Response to Referee #1 comments:

Overview: The authors run a sophisticated global climate model (GCM) with a surface that is covered by a sophisticated land model. They assume a globally uniform ground water table, representing efficient surface water transport. Interestingly, they find bistability between two climate states, a hot and dry (HD) state and a cold and wet (CW) state. I have never seen anything like this before and it is definitely worth publishing. I think the authors should do a bit more work to understand why the model produces this behavior, then the paper will be ready to be published. I have some comments that hopefully will help with this.

We thank our first referee Dr. Dorian Abbot for the very immediate yet a detailed review of our manuscript. Please find below our responses to his comments.

Comments:
Referee #1 comment - Mechanism: In the final paragraph of the introduction the authors restrict the scope of the paper so that it doesn't include investigating the mechanism of bi-stability. I think at least some investigation of the mechanism is necessary so that this paper stands as an independent work that doesn't rely on future work and to convince the reader that the observed behavior isn't simply due to some bug in the land surface scheme.

Authors' response: *We do understand that including the mechanisms of bi-stability in the same paper would give a more complete picture to the reader. However, including the mechanisms explaining the emergence of the bi-stability would drastically increase the length of the paper. A complete paper on the mechanisms of bi-stability is already in preparation. If the Editor feels it is necessary, we could think about submitting our forthcoming paper on the mechanisms of bi-stability as a part two of the present paper to ESD as well so that together part one and part two papers could stand as an independent work.*

Referee #1 comment: The way I would approach this is to first run the model in "swamp" configuration: with a global mixed layer ocean of 1 m depth and zero ocean heat transport. Presumably you will reproduce a roughly Earth-like climate. Then I would turn on the land surface model, but choose schemes and parameters to match the swamp configuration as closely as possible. Then slowly turn more schemes on or change parameters until you get bistability. This should allow you to identify the specific physical parameterization that allows for bistability. It must be related to evapotranspiration, since that's the key difference between a swamp surface and a real land surface.

Authors' response: *We thank Referee #1 for suggesting an approach to better understand the mechanism behind the bi-stability. Incidentally, we already performed simulations of the type proposed by the Referee #1 and this was indeed how we found the bi-stability that we describe in our paper. Our model in the "Swamp configuration" is able to successfully reproduce the climate of an "Aqua-planet" configuration. Starting from this setup, we sequentially changed different parameters and schemes in our land surface model (Table 1) and we clearly saw that when the ground water table was lowered, the bi-stability emerged. In Table 1 we list our sequence of simulations and in Fig. 1 we show the resulting zonal structure for temperature and precipitation. With this additional information, we hope it is convincing enough for the reader to believe that the bi-stability is not due to some bug in the model's land surface scheme. We will include this information in the Appendix of the manuscript to demonstrate that indeed the restricted atmospheric access to water causes the appearance of the bi-stability.*

Referee #1 comment – Surface energy balance: Surface energy balance is important for global-mean evaporation, and therefore precipitation. All else equal, more absorbed shortwave at the surface should mean more evaporation and more precipitation. That's why it seems odd that the planetary albedo should be lower in the HD state, but the global-mean precipitation should also be so much lower.

Authors' response: *Referee #1's statement "more absorbed shortwave at the surface should mean more evaporation and more precipitation" – is only valid for an Earth-like planet with large oceans. However, in our HD state, even though the tropics receive huge amounts of net radiation at the surface, the uppermost soil layers in the tropics dry out quickly. Dry uppermost soil layers imply small evapotranspiration leading to no precipitation which in turn leads to even less evapotranspiration. This self stabilizing mechanism maintains the HD state.*

Referee#1 comment: One possibility is that much more of the surface heat is lost through sensible rather than latent heat in the HD state. Another is that the planetary shortwave absorption is not a good proxy for surface shortwave absorption because of differential atmospheric absorption of radiation in the two cases. I think it's worth calculating the terms in the surface energy balance (both zonal mean and global mean) and using this to explain why the HD state seems to be able to absorb so much more shortwave yet have such a low evaporation. If you can explain this, it might also help your investigation into the mechanism for bistability.

