasonal Hadley circulation has a similar trend?

We thank the reviewer for pointing this out. Like in the present-day climate, the annual mean Hadley cells are quite similar to the cells during spring and autumn seasons, while in the winter season, the circulation is dominated by a single cell, the one of the winter hemisphere Lindzen & Hou (1988); Dima & Wallace (2003). Thus, we agree that it is useful to show the winter Hadley circulation, for example in a new Appendix (see Fig. 2 in this response). The following text can be added at line 176, section 3.1:

*In the winter season, the Hadley circulation is dominated by a single cell, the one of the winter hemisphere Lindzen & Hou (1988); Dima & Wallace (2003), as shown in Fig. (in the appendix). The austral winter cell in the hot state becomes weaker and slightly wider than that of the cold state, in agreement with the trend observed in simulations of the Pangea hot climate at ca. 250 Ma in comparison to pre-industrial conditions Zhang et al. (2023). The boreal winter cell has a similar width in the three attractors, while its intensity is maximal and more shifted towards the Equator in the cold state.*

These trends of the winter cells are thus also consistent with what is observed in the mean annual Hadley circulation in Fig. 6 in the manuscript.

Figs. 7 and 8: I think these two figures can be combined into one

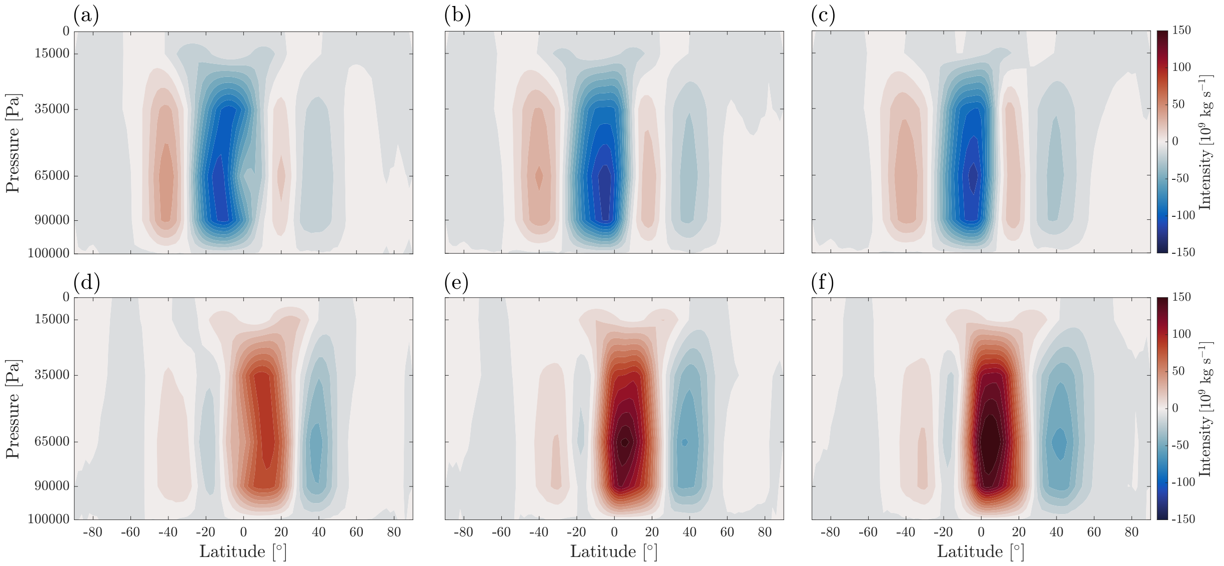

Figure 2: Seasonal mean atmospheric meridional overturning circulation for hot state (a,d), warm state (b,e) and cold state (c,f). Panels (a-c) and (d-f) corresponds to summer (June-July-August, JJA) and winter (December-January-February, DJF) seasons of the northern hemisphere, respectively.

We agree with this proposition.

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