Response to Referee #2

This manuscript investigates the chaotic vs. physical effects of dust aerosols on Indian Summer Monsoon (ISM) precipitation using large ensemble simulations with the iAMAS model. The study focuses on a 20-day period in June 2016 and quantifies the spread and convergence of dust-induced impacts using 50-member ensembles. The authors use the Indian Summer Monsoon (ISM) system as a case study to show that even with the same physical forcing (e.g., dust aerosol), the simulated response varies widely due to initial condition perturbations. The novel aspect lies in highlighting the limitations of small ensemble sizes in drawing robust conclusions about aerosol effects.

Response: We sincerely thank Referee #2 for the careful review and insightful summary of our manuscript. We have carefully addressed all your specific comments and suggestions in the revised manuscript, as detailed in our point-by-point responses below. We believe these revisions have helped us improve the clarity of our presentation and strengthen our conclusions and hope that they adequately address your concerns.

The major comments are:

- ***1. The final paragraph of the introduction should more clearly articulate the main objectives of the study and provide a concise roadmap of the manuscript's structure. Currently, the paragraph combines motivation and definitions without explicitly stating specific research questions or outlining the paper's structure.***

Response: We sincerely thank the reviewer for this suggestion to enhance the clarity of our introduction's final paragraph. We have revised this section and added our main objectives and provide a clear roadmap as follows: "This study has three primary objectives: (1) to quantify the uncertainties in simulating aerosol impacts introduced by chaotic effects, (2) to distinguish between physical and chaotic effects in the dust aerosol impacts on ISM system, and (3) to determine whether simulated aerosol impacts on the ISM are predominantly driven by physical processes or significantly influenced by chaotic behaviors. We define the "physical effect" as the deterministic response of meteorological fields to aerosols that remains consistent across ensemble members despite initial condition perturbations. The ensemble-mean approximates this underlying physical effect by averaging out chaotic influences. Conversely, the "chaotic effect" represents internally generated variations arising from initial condition perturbations, manifested as the spread among ensemble members (Feng et al., 2024a).

The remainder of this paper is structured as follows: Section 2 describes our methodology, including the iAMAS model employed (Section 2.1), experiments configurations and methods for generating perturbed initial conditions (Section 2.2), and observational datasets used for validation (Section 2.3). Section 3 presents our analysis of chaotic effects on dust aerosol impacts on the ISM and discusses the relationship between ensemble size and chaotic uncertainties. Section 4 provides conclusions and summarizes the implications of our findings and discusses the limitations of this study."

- ***2. The description of the iAMAS model is currently scattered within the introduction, primarily through citations to previous studies. However, a dedicated and concise model description paragraph is missing from the Methodology section, which is where readers expect to find details about the modeling framework used in the experiments. I recommend moving the relevant model description content from the introduction to Section 2.1, ensuring it covers key features (e.g., dynamics, resolution, aerosol treatment, