Response to Referee #3 comments:

Summary:
This paper explores a climate bifurcation for dry/desert planets, including implicit water cycling through the assumption of a sub-surface aquifer. This work represents a step forward from the classic work by Abe et al. 2011. I feel that this paper is interesting and deserves to be published. I suggest that the authors try to do more to explain why this transition happens, in terms of the cloud albedo and water vapor greenhouse forcing.

We thank our referee for very interesting comments and suggestions on our manuscript. Please find below our responses to the referee#3 comments.

General comments:
Referee #3 comment: "It should be noted that the present paper is mainly descriptive in nature and is not meant to explain the mechanisms for the emergence of the two climate states and the way the transition between them happens. This is still under investigation." You should explain the mechanisms for the emergence of the two climate states in this paper. This should be included in this paper to make it complete. I think you can do so by examining the changes in cloud albedo and water vapor greenhouse effect.

Authors' response: *We thank the Referee#3 for suggesting us to look at the role of clouds and water vapor greenhouse forcing to explain the emergence of two drastically different states. Indeed, it is true that the two terra-planet climate states display considerably different patterns of cloud cover and water vapor in the lower latitudes (Fig. 1). In the HD state, the cloud cover in the low latitudes is exclusively composed of high level clouds with very low liquid water content (Fig. 2). The reason being, the high surface temperatures in the lower latitudes in the HD state raise the water vapor saturation limit of the atmosphere and the height at which condensation and cloud formation occurs. High clouds are more transparent to shortwave radiation, at the same time they reduce outgoing longwave radiation and thereby keep the planet hot and stabilize the HD state. With an increase in background soil albedo beyond the bifurcation threshold, the water vapor saturation limit of the atmosphere and the height at which the clouds can form is lowered due to the lowering of surface temperature, thus leading to an increase in low level cloud cover. Increase in low level cloud cover increases the planetary albedo and keeps the planet cool and self stabilized in the CW state. Overall, the self stabilizing cloud albedo feedback does play a role in the transition from the HD to the CW state (we briefly mentioned this in Sections 6 and 8 in the original manuscript). However, a complex sequence of steps is involved in the formation of low level clouds before the self stabilization of the planet in the CW state by the cloud albedo feedback. Including all these complex mechanisms would drastically increase the length of the paper and hence we prefer to present the explanations regarding the mechanisms involved in the transition in a separate paper (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 #3 comment: In your simulations, water is in theory made available everywhere on the planet via diffusion of water from the subsurface water-table into the atmosphere. How is the temperature, clouds, and water vapor in your terraplanet simulations different from an aquaplanet case, given an equal albedo? It would be useful to run 1 aquaplanet simulation with albedo = 0.07 for comparative purposes. (Note that 0.07 is fine for a typical ocean albedo).

Authors' response: *This is part of what we already did: We performed a series of simulations starting from an aqua-planet setup to arrive at the bi-stability (please see Fig. 3 and Table 1 below). In Fig. 4 below you find the requested plots for annual mean meridional profiles of (a) surface temperature, (b) vertically integrated water vapor, (c) vertically integrated cloud cover for an aqua-planet simulation with albedo = 0.07 and terra-planet simulations with the same background soil albedo value (0.07) but initialized differently: from a warmer state (HD – 0.07 simulation) and from a colder state (CW - 0.07* *simulation).*

The aqua-planet climate resembles more closely to the CW - 0.07 simulation and is about 22K colder than the HD-0.07 simulation. However, the atmosphere in the terra-planet simulation (HD – 0.07) can hold a similar amount of water vapor as in the aqua-planet simulation due to higher temperatures in HD-0.07 (Fig. 4b). The cloud cover at the lower latitudes in terra-planet simulation (HD – 0.07) is lower compared to that of the aqua-planet simulation (Fig. 4c) and is mainly comprised of high level clouds whereas in the aqua-planet case (also for CW-0.07 simulation), it is dominated by low level clouds.

