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 over the Sahara. The subsequent radiative effects from water vapor and clouds then feed back into the circulation, further amplifying it (as mentioned in 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 by advecting moisture and subsequently through the formation of clouds. 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. 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 that 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 1). 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.

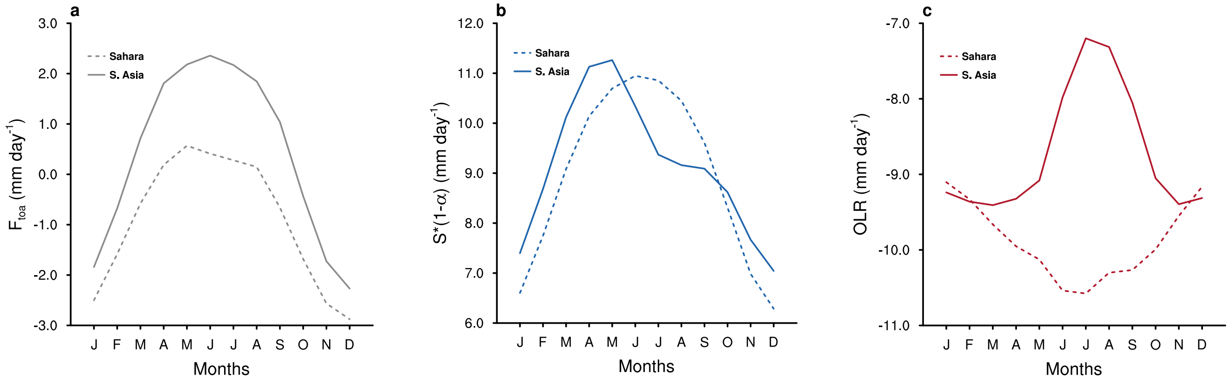

Figure 1. Seasonal cycle of F_{toa} and its components. The time series of (**a**) F_{toa}, (**b**) Net shortwave at the top of atmosphere, and (**c**) outgoing longwave radiation from ERA-5 climatology (based on 1981-2020). The solid line represents the area average over the domain (70°E-105°E and 15°N-30°N), 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 for the 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. In an interesting study, Byrne et al. (2018) demonstrated the impact of clouds and water vapor radiative effects on monsoons using radiation-locking simulations in an axisymmetric slab-ocean model. In contrast, our approach focuses on comparing distinct climate regimes (monsoon vs. desert, or RETRO vs. control) to isolate the roles of clouds and water vapor without interfering with the ESM's underlying physics.

   Radiative kernels, which are commonly used for such diagnostics, are linearized around a specific base climate. The 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) (MPI-ESM uses RRTMG). We prescribe the thermodynamic profiles and aerosol properties.

   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 1, the reflected shortwave radiation at TOA over the Sahara and South Asia during JJA have a difference of approximately 25 W m^{-2} (1 mm day^{-1} = 28.98 W m^{-2}) (this is consistent in both the CERES and ERA5 datasets). The dominant contributor to the TOA energy budget difference between these regions is the OLR (about 90 W m^{-2}). Hence, we further examine the impact of various factors on OLR. 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. This result is less pronounced in the RETRO Sahara simulation (Figure 3), primarily due to the domain selected. Pre-monsoon rainfall in the RETRO Sahara, especially in the northernmost part of the domain, is largely influenced by transient mid-latitude storms (In this animation the propagation of mid-latitude storms over the northern Sahara in RETRO can be seen - link). These storms are driven by baroclinic instabilities and lead to rapid cloud development through frontal lifting. Consequently, changes in water vapor are closely tied to cloud evolution. As a result, distinguish-

