Response to referee 1's comments "Energetics of monsoons and deserts: role of surface albedo vs water vapor feedback"

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The authors thank the referees for their time and inputs. We have provided a point-by-point response to each of their comments.

***General comment*:** *In this manuscript, the authors present a compelling argument that the top-of-the-atmosphere (TOA) radiation budget contrast between monsoon and desert regions is primarily driven by water vapour feedback, with surface albedo playing only a secondary role. This challenges the classical Charney (1975, https://doi.org/10.1002/qj.49710142802) hypothesis, which emphasises albedo-driven desertification feedbacks. The study employs a combination of theoretical reasoning and a novel climate model experiment (RETRO, in which Earth's rotation is reversed) to support its claims. While the hypothesis is intriguing and potentially significant for understanding monsoon-desert radiative dynamics, I have some serious concerns regarding the experimental design and interpretation of results.*

1. ***Comment*:** *Major Concern: Limitations of the RETRO Experiment*
   The central issue with this study lies in its reliance on the RETRO experiment to "confirm" the hypothesis. While reversing Earth's rotation is a creative way to alter large-scale climate asymmetries, it is not an appropriate experimental framework for isolating the specific roles of water vapour versus surface albedo in TOA radiation budgets. My concerns are as follows:

   Fundamental Alteration of Planetary Dynamics
   Reversing Earth's rotation drastically changes the Coriolis force, jet stream pathways, ocean circulation, and storm tracks. These modifications introduce confounding dynamical effects that are unrelated to water vapour's radiative role. The resulting climate (e.g., a Sahara monsoon and Southeast Asian desert in the RETRO simulation) is influenced not just by humidity and radiation but also by completely reconfigured atmospheric and oceanic circulations. Thus, attributing the TOA budget differences solely to water vapour is problematic.

   ***Reply*:** It is true that reversing the direction of planetary rotation alters large-scale atmospheric dynamics. Our central proposition is that this shift acts as an initial trigger for the onset of monsoon conditions over the Sahara. The subsequent radiative effects from water vapor and clouds then feed back into the circulation, further amplifying it (see Lines 132–137 and 151–153 of the main text). This feedback emerges organically in the RETRO simulation. Notably, even in the first year of the simulation—when surface albedo remains high—the large-scale circulation modulates the local radiative budget over the Sahara. During this period, F_{toa} becomes positive and monsoon-like conditions develop. This provides compelling evidence that surface albedo is not the primary limiting factor for monsoon onset. Thus, this simulation reveals how radiative feedbacks from water vapor and clouds reinforce the dynamical changes that occur upon reversing the rotation. It also supports the argument surface properties are not the primary limiting factor.

We address two key aspects in this context:

– **Climatological differences in F_{toa} and their link to low-level mass convergence** Neelin and Held (1987) demonstrate that, under steady-state conditions, low-level mass convergence is proportional to F_{toa} (over land, over oceans one must consider the surface energy fluxes as well), with the gross moist stability (GMS) serving as the proportionality constant. Equation 2.12 in their paper encapsulates this relationship. When F_{toa} is near zero or negative, it implies minimal or divergent low-level flow—exactly the condition observed over the Sahara. Thus, spatial variations in low-level circulation can be diagnosed through F_{toa}. In our analysis, differences in F_{toa} between monsoon and desert regions point to a dominant role played by water vapor and cloud radiative effects.

– **Seasonal evolution of F_{toa} and its relationship to large-scale circulation** Before the onset of the South Asian monsoon, the absorbed shortwave radiation (ASR) and OLR over South Asia are similar to those over the Sahara (see Figure **??**). The main difference arises in the evolution of OLR. Initially, rising water vapor levels increase F_{toa}, which enhances low-level convergence (from Neelin and Held (1987)). This, in turn, draws in more moisture, further increasing F_{toa} and reinforcing the circulation. Cloud radiative effects lag behind those of water vapor by a few days, but once clouds begin to form, they contribute additional radiative forcing that further modulates F_{toa} and the low-level convergence.