Specific comments:

Referee #3 comment: I may suggest changing the title from ". . .Earth-like terra planet" to ". . .Earth-like Dune planet", or ". . .water-limited terrestrial planets." The term "terra-planet" isn't a common term in the literature. Also, the adjective "Earth-like" connotes a planet where surface liquid water is freely available. These dry worlds are perhaps more so Mars-like in description. OR, due to the ambiguity of the term "terra-planet", you should explicitly state somewhere early in the Abstract, perhaps the in the first sentence, that you are dealing with water-limited land planets.

Authors' response: *Our main idea behind naming the planet as terra is to contrast it from the well known aqua-planet. The word "terra" means "land" in Latin. To avoid ambiguity regarding the term "Earth-like", we shall in our revised manuscript explicitly define "Earth-like terra-planet" as a water limited terrestrial planet in the first sentence of the abstract.*

Referee #3 comment: Page 2, line 5 "Second, terra-planets with optically thin atmospheres (like present day Earth's atmosphere) can maintain their inner edge of the habitable zone much closer to their parent star compared to aqua-planets due to their higher surface albedo (Abe et al., 2011; Zsom et al., 2013)." While it is true that dry planets will have a higher albedo than ocean planets, this is just one piece of the puzzle, and I don't think the dominant one. One of the primary reasons that dry planets can maintain habitability at higher stellar fluxes is due to the lack of available water vapor. With less water in the system, the water-vapor greenhouse feedback is severely muted and thus there is significantly less greenhouse warming of the climate system. This is true regardless of surface albedo.

Authors' response: *We thank the referee#3 for pointing out the primary reason why dry planets can maintain habitability even at higher stellar fluxes. We will modify the text as suggested by the referee#3 in our revised manuscript.*

Referee #3 comment: Page 3, line 5. Can you give the model horizontal resolution in either degrees lon X degrees lat, or in number lon grids X number of lat grids?

Authors' response: *The model has a horizontal resolution of R2B04 equivalent to a resolution of an evenly distributed rectangular grid of about ~ 160 Km. We would modify the text in the revised manuscript to make it more clear for the reader.*

Referee #3 comment: what does "Leaf Area Index (LAI) =3" mean? Is your surface vegetated or bare soil? How might the vegetation type affect your results?

Authors' response: *Yes, there is something that one could call vegetation, because our model includes besides bare soil evaporation also a transpiration pathway for soil water to reach the atmosphere. The value of LAI controls how much surface in a grid cell participates in transpiration, while the rest exhibits bare soil evaporation. But we consider the value of the LAI here only as a means to parameterize the atmospheric access to water, like other hydrological parameters of the model, e.g. soil porosity, hydraulic conductivity, or depth of the 'subsurface reservoir'. Therefore, and because other aspects of vegetation like plant growth or phenology are missing, we do not use the word 'vegetation' in our paper. We would rewrite the the text regarding the LAI in the revised manuscript to make it more clear for the reader.*

Referee #3 comment: "overland water recycling" You are not really considering overland water recycling. You are considering a ubiquitous sub-surface aquifer that sources water into the model. Thus you are considering "subsurface" water recycling.

Authors' response: *We agree with the Referee#3's comment regarding the term "overland water recycling". However, it also not just "subsurface" water recycling but imagine it as a combination of recycling happening via ice/river flows over the land and, subsurface flows. We will try to find a more concise and appropriate term which represents both these flows for our revised manuscript.*

Referee #3 comment: "_ varying from 0.07 to 0.24" what kind of land surfaces are these appropriate for? igneous rock? desert sand?

Authors' response: *Vegetated surfaces, but also deserts with mainly rocky surfaces have albedo values within this range. Sandy deserts typically have higher albedo values.*

Referee #3 comment: Page 3, line 32. While the surface temperatures reach equilibrium quickly for dry planets, what about the atmosphere-land water balance? It is my understanding that in some models it can take a considerable amount of model time for water to permeate out of the sub-surface aquifer.