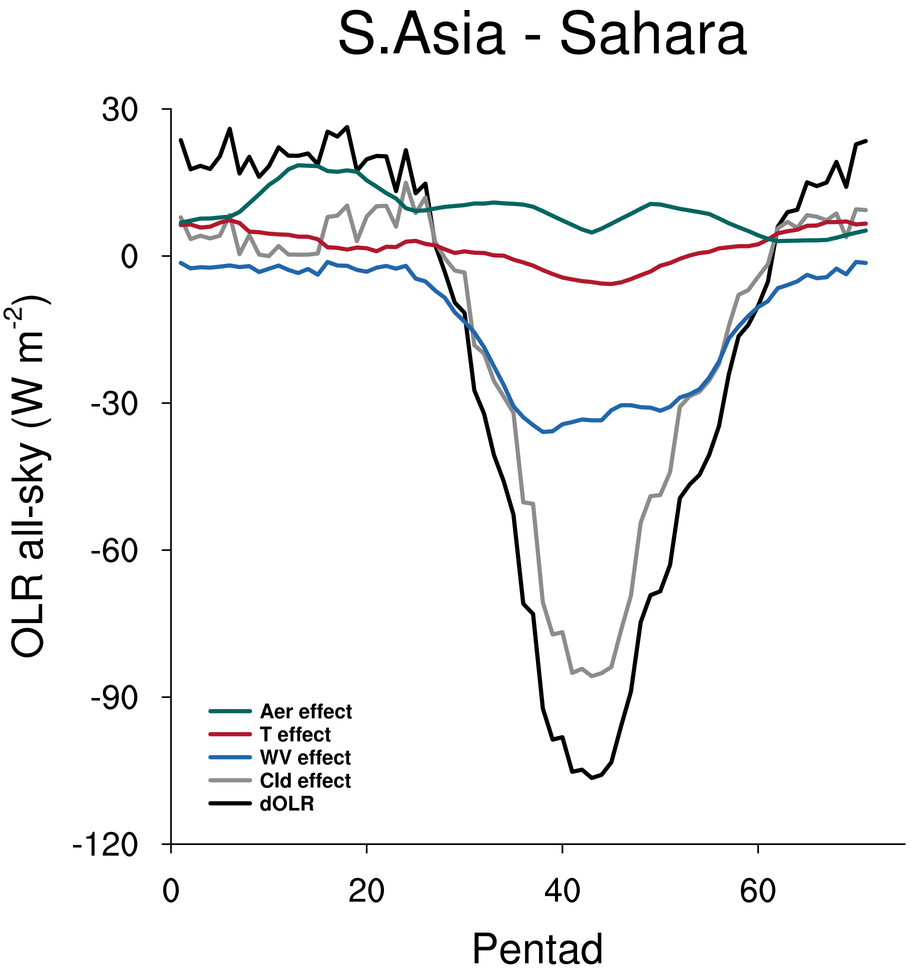

Figure 2. Decomposing longwave emission The time series of all-sky OLR difference between South Asia and the Sahara based on offline RRTMG calculations. The black line represents the total all-sky OLR difference. Individual contributions from clouds, water vapor, temperature (surface and atmosphere),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

ing the lead–lag relationship between water vapor and cloud radiative effects on OLR during non-monsoonal months is challenging at daily resolution. In contrast, monsoon onset is governed by large-scale dynamics, where moisture is gradually advected from the oceans over a relatively stable region. Once sufficient moisture accumulates to destabilize the atmosphere, convection initiates and clouds form. Therefore, during monsoon onset, water vapor radiative effects precede those of clouds. Selecting a region within the RETRO Sahara that is less affected by baroclinic instabilities allows for a clearer representation of monsoon onset and the sequential radiative impacts of water vapor and clouds. We choose the region depicted in the inset map in Figure 4. This figure demonstrates that our results do not change when we choose a different domain. All the changes in moisture convergence (P-E) is related to changes in F_{toa} (Figure 4a). Decomposing F_{toa} into its components indicates that OLR is the dominant factor (Figure 4b). Our analysis with the

RRTMG reveals that water vapor radiative effects dominate initially and subsequently the cloud radiative effects take over (Figure 5).