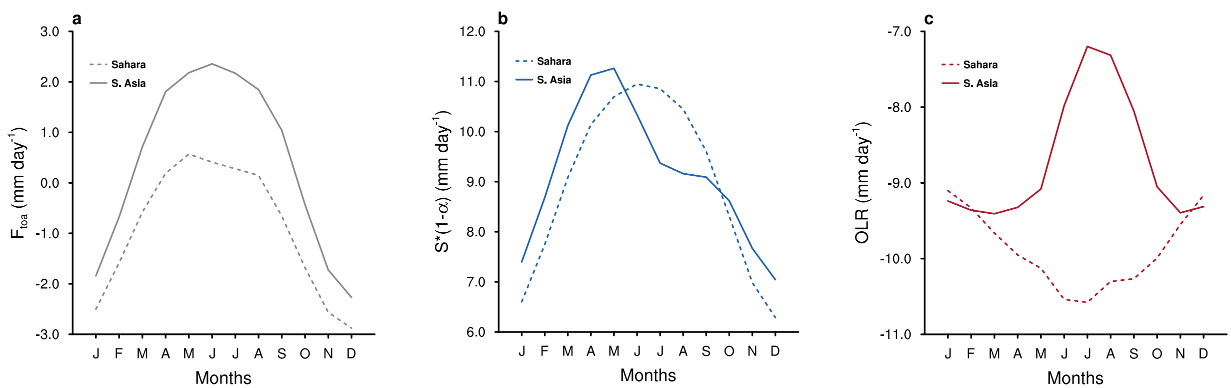

Figure 1. Seasonal cycle of F_{toa} and its components. The time series of (**a**) F_{toa}, (**b**) Net shortwave at the top of atmosphere, and (**c**) outgoing longwave radiation from ERA-5 climatology (based on 1981-2020). The solid line represents the area average over the domain (70°E-105°E and 15°N-30°N), while the dashed line shows the area average over the domain (0°E-30°E and 15°N-30°N).

2. ***Comment**: Lack of a Clean Sensitivity Test A more robust approach would involve directly perturbing water vapour concentrations (e.g., through a "dry world" vs. "moist world" experiment) while keeping Earth's rotation unchanged. Alternatively, radiative kernel analysis could quantitatively separate the contributions of water vapour, clouds, and surface albedo to the TOA budget. Please refer to Soden et al. (2008, https://doi.org/10.1175/2007JCLI2110.1) for further details.*

   Reply: We thank the referee's suggestion. Conducting "dry world" versus "moist world" experiments is indeed an interesting idea. However, implementing a fully dry atmosphere in a comprehensive Earth System Model (ESM) would introduce unintended consequences. Radiative kernels, which are commonly used for such diagnostics, are linearized around a specific base climate. Te RETRO simulation represents a substantial shift in climate. Radiative kernels suitable for RETRO do not exist.

   Our primary objective is to diagnose the dominant factors contributing to the TOA energy budget differences between monsoons and deserts. For this purpose, we find that an offline radiative transfer model offers a more controlled and transparent framework. We use the Climlab implementation of RRTMG (Rose, 2018), which is consistent with the radiative scheme employed in our MPI-ESM simulations. We prescribe the thermodynamic profiles and aerosol properties are prescribed.

   The model reproduces clear-sky and all-sky OLR with errors below 1%. Errors in ASR are slightly higher (2–3%), primarily due to the absence of cloud optical properties in the standard model output, which are needed for accurate ASR calculations. To isolate the contributions of individual components—such as temperature, water vapor, and clouds—we apply the Partial Radiative Perturbation (PRP) technique (Box, 2002), which allows us to quantify their respective impacts on TOA fluxes.

   As shown in Figure **??**, the reflected shortwave radiation at TOA is nearly identical over the Sahara and South Asia during JJA, with a difference of approximately 25 W m^{-2} in both the CERES and ERA5 datasets. The surface albedo of the Sahara is nearly the same as the TOA albedo over a cloud covered South Asia. The dominant contributor to the TOA energy budget difference between these regions is the OLR (about 90 W m^{-2}). The figure below (Figure 2) shows the individual contributions of clouds, water vapor, temperature (surface and atmospheric), and aerosols to the difference in all-sky OLR between South Asia and the Sahara. Clouds and water vapor exert the strongest influence. Particularly, during the onset of the monsoon, the radiative impact of water vapor increases first, followed by a more pronounced contribution from clouds. In the RETRO simulation,

3.