Authors' response: *We agree with the Referee #1 about his first suggestion that much more of the surface heat is lost through sensible rather than through latent heat in the HD state (see Fig. 2 below). Additionally, most of the heat is lost from the surface by terrestrial radiation in HD state. Upon re-submission we would include a brief discussion about the surface energy balance in section 3 of our revised manuscript and add a figure in the appendix (Fig. 2 here).*

Referee #1 comment: Also, I wonder if this could be connected to why bistability is lost for Earth-like obliquity. It would be really great if you could explain why increasing obliquity disrupts the bistability, and maybe analyzing the surface energy balance would help.

Authors' response: *We have so far not analyzed the reason why bi-stability is lost for Earth-like obliquity in detail and it is one of our plans for the future. But we speculate that for Earth-like obliquity, the bi-stability is lost due to the seasonal migration of the rain bands towards the lower latitudes. The seasonal migration of rain bands facilitates seasonal rain in the dry tropics. Since soil moisture has a memory lasting for several weeks to months this causes the soils in the tropics to remain wet even during the dry season. Thus there is always soil moisture in the originally dry tropics to allow for continuous evapotranspiration and precipitation. And this destroys the HD state so that the planet is always self stabilized in the CW state. We will include this speculation in the section about seasonality in our revised manuscript.*

Referee #1 comment – Vertical Temperature Structure: One thing I was wondering about is the vertical temperature structure in the two states, since convection is probably important for the bistability. I think it would be worth plotting and thinking about this.

Authors' response: *We have attached the figure for vertical temperature profile including potential temperature in the tropics for the two terra-planet states (see Fig. 3 below). But vertical temperature structure does not explain much about the bi-stability, the restricted atmospheric access to water causes the appearance of the bi-stability*

Referee #1 comment – A related point is that near the outer edge of the habitable zone we expect very high CO2 levels, probably at least 1 bar. A large radiative cooling in the atmosphere could strongly affect the vertical temperature structure. It would be interesting to do some test runs at very high CO2 and see if the HD state can persist under these conditions, since the authors connect the HD state with the outer edge of the habitable zone.

Authors' response: *We thank the Referee #1 for his interesting suggestion. Unfortunately, we cannot run such simulations as our model parameterizations are not suited for very high CO_2 concentrations and hence it is beyond the scope of the present paper.*

Simulations	Background soil albedo	Surface roughness	Heat capacity	Snow albedo	Water reservoir depth
Aqua-planet	0.07	Ocean	Ocean	0.07	50 m slab ocean, no heat transport
Swamp1	0.07	Ocean	Ocean	0.07	Constant ground water table at a depth of 0.3 m
Swamp2	0.07	Land	Land	0.07	Constant ground water table at a depth of 0.3 m
HD	0.07-0.14	Land	Land	Dynamic (0.4 -0.8)	Constant ground water table at a depth of 1.2 m
CW	0.15-0.24	Land	Land	Dynamic (0.4 -0.8)	Constant ground water table at a depth of 1.2 m

Table 1. Summary of simulations performed to illustrate the procedure followed by which we found bi-stability on our terra-planet.