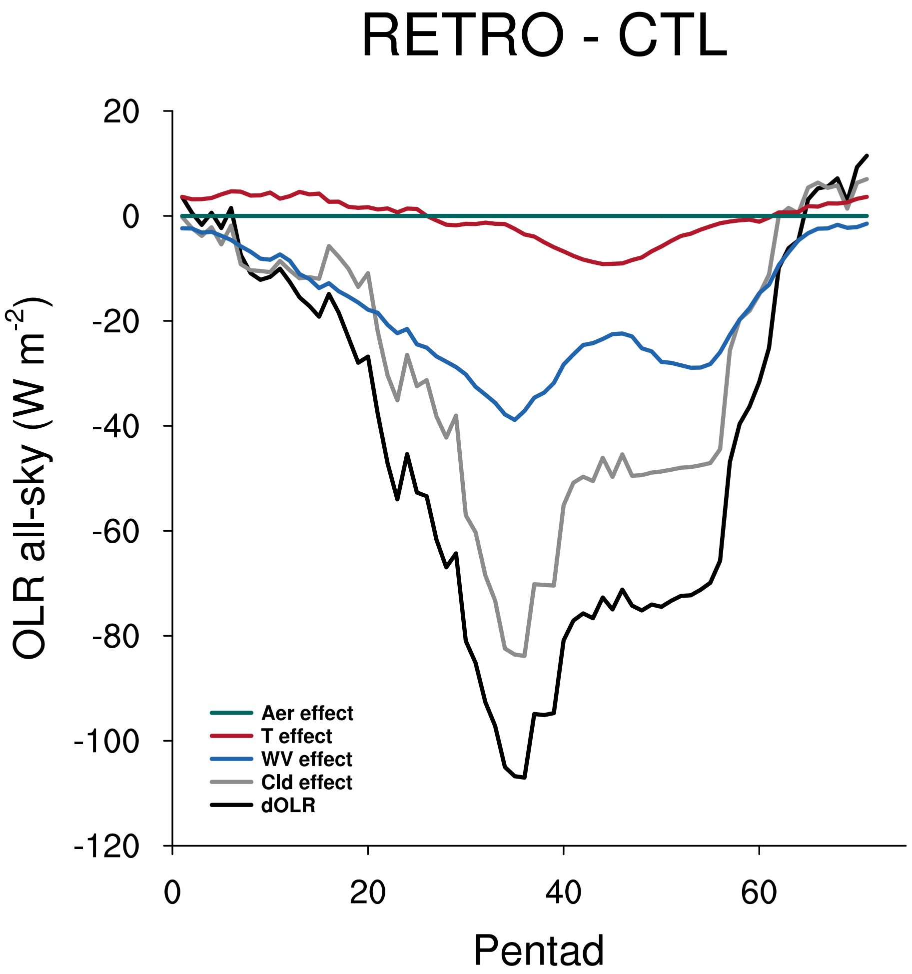

Figure 3. Decomposing longwave emission in RETRO Sahara The time series of all-sky OLR difference between RETRO and CTL over the Sahara based on offline RRTMG calculations. IThe black line represents the total all-sky OLR difference. Individual contributions from clouds, water vapor, temperature (surface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

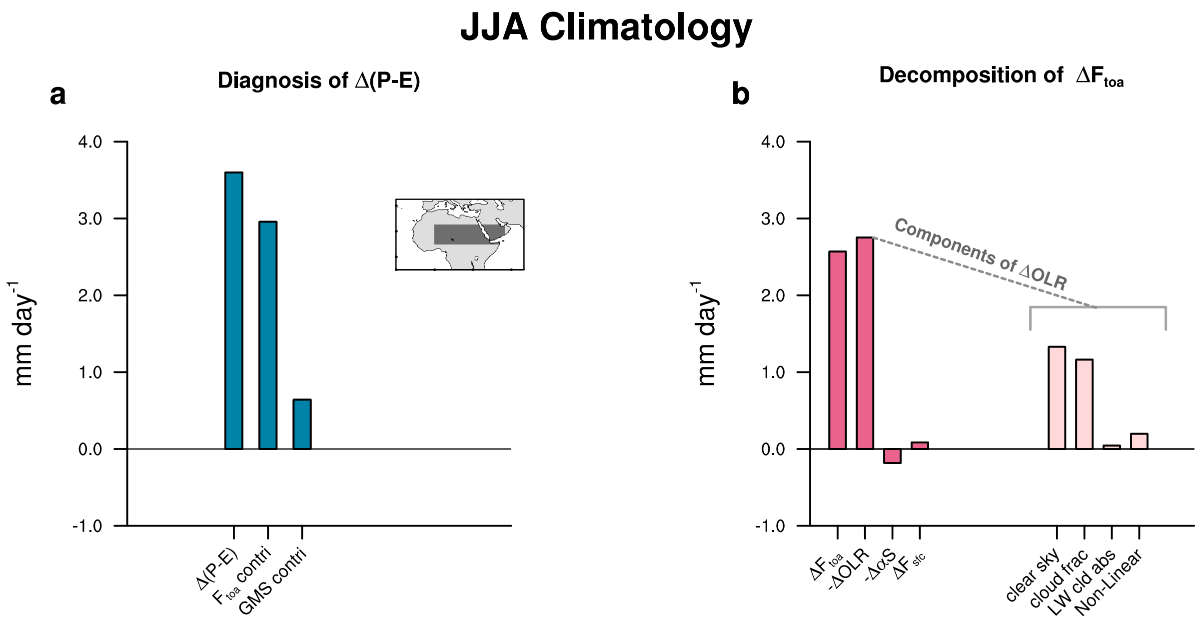

Figure 4. Diagnosis of change in moisture convergence during the first year of simulation. Bar graph of (**a**) change in (Precipitation - Evaporation; P-E), contribution of F_{toa}, and GMS, & (**b**) the change in F_{toa} and its components (see methods). The changes between Jun-Jul-Aug average of the first year of simulation from the RETRO and Jun-Jul-Aug climatology from the CTL over the domain (20°E-50°E and 10°N-25°N (land only grids) shown in grey shading in the inset map), is considered for this analysis. The change in OLR is further decomposed into changes due to clear sky OLR, changes in cloud area fraction, the longwave cloud absorption, and non-linear term (see methods).

