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Climate of the Past
Discussions

Interactive comment on "An Energy Balance Model for Paleoclimate Transitions" *by* Brady Dortmans et al.

Anonymous Referee #1

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General comments:

The idea of looking at different Palaeoclimate regimes and transitions with a single EBM is an interesting approach and has good potential to increase the basic understanding of several problems that are hard to tackle with full-complexity GCMs. The authors nicely work out and motivate significant extensions to an existing EBM, mainly dividing the earth into different regions with the associated fluxes and adding the effect of water vapour as a greenhouse gas. The technical details on the model are then accompanied by an extensive overview of several experiments to test it's ability to reproduce different time frames. Especially the result showing Antarctic glaciation as a result of combined radiative forcing and meridional heat flux reduction is interesting and worth looking at in more detail.

A caveat here is that reduced ocean heat transport linked to a weaker ACC is probably not the sole or even main reason for reduced polar warmth; other possibilities include more subtle changes in geography, vegetation or atmospheric circulation. This also shows the still limited possibilities of the EBM that should be acknowledged; it does not include the effects of e.g. precipitation, atmospheric circulation and land/sea distribution that all play an important role in the problems visited in the paper.

While informative, especially the technical part should be shorter and more focussed and the readability/quality of the overall text improved (try to avoid repetition of similar concepts). Additionally, there is often no visual distinction between different lines in figures which occasionally makes them hard to interpret and less transparent.

Overall comparisons with previous results from both proxy and modelling studies on the palaeoclimate should be greatly improved (some recent modelling work on the Eocene, see e.g. Lunt et al. 2016,2017, Baatsen et al. 2018, Hutchinson et al. 2018 and references therein). Many claims are being made on either climatic or geological changes that are poorly referenced, some of them being invalid or uncertain. Especially the story in section 3.2 needs to be reconsidered, checked and referenced properly, while being unnecessarily lengthy in the scope of this paper.

Several nice results were obtained using the EBM, but most claims on having solved these while previous model studies using full-complexity GCMs are exaggerated or untrue.

Specific Comments:

P1

P2

L9: motivation/citation for weak seasonality in equable climate? L17: Full-complexity climate models are also highly nonlinear and have multiple states L20: geological shift of Antarctica is not that large during the Eocene, the onset and effect of a strong ACC is highly uncertain

P3

L4: if the real world situation is more complex, there is no guarantee that similar bifurcations exist. L27: is there no effect of albedo, both atmospheric and surface? (extended later)

P4

L12: typo 'in' should be 'is' L14: two thirds reach? L15: could use some more motivation and precise citation for the b=0.63 value.

P5

In Table 1: Ts max +20C seems low for tropical, similarly 9km seems high for a polar TP.

P6

Nice to have the addition of a smooth transition between cold and warm state. Motivation for symmetric transition?

P7

L1: Motivate why I_A would be easier to observe, rather than T_A. F2: plain tanh does not add much; maybe show the full equation (5) and highlight effect of different parameters Make captions/titles/legend clearer Highlight the difference between the red lines (colour/linestyle), now they are indistinguishable Caption: rather use a) instead of 'subfigure a)' Where is figure 2b referenced in the text? L15: remove 'degree' with K

P8

L5: why use a temperature scaling that is preliminarily ill-posed?

P9

L11: I assume CH4 is not considered because it behaves mostly similar to CO2 and the combined effect can be considered as an increased CO2 forcing. Argument this, as in most cases CH4 is a more important GHG than CO2.

P10

L18: Addition of a second way to calculate this seems redundant

P11

F3: Although rather straightforward, it would be nice to indicate in the figure which lines belong to high/low CO2 L8: I would assume CP readers should be familiar with bifurcation diagrams and saddle node bifurcations.

P12

L3: Make this a separate sentence L10: more nearly?

P13

P14

F4: It makes little sense to have a scale up to tau_s = 1.8, meaning T_s > 400K in a climate perspective

P15

L13: no need to explain positive feedback L25: This sentence suggests that Antarctica was ice free up to 23Ma L30: double 'the'

P16

L2: would prefer the term development rather than creation, this is an extremely simplified view on a complex geological and oceanic evolution that took place over $\sim$20Ma L5: what motivates the lower bound of 30W/m2? L6: use Ma or million years ago, missing a reference here regarding the EOT/glaciation L7: re-phrase this; if CO2 is not the same as elsewhere, it cannot be worldwide

F5: even at 1500ppm CO2, a stable cold solution still exists in the EBM. This is a major discrepancy with higher complexity models, that generally don't allow glaciated states at $>\sim$1000ppm and should be adressed.

P17

L17: this is a nice assumption for the experiment, but CO2 was almost certainly not linearly decreasing in this time frame (see e.g. MECO, PrOM event, post-EOT recovery). This is only mentioned later. L29: While the timing at 35Ma is nice and shows a good qualitative agreement with the geological record, the exact number is directly related to the assumptions made and not very useful.

P18

L7: reference? L9: the crossing of a CO2 threshold with/without the effect of Southern Ocean Gateways has been suggested many times before, just not in an EBM framework.