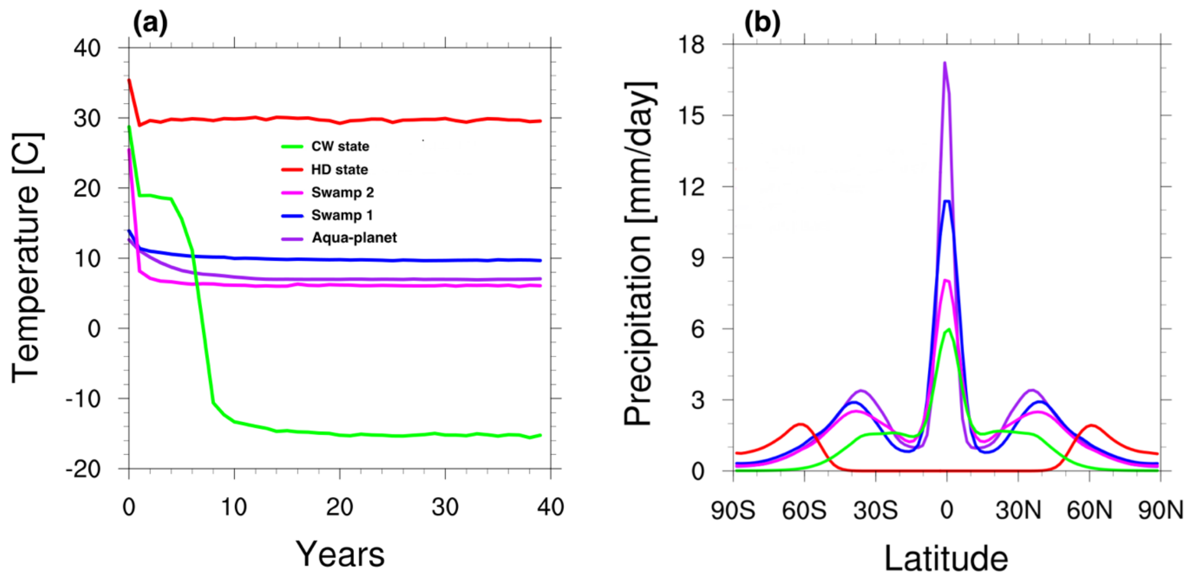

Figure 1: (a) Time series of global mean surface temperature (°C) and (b) annual mean meridional profile of precipitation (mm day^{-1}) for different simulations performed to illustrate the procedure by which we found bi-stability on our terra-planet.

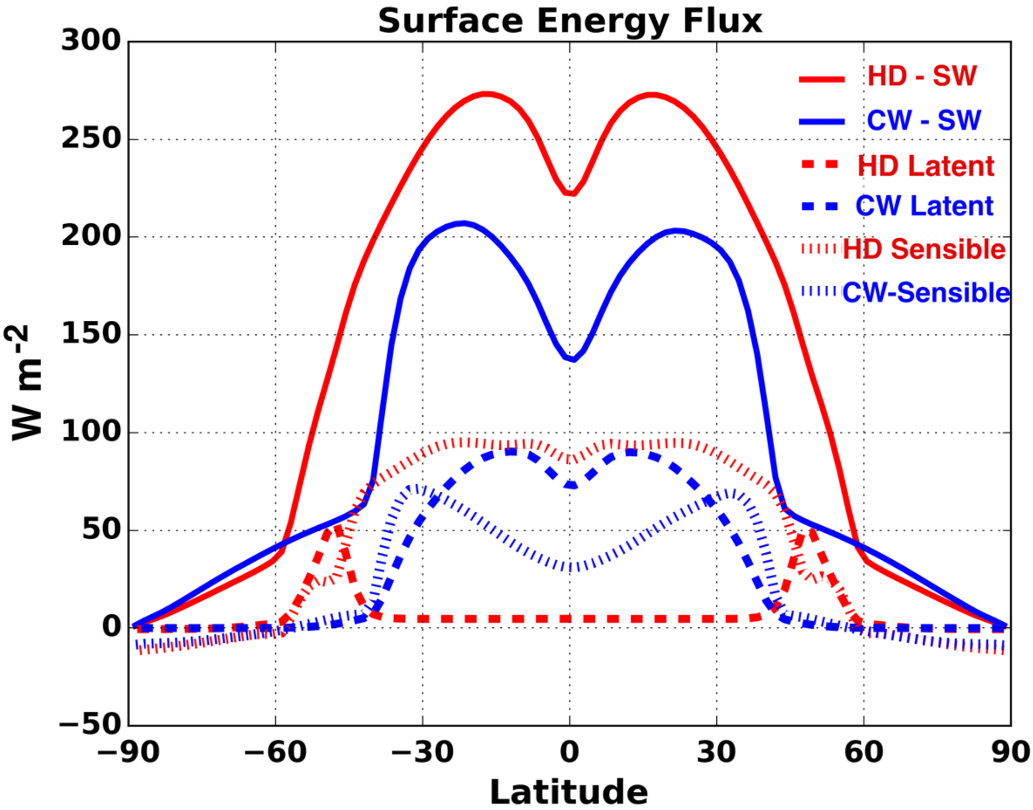

Figure 2: Annual mean meridional profiles of Net shortwave radiation at surface (SW), latent heat flux (Latent) and sensible heat flux (Sensible) for the two terra-planet states: HD (α = 0.14) and CW (α = 0.15) in the simulations Z14 and Z15 averaged over a period of ten years.