Authors' response: *Referee#3's remark "it can take a considerable amount of model time for water to permeate out of the sub-surface aquifer" is indeed valid in the case of a geological reservoir on a real planet where recycling does have long internal timescales and the equilibration of surface temperature may require a considerably longer time than spanned by our simulations. However, the sub-surface reservoir that we consider in our study just refers to the bottom two layers of the soil. The total soil depth in our study is about 10 meters of which the layers below a depth of 1.2 meters are almost completely filled with water homogenously all over the globe and should not be misunderstood as a geological reservoir. Only the top three layers of the soil are dynamic which take around three years to equilibrate.*

Referee #3 comment: It would be interesting to see a figure similar to figure 5, but showing the integrated water vapor column amount, the integrated cloud water amount, and the integrated cloud fraction.

Authors' response: *As requested, we show in figure 5 below the vertically integrated water vapor column amount, vertically integrated cloud water amount, and vertically integrated cloud fraction for different stages of the transition from the HD state to the CW state similar to figure 5 in the original manuscript.*

In the HD state, the lower latitudes are mainly covered by high cloud cover (Fig. 2) with very low liquid water content and huge amount of water vapor in the atmosphere.

Stage 1: *Once the albedo is increased beyond the threshold, precipitation clusters start to appear close to the equator, more rain reaches the surface filling up the dry uppermost soil layers in the lower latitudes. With increased soil moisture availability, evapotranspiration increases resulting in a transient increase in atmospheric water vapor content and cloud liquid water content in the lower latitudes (Fig. 5).*

Stage 2 & 3: *As the temperature drops further in the later stages, water vapor saturation limit and the height at which clouds can form is lowered leading to an increase in low level cloud cover with high liquid water content at the lower latitudes. Increase in low level cloud cover increases the planetary albedo and results in the rapid cooling of the surface and a decrease in atmospheric water vapor content and eventual stabilization of the CW state.*

Referee #3 comment: It would be interesting to see additional panels on figure 7 showing cloud and TOA albedo, and also the greenhouse effect. You can estimate the greenhouse effect as G=sigma*Ts^4 – OLR

Authors' response: *As requested, we show in figure 6 below cloud albedo, TOA albedo, and greenhouse effect as a function of background soil albedo similar to Figure 7 in the original manuscript. We notice that for an increase in background soil albedo, the planetary albedo increases due to an increase in low level cloud cover at lower latitudes.*

Also, at a higher background soil albedo, the greenhouse effect is much lower compared to that for lower background soil albedo due to decrease in atmospheric water vapor greenhouse warming (Fig. 6c).

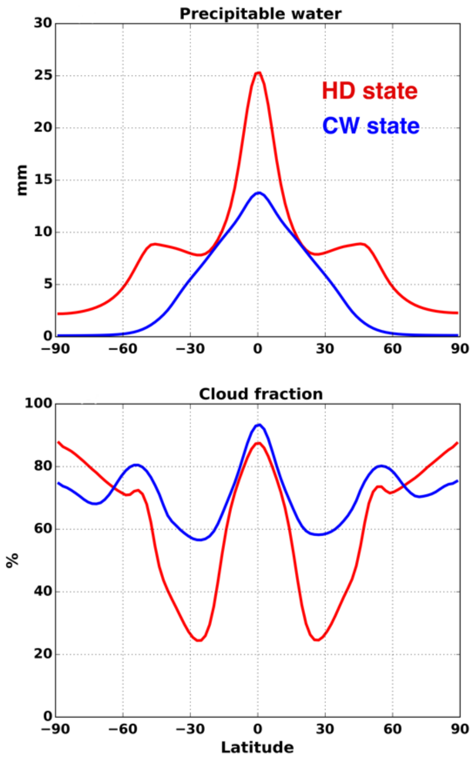

Figure 1: Annual mean meridional profiles of precipitable water (top panel) and cloud cover fraction (bottom panel) for the two terra-planet states: HD (α = 0.14) and CW (α = 0.15) in the simulations Z14 and Z15 averaged over a period of ten years.