   The study does not account for dust aerosols, which are prevalent over deserts and significantly influence both shortwave (albedo) and longwave (trapping) radiation (Osborne et al., 2011, QJRMS, https://doi.org/10.1002/qj.771). The role of cloud feedbacks, while briefly mentioned, is not rigorously disentangled from water vapour effects. Since clouds co-vary

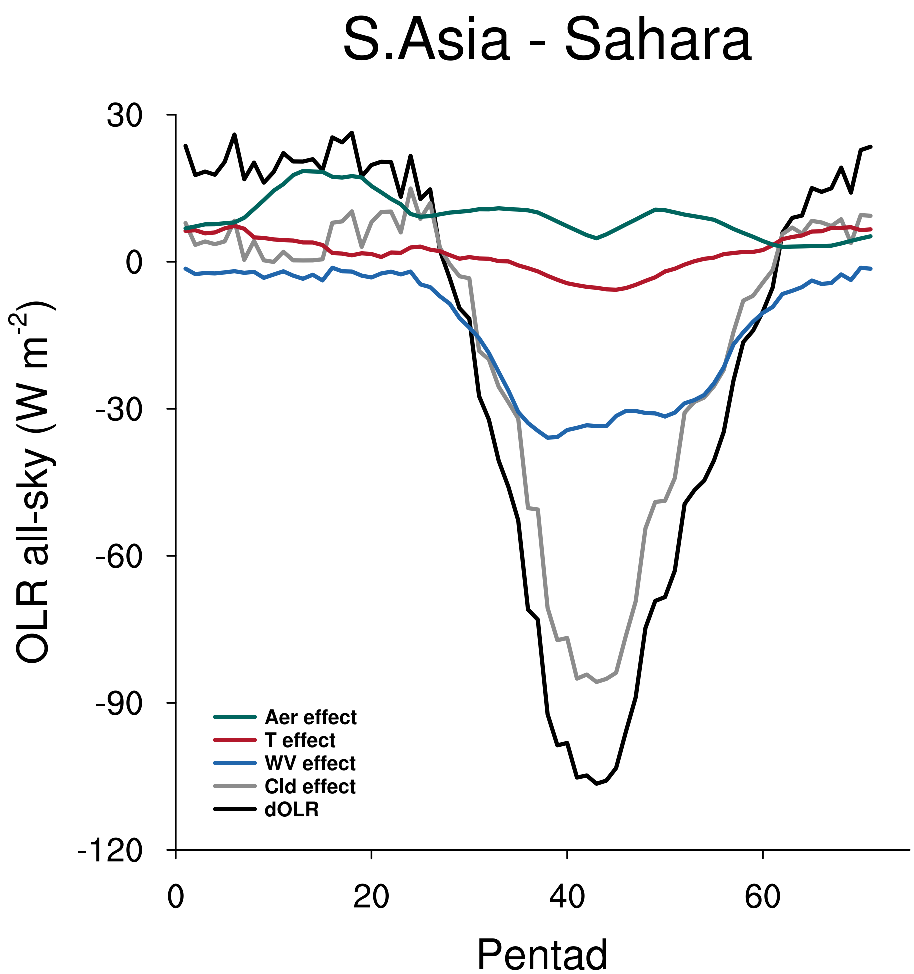

Figure 2. Decomposing longwave emission The time series of all-sky OLR difference between South Asia and the Sahara based on offline RRTMG calculations. IThe black line represents the total all-sky OLR difference. Individual contributions from clouds, water vapor, temperature (surface and atmosphere), and aerosols are shown in grey, blue, red, and green, respectively.

with humidity, their radiative impact could also explain part of the TOA contrast. ***Comment**:* *Overlooked Factors: Dust Aerosols and Clouds*

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***Reply**:* *Thank you for your the comment. We have now included in our analysis an assessment of the impact of aerosols. We find that aerosols play a minor role during JJA. Their influence on all-sky OLR is relatively higher during*