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

   ***Reply*:** Thank you for 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 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.

   The radiative effects of clouds on monsoons has been examined in previous studies (Berry and Mace, 2014; Li et al., 2017; Byrne and Zanna, 2020; Stephens et al., 2024; Wang et al., 2020). In contrast this study highlights the role of water vapor radiative effects. To our knowledge, Byrne et al. (2018) is the only other study to have examined the impact of

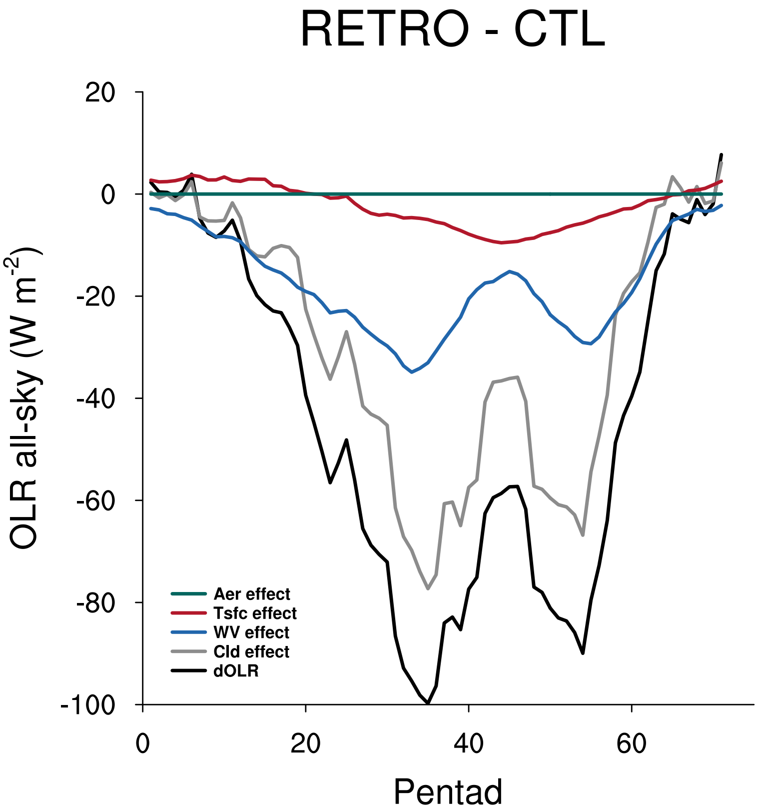

Figure 5. Decomposing longwave emission in RETRO Sahara The time series of all-sky OLR difference between RETRO and CTL over the Sahara based on offline RRTMG calculations. IThe black line represents the total all-sky OLR difference. Individual contributions from clouds, water vapor, temperature (surface and atmosphere), and aerosols are shown in grey, blue, red, and green, respectively. The domain bounded by 20°E-50°E and 10°N-25°N (land only grid points) is used for this analysis.

water vapor radiative effects on monsoon, albeit in a simplified and idealized model. Hence, our focus has been on the radiative effects of water vapor. In the new manuscript we will enhance the discussion about aerosols and clouds.

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Response to referee 2's comments "Energetics of monsoons and deserts: role of surface albedo vs water vapor feedback"

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

General comment: *Despite positioned along the same latitude in the norther hemisphere, dry-warm dessert exists over Sahara while wet monsoonal region is seen over south Asia in the present climate. In this manuscript, authors show that this difference is because of the presence of water vapor in the air. Water vapor is a strong absorber of longwave radiation emitted by the surface. Abundance of water vapor over South Asia enables high amount of longwave absorption such that the net radiation at the top of the atmosphere becomes positive, a necessary condition for monsoon to exist. Such a condition is not prevalent over Sahara on account of lack of water vapor. Authors confirm this by a GCM experiment where they performed two simulations with opposite rotation direction of the earth around its own axis.*
The overall theme of the study is excellent. The results are useful to understand both monsoons and desert mechanisms. However, I have two primary concerns regarding its current version. Firstly, several figures are in the supplementary which make the text hard to follow. I suggest moving some important figures to the main text and expand discussions around them. Secondly, the data sets are from reanalysis. It is well known that reanalysis products, an output of numerical models, suffer from reasonably capturing clouds, a key component of the radiation budget of the climate. My detailed comments are given below. Although a figure is shown in Supplementary comparing ERA5 Fnet with that from CERES, I'm not convinced by it. The reason being, this study further divides its components, and it is highly likely that components of Fnet could be very different in ERA5 as compared to satellite-based estimates. It is advised to compare other components of radiation budget in the manuscript to make it more robust.