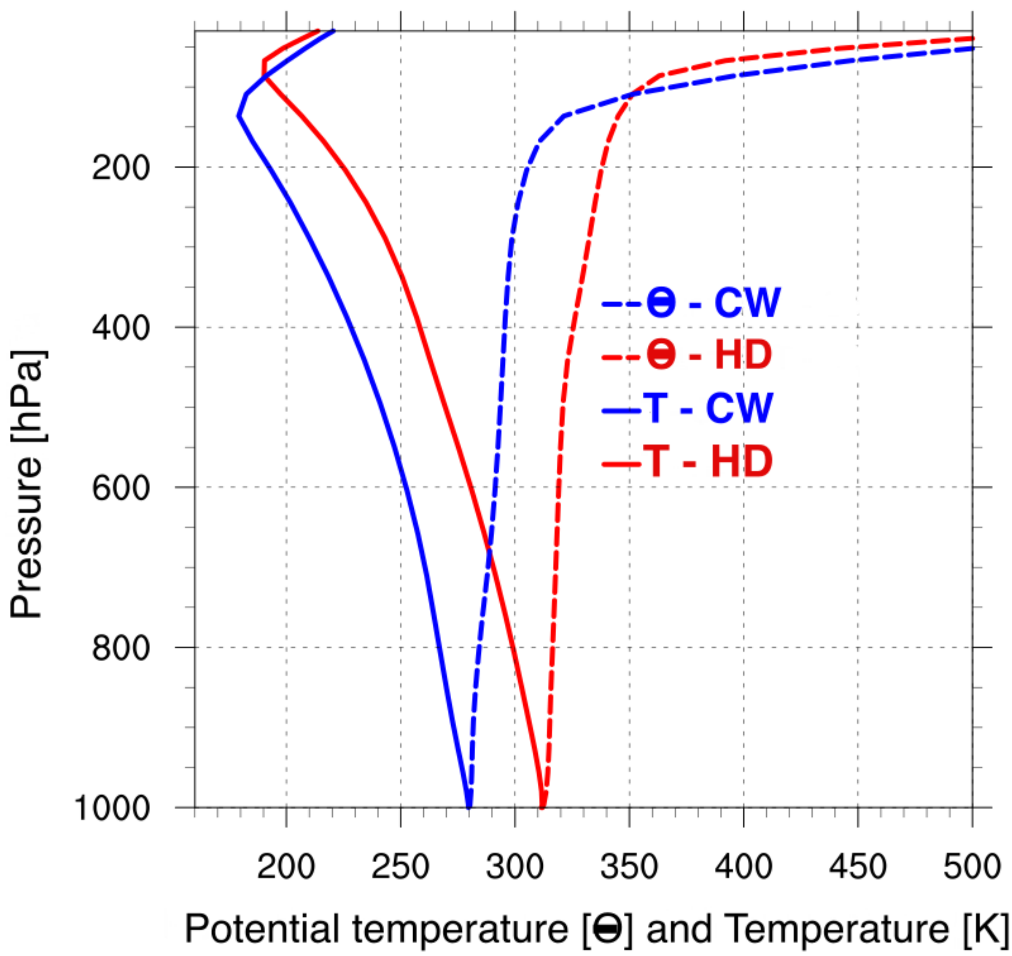

Figure 3: Vertical profiles of Temperature and potential temperature in the tropics for the two terra-planet states in the simulations Z14 (HD state) and Z15 (CW state) averaged over a period of ten years.