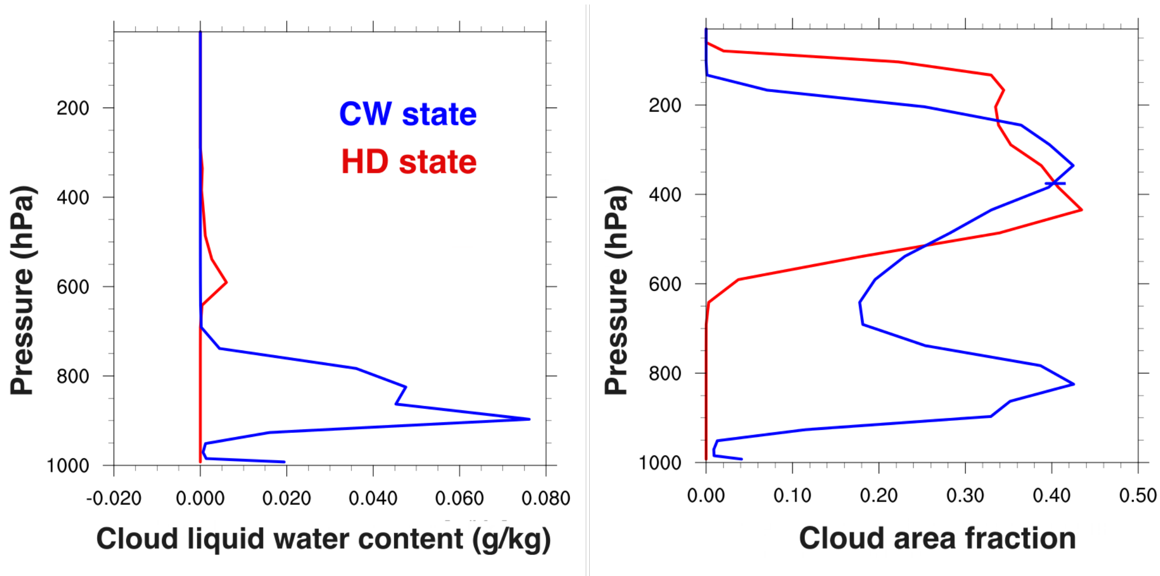

Figure 2: Vertical profiles of cloud liquid water content (g kg^{-1}) and cloud area fraction for the two terra-planet states in the simulations Z14 and Z15 averaged over a period of ten years.

Simulations	Background soil albedo	Surface roughness	Heat capacity	Snow albedo	Water reservoir depth from the surface
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 by which we found bi-stability on our terra-planet.

