

Response to RC2 by Yonggang Liu

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.

First of all we would like to thank Yonggang Liu for his positive evaluation and constructive review of our manuscript for which we are really grateful. Our response to the individual comments can be found below.

The major reason that the ice edge cannot be stabilized at $\sim 30^\circ$ 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.

Many thanks for this interesting idea. We will analyse the model diagnostics to check the balance between the surface energy budget within the Hadley cells and the total meridional heat transport at 30°N/S. We will also look into the role of the oceanic heat transport in stabilising the Hadley states and will modify the manuscript accordingly.

Minor questions:

How are the poles treated in the ocean module of this model since an aquaplanet is simulated?

In contrast to other coupled model simulations of aquaplanets, we do not place small islands at the poles, so the poles are treated similar to the North pole in present-day simulations with ocean models using spherical grids, applying filtering in the polar regions in order to be able to increase the ocean model time step without causing numerical instabilities. We will add this information to the revised version of the manuscript.

Is the boundary of the Ferrel cell also fixed in this model?

In the annual mean, the poleward boundary of the Ferrel cell is indeed at 60°N/S. However, as for the Hadley cell, there is a small shift in the boundary reflecting the seasonal shifts of the thermal equator and the changes of atmospheric circulation patterns, see Petoukhov et al. (2000, Section 3.2). As promised also in our response to Reviewer 1, we will describe this in more detail in the revised version of the manuscript.

Can the oceanic and atmospheric heat transport be calculated separately in this model?

Yes, the heat transport in the atmosphere and the ocean can be diagnosed separately.

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Thanks for spotting this typo which will be corrected in the revised version of the manuscript.