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Comment on esd-2022-36

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Referee comment on "Tracing the Snowball bifurcation of Aquaplanets through time reveals a fundamental shift in critical-state dynamics" by Georg Feulner et al., Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2022-36-RC2, 2022

Feulner et al. traced the snowball bifurcation of an aquaplanets through the history of the Earth using a climate model of intermediate complexity. To my knowledge, this has never been done before. Importantly, they did get some very interesting results from such practice and found that the critical climate state was different under low and high solar constants. In particular, they found that once the sea-ice edge crosses ~40° latitude, it would march forward to the equator without any external forcing when the solar constant is low. While when the solar constant is high, this critical latitude is at ~30° latitude, i.e. the boundary of the Hadley cell. Therefore, I think the work provides new knowledge about the stability of the Earth's climate to the society and definitely worth publication. However, there are still a few relatively small things that need to be clarified. Especially, the mechanism for the stability of the 'Hadley state' may be explained better.

The major reason that the ice edge cannot be stabilized at ~30° latitude when the solar constant is low, I think, is because the atmosphere+ocean heat transport across the 30° latitude exceeds the energy that can be received by the oceans equatorward. This will cause a continuous cooling of the tropical region and eventually allows the ice edge to march forward towards the equator. The rate of this cooling should be inversely proportional to the solar constant and is indeed well indicated by their Fig. 4. Therefore, I hope they can demonstrate this mechanism more clearly by showing explicitly the total meridional heat transport at 30°S and 30°N and the solar energy received by the oceans within 30° latitudes. These should be shown for the transient stage in one of the simulations, for example, at year 100 of the 1500 Ma simulation in Fig. 4.

If the point above can be confirmed, then the mechanism for stabilizing the ‘Hadley state’ may need to be modified (such as the last sentence of the abstract). It is stabilized by enhanced oceanic heat transport once the sea-ice edges approach the boundary of Hadley cell. The enhanced heat transport is expected to be due to stronger easterly winds as normally seen in other models and thus stronger poleward Ekman transport. This mechanism always works as clearly shown in Fig. 4 but it can stabilize the climate only momentarily when solar constant is low because the enhanced heat transport extracts more energy than the tropical ocean can receive; the heat content of the tropical ocean is drained out quickly. While for a high solar constant, a balance can be achieved easily (other feedback processes are naturally involved, especially the outgoing longwave radiation, latent heat flux etc. so that the tropical ocean will lose less energy in these ways) unless the CO_2 concentration is lowered further. This is likely also the major reason that the slope in Fig. 1 increases once such balance can be achieved.

Minor questions:

- How are the poles treated in the ocean module of this model since an aquaplanet is simulated?
- Is the boundary of the Ferrel cell also fixed in this model?
- Can the oceanic and atmospheric heat transport be calculated separately in this model?
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