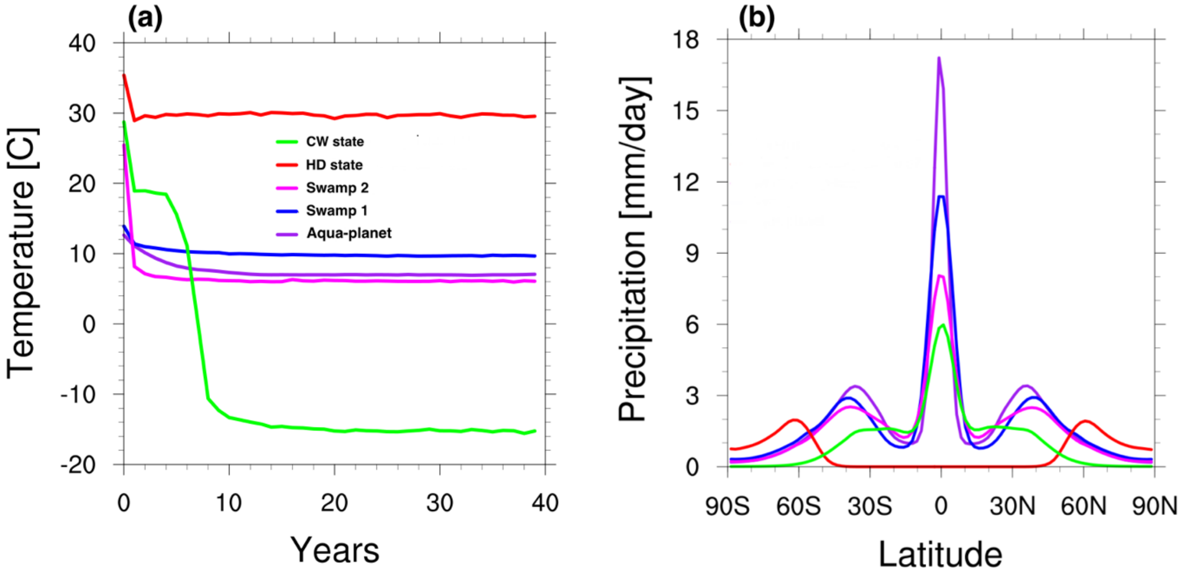

Figure 3: (a) Time series of global mean surface temperature (°C) and (b) annual mean meridional profile of precipitation (mm day^{-1}) for different simulations performed to illustrate the procedure by which we found bi-stability on our terra-planet.

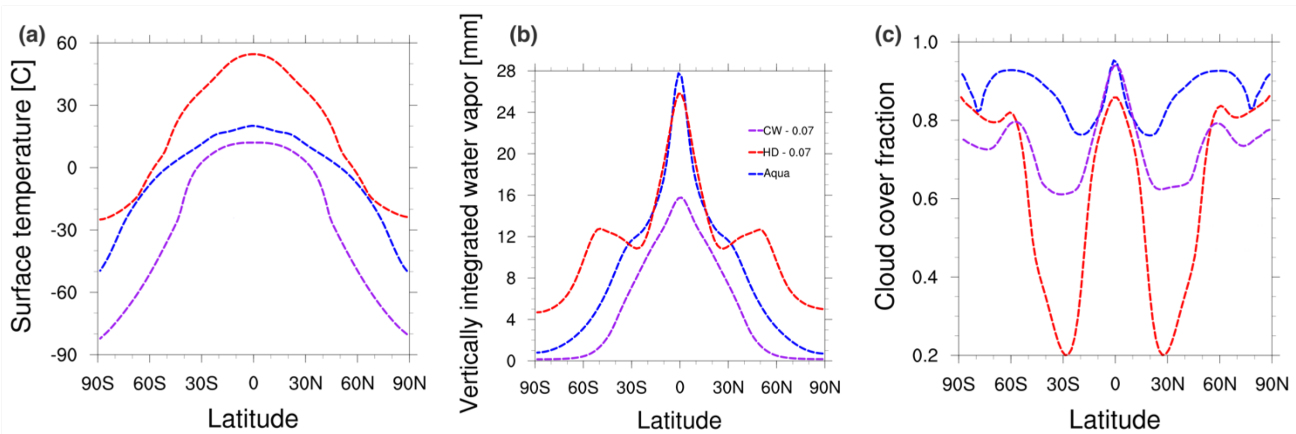

Figure 4: Annual mean meridional profiles of (a) surface temperature (°C), (b) vertical integrated water vapour (mm), (c) cloud cover fraction for an aqua-planet simulation with albedo = 0.07 and terra-planet simulations with the same background soil albedo value (0.07) but initialized differently: from a warmer state (HD – 0.07 simulation) and from a colder state (CW - 0.07 simulation).