Reply: Thank you for your encouraging feedback. We will move the relevant figures from the supplementary text to the main text to improve the readability. The referees' concerns regarding the reanalysis datasets are well taken and we acknowledge the limitations of reanalysis data. Our choice to use reanalysis data was primarily driven by the availability of all necessary atmospheric variables required for calculating TGMS. Despite known issues, these variables exhibit consistency with top-of-atmosphere (TOA) measurements. To further address the referees' concerns, we now include a comparison of TOA radiative fluxes from ERA5 with those from CERES. These will be added in the supplementary of the new manuscript.

Figure 1 shows the comparison between TOA fluxes taken from ERA-5 and CERES. The F_{toa} has small deviations, however, the net shortwave at TOA and OLR have larger differences due to the misrepresentation of clouds. Nevertheless these discrep-

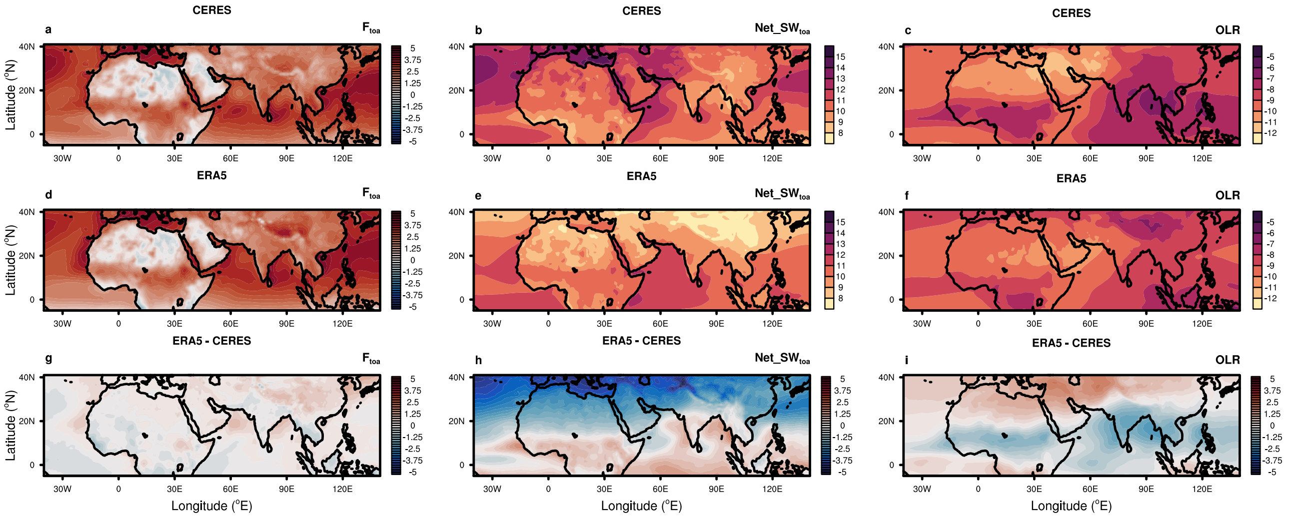

Figure 1. F_{toa} and its components. The spatial distribution of the total energy budget at the top of the atmosphere (F_{toa}) and it's components is shown by using ERA-5 climatology (1991-2020) and CERES climatology (07/2005 - 06/2015). The maps represent the Jun-Jul-Aug mean. The top row (**a-c**) displays data from CERES, middle row (**d-f**) depicts the data from ERA-5, and the bottom row (**g-i**) shows the anomaly between ERA-5 and CERES. The left column (**a,d,g**) presents F_{toa}, center column (**a,e,h**) depicts the all-sky net shortwave radiation, and the right column (**c,f,i**) represents the outgoing longwave radiation.

ancies do not impact our main result. In Figure 2, we show that the relative contribution of net shortwave at TOA and OLR to the F_{toa} difference between the Sahara and S. Asia are similar. In both datasets, the largest term is the OLR. Decomposing it further suggests significant contributions from water vapor (in the clear-sky) and cloud effects. Notably, the cloud contribution is stronger in CERES, but this does not alter our overall conclusions.