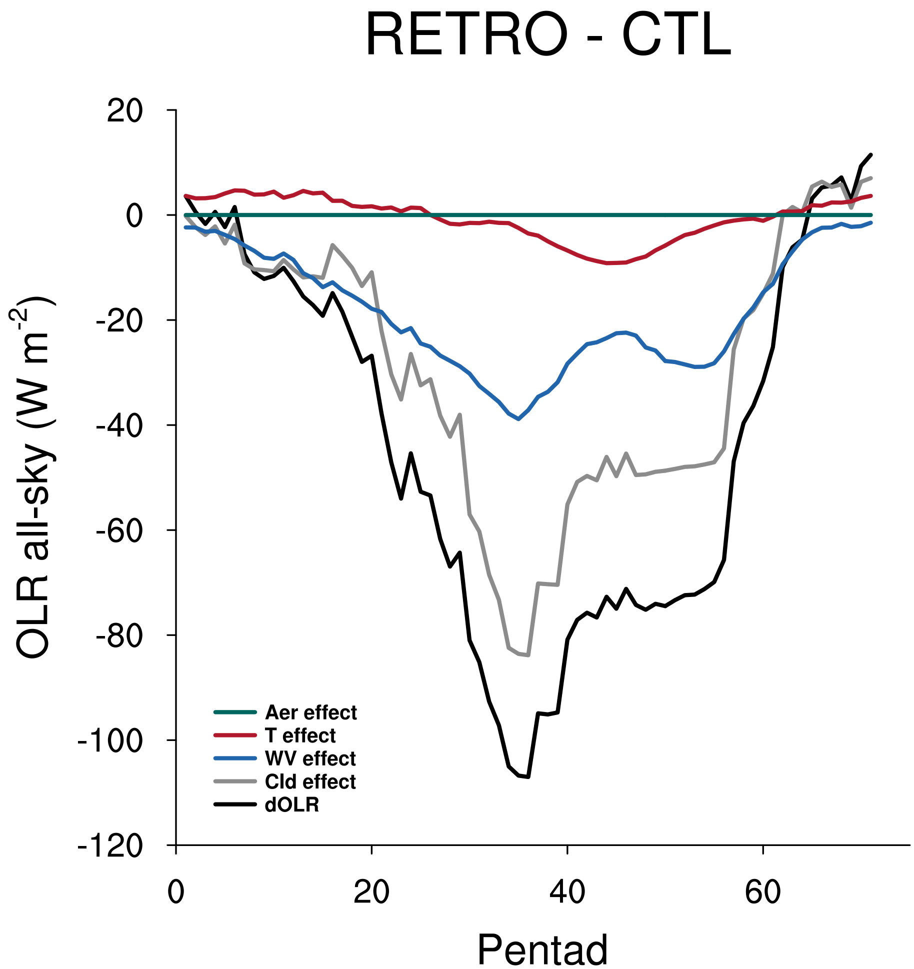

Figure 3. Decomposing longwave emission in RETRO Sahara The time series of all-sky OLR difference between RETRO and CTL over the Sahara based on offline RRTMG calculations. IThe black line represents the total all-sky OLR difference. Individual contributions from clouds, water vapor, temperature (surface and atmosphere), and aerosols are shown in grey, blue, red, and green, respectively.

the pre-monsoon period. Since, pre-industrial aerosols are prescribed to the RETRO, their contribution to the TOA budget does not change. Aerosols contribute about 10 W m$_{-2}$ to the ASR at TOA (not shown) and thus, play only a minor role. Cloud radiative effects lag the water vapor radiative effect (Figure 2 & 3). This lag is not as pronounced in RETRO.

References

Box, M. A.: Radiative perturbation theory: a review, Environmental Modelling & Software, 17, 95–106, 2002.

Neelin, J. D. and Held, I. M.: Modeling tropical convergence based on the moist static energy budget, Monthly Weather Review, 115, 3–12, 1987.

Rose, B. E.: CLIMLAB: a Python toolkit for interactive, process-oriented climate modeling., J. Open Source Softw., 3, 659, 2018.