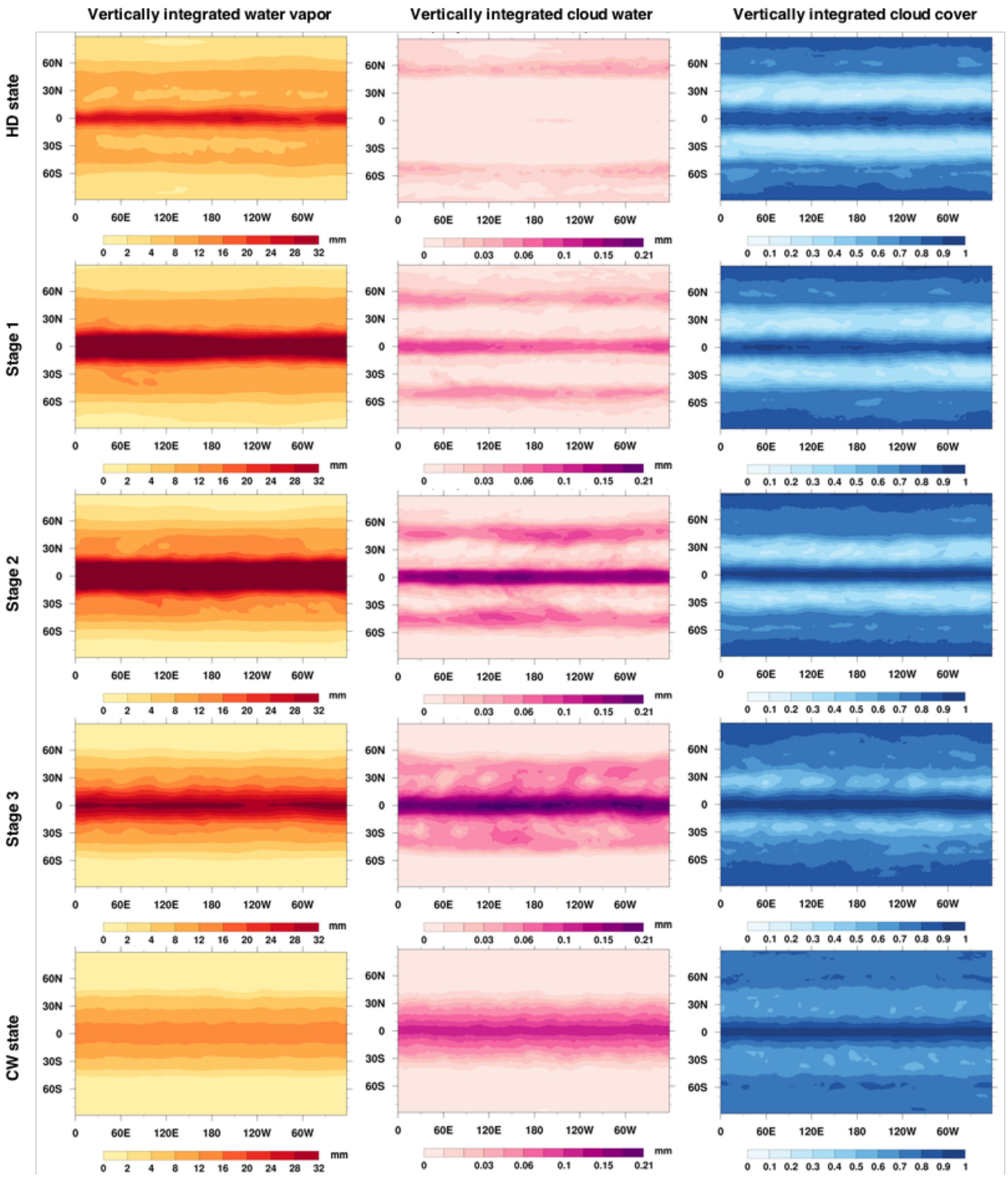

Figure 5: Annual mean vertically integrated water vapor (left panels), vertically integrated cloud water (centre panels) and cloud cover cover fraction (right panels) for different stages of the transition (TRANS simulation) from the HD state to the CW state similar to the Fig. 5 in the original manuscript.