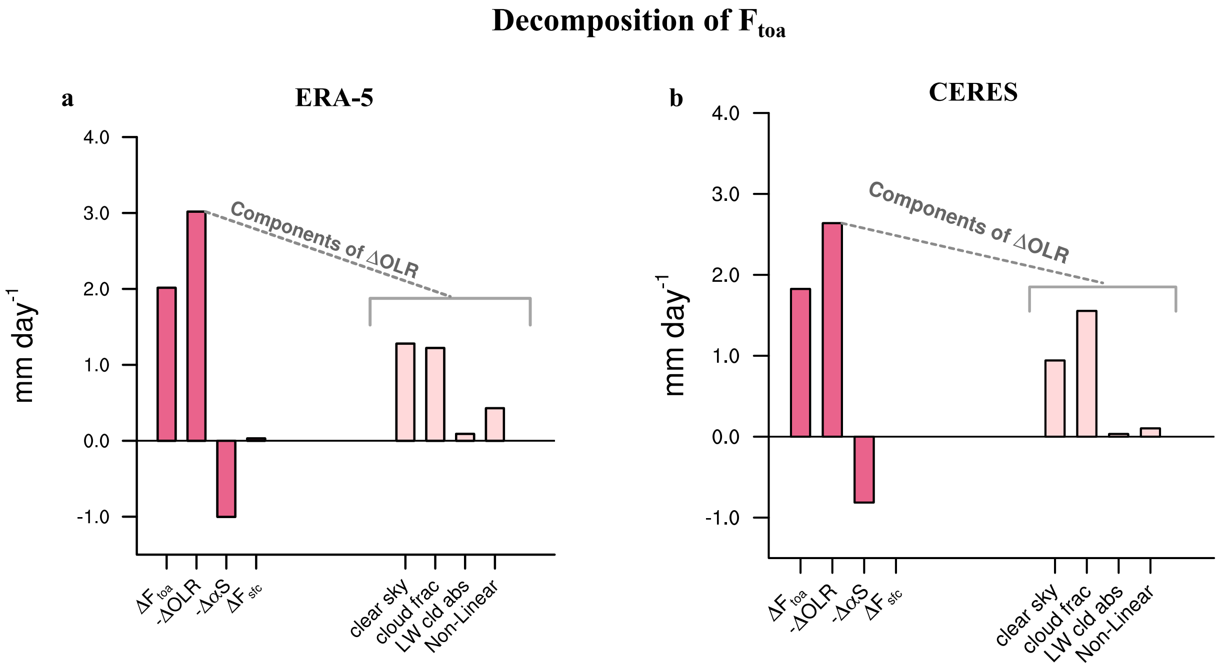

Figure 2. Decomposing F_{toa}. The bar chart illustrates the differences in the TOA fluxes and their components between Sahara and S.Asia. (**a**) is taken from ERA-5 climatology (1991-2020) and **b** is from CERES. Jun-Jul-Aug means are used for these climatologies.

1. ***Comment***: *Fig 1: Fnet is close to zero over Sahara. But the text all along says that Fnet is negative over Sahara (Lines 1, 13). Please correct the sentences accordingly.*

   Reply: F_{net} is zero when averaged over the domain shown in Figure 1 of the manuscript. However, there are large regions where F_{net} is negative, especially, in eastern Sahara. The text primarily refers to these regions and not the average F_{net} over the domain under consideration. We agree with the reviewer and consistency should be maintained in the text and the figures. We will change this in our revised manuscript.

2. ***Comment***: *Overall, the manuscript can be expanded to make it a ‘long-paper’. I suggest*

   (a) moving the sub-sections under ‘Appendix’ under a new a section ‘Data and Methods’ after Introduction.

   (b) moving some key figures from the supplementary to the main text.

   (c) Organize the text such that the flow is a bit more natural. I suggest keeping the entire observation part at the start. Then the modeling part can start. Or keep the modeling component from the beginning to the end of the centerpiece and use observations only as evidence to the proposed theory.

Reply: Thank you for the suggestion. The 'Data and Methods' is in the Appendix since the manuscript was originally submitted for consideration as ESD letters. In the revised manuscript, we will move the 'Data and Methods' section below introduction and some of the key figures from the supplementary will be shifted to the main text. The text will then be organized such that the observation will be in the initial part of the revised manuscript followed by the modeling part.