P19

L16: During the entire Cenozoic, the polar climates were in fact mostly different with Antarctica being considerably warmer than the Arctic during the Paleocene/Eocene. Going back to the mid-Cretacious, the poles were probably similar as they were both marine, but anything further back in time is highly uncertain. L18: The Arctic had no considerable land ice, but did have sea ice in the Oligocene/Miocene/Pliocene. The possible presence of land ice in the Arctic since the Eocene is also still debated. L19: In the present climate, RH is actually pretty high in most of the Arctic due to the low temperatures and marine influence. L25: Most model/proxy studies show southern high latitudes being noticeably warmer than the Arctic region. Furthermore, a high oceanic heat transport into the Arctic is unlikely considering the Arctic Ocean was mostly isolated by the geography. L29: typo: 'decreased' L31: If the glaciation of Antarctica was abrupt, then the sea level drop could not have been gradual. L34:

Model results show the exact opposite; cold, fresh waters from the Arctic flowing into the North Atlantic. L35: The North Atlantic exists since long before the Eocene, it was only narrower at not always connected to the Arctic Ocean.

P20

L1: typo: 'the' L1: the Turgai Strait probably already closed in the middle-late Eocene, missing ref here. Similarly, connections between the North Atlantic and Arctic have been there (but not continuously) since the middle Eocene. L3: The Pacific is not generally cooler than the Atlantic, locally it will be when comparing the equatorial cold tongue (EPac) and warm pool (WAtl). L7: This reasoning seems pretty far fetched and a way to get around missing the effect of enhanced precipitation in this model. In the end, qualitatively the exact same problem is being solved as for the Antarctic glaciation thus adding little to our understanding. One could instead argue that a similar reasoning can be followed to also look at the Pliocene. L15: This discussion, including F7 is mostly a copy of the one in the previous section. L30: most proxy reconstructions show little variation in CO2 during the Oligocene and Miocene

P21

F7: Only a glaciated solution exists for CO2$<\sim$400ppm, which disagrees with most of the Miocene/Pliocene and interglacials.

P22

L2: This is a simple solution to a simple problem: a cooling system including an ice-albedo feedback will cross a threshold for glaciation. Whether this solves the Pliocene paradox is doubtful. L5: The early Pliocene Arctic climate was relatively mild, but the climate was not equable such as that of e.g. the early Eocene. L14: The main reason for this asymmetry is simple geography, not captured in the model: Antarctica is a continent surrounded by oceans, while the Arctic is an ocean surrounded by continents. L23: This is untrue: a proper GCM spin-up starts from a specific initial condition that is not related to the present-day climate. L29: ENSO has been shown to be present in the climate since the Eocene.

P23

L1: With the onset/strengthening of an AMOC, the equator to pole gradient should become smaller instead of larger (before glaciation). Further more, the Hadley circulation has little effect on middle-high latitude meridional heat fluxes.

P24

P25

L2: There are indeed no bifurcations, but if the change in tau_s is considered it would mean tropical temperatures decreased from ∼55C to ∼25C. A drop of 30C is certainly not small in the tropics and does not agree with the geological record. L16: More recent tropical proxies have gone up to ∼35C, while tropical temperatures in warm GCM simulations have gone down to 35-40C, bringing both estimates closer to agreement.

P26

L11: The EBM indeed shows the existence of a warm solution at the tropics and both poles, but still with a difference of 0.1-0.15 in tau_S corresponding to 27-40C which does not correspond to an equable climate (usually <20C). L14: 'The tropics' - 'their' L15: Again, this is not how computer simulations are set up to model warm climate states.

P27

L6: refrain from using the statement 'failed' here, the equable climate is a difficult problem but there has been significant modelling progress.

Similarly to 3.3, section 3.5 is a copy of 3.4 and does not add any information or physical understanding.

Conclusions:

The EBM indeed shows interesting nonlinear behaviour and is capable of showing realistic climate solutions. I only partially agree on it showing new insights in Cenozoic climate transitions or being able to better represent the cases considered.

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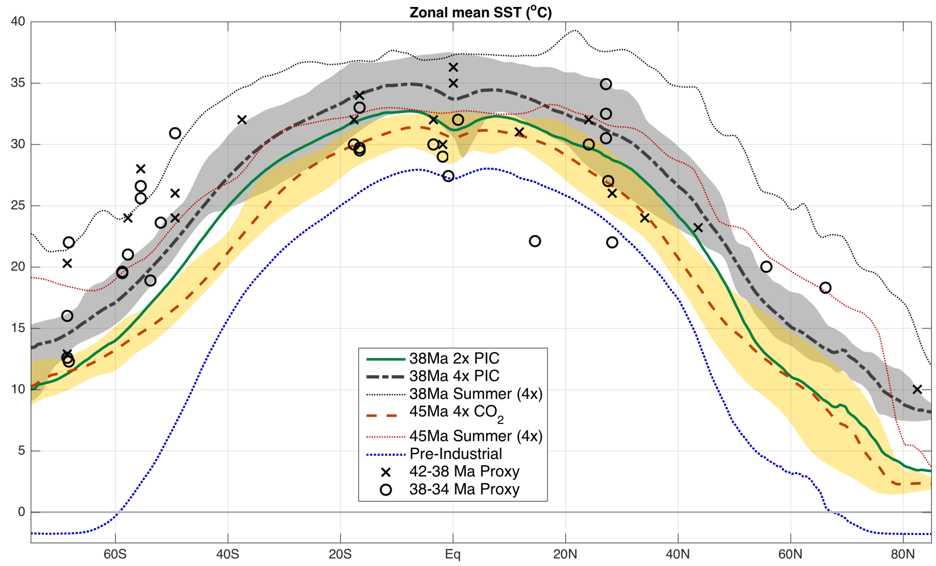

Fig. 1. Overview figure of SST proxies and several model studies for the middle-to-late Eocene, showing improving model-data agreement.