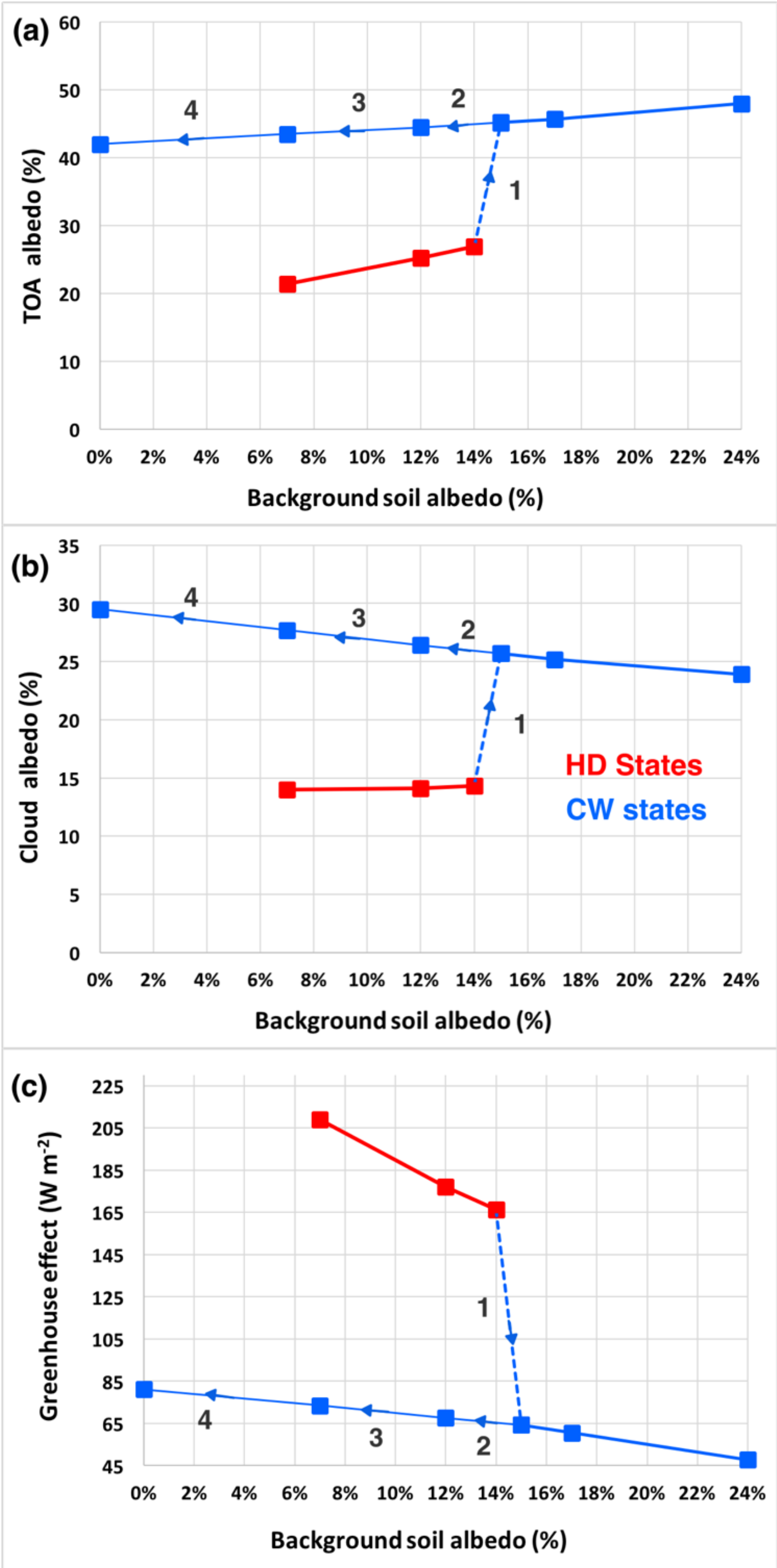

Figure 6: **TOA albedo (a), cloud albedo (b) and Greenhouse effect (c) plotted as a function of background soil albedo (α). Path 1 denotes the spontaneous transition from the HD to the CW state when increasing background soil albedo and paths 2, 3 and 4 denote the reverse state development upon stepwise lowering of background albedo starting from the threshold value ($\alpha = 0.15$) to $\alpha = 0$.**