3. ***Comment***: *Line 72: Fig 2c and 2d show the relationship of OLR with CWV and Ts, respectively. Please correct.*

   Reply: The figures show a scatter between the clear-sky OLR over the Sahara and the South Asian monsoon region vs CWV and Ts, respectively. The text in Line 72 has the order reversed. Thank you for pointing this out. We will correct this in the revised manuscript.

4. ***Comment***: *Line 74: "CWV over the Sahara does not exceed 25 kg m-2, and does not influence the clear sky OLR". Figure 2b suggests that OLRclearsky increases sharply with an increase in CWV over the Sahara.*

   Reply: Clear-sky CWV over the Sahara is influenced by both, the surface temperature and the moisture content in the atmosphere. The impact of CWV on clear-sky OLR is much smaller over the Sahara. This is evident in a better way through the radiative transfer model calculations. We have run RRTMG in off-line mode with surface temperature, atmospheric temperature, and humidity prescribed. Figure 3 below shows the contribution of CWV (column integrated water vapor) & T (surface + atmospheric temperature) to clear-sky OLR over the Sahara and the South Asian monsoon domains. Over S.Asia, the clear-sky OLR when both CWV & T are being updated follows the red plot (T effect) closely during the pre-monsoon period. After monsoon onset it follows the blue plot (CWV effect). Contrarily, in the scatter plots used in the earlier manuscript does not highlight the impact of Ts vs CWV. Hence, we will move the scatter plots to the supplementary and instead keep the following figures in the main text.

5. ***Comment***: *Line 76: "As CWV increases during the onset and progression of the monsoon, clear sky OLR transitions from a state where it depends on surface temperature to a state where it depends on CWV." It is not clear to me from the plot. I suggest making another figure to clearly visualize and justify this statement.*

   Reply: Thank you for your comment. We will replace the scatter plots with timeseries plots showing the relative contributions of CWV, and Ts. This graph shows in a better way the transition of clear-sky OLR (over South Asia) from being dominated by Ts to being dominated by CWV during monsoon onset.

6. ***Comment***: *It will be good to see the difference in SST between the two experiments. Is there any significant change over the Atlantic Oceans?*

   Reply: In the new manuscript we will include the SST differences between the two experiments. Due to the large-scale changes in atmospheric and oceanic dynamics, the SSTs are different (Figure 4). This affects the spatial distribution

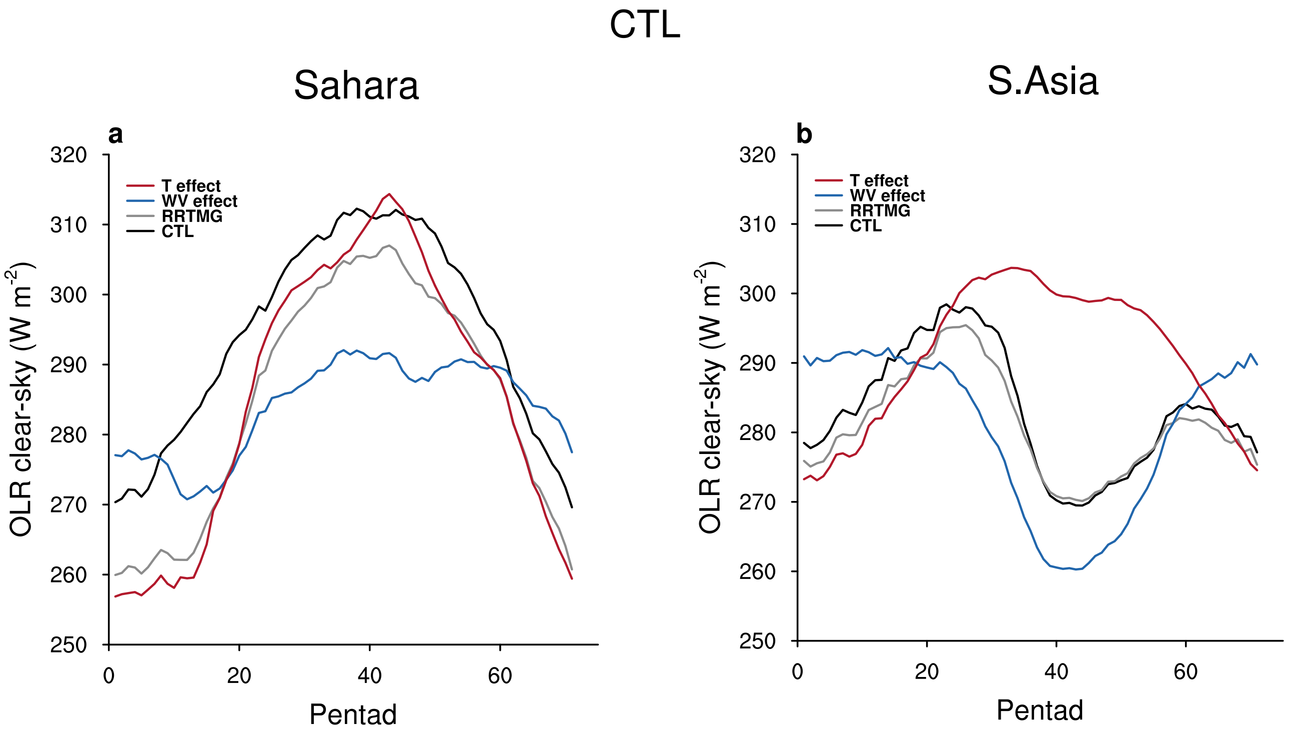

Figure 3. Influence of water vapor and surface temperature on clear-sky longwave emissions The time series of clear-sky outgoing longwave radiation (OLR) includes four datasets: the MPI-ESM pre-industrial control simulation (CTL) shown in black, the RRTMG offline run in grey, the RRTMG simulation isolating the effect of water vapor in blue, and the RRTMG simulation highlighting the impact of temperature (surface + atm) in red. To isolate the influence of water vapor, temperature is held constant at its April–May mean value while water vapor is varied. Conversely, to assess the impact of surface temperature, water vapor is fixed at its April–May mean while surface temperature is updated. Pentad means are used to construct the seasonal cycle.

of tropical precipitation/monsoons. However, this is only an initial trigger for the monsoon onset over the Sahara. The progression of monsoon over the Sahara is enhanced by the radiative feedback of water vapor.

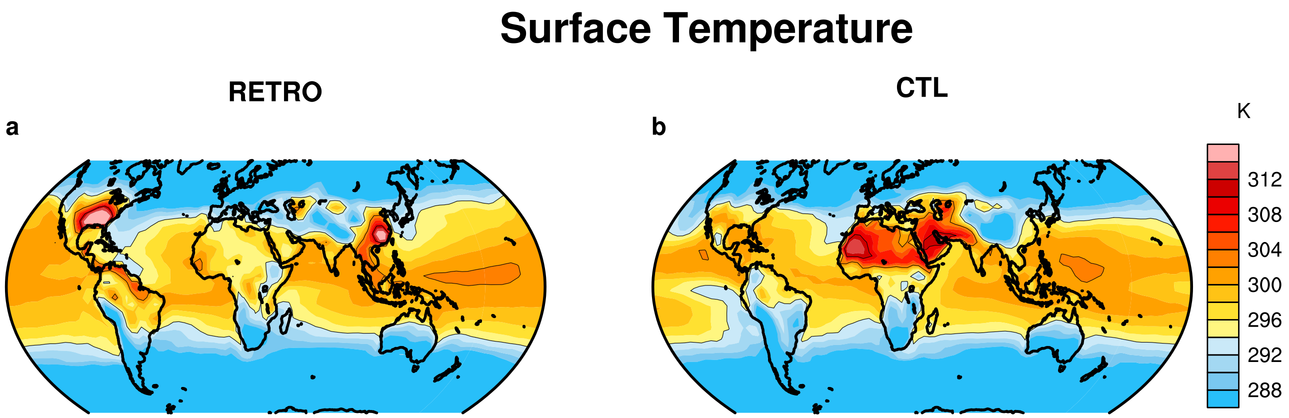

Figure 4. SST in RETRO and CTL. TThe spatial plots in panels (**a**) and (**b**) show the June–July–August (JJA) mean climatology derived from the RETRO and CTL simulations, respectively. The climatologies are computed using data from the final 100 years of each simulation.

7. ***Comment**: There's a key difference between the two descending regions in RETRO and CTL. Over Sahara in CTL, the descent does not have any seasonal cycle. However, over East Asia in RETRO, a strong seasonal cycle is prevalent. This indicates that the 'monsoon' happens during northern winter over East Asia in RETRO. What's the reason for this difference?*

   Reply: Thank you for your interesting question. We believe the winter 'monsoon' over the East Asia in RETRO is due to the orographic effects of Tibet, particularly, its interaction with the mid-latitude storms. While this is an interesting question to address, we believe it is outside the scope of the current study, and we plan to include a detailed analysis in the follow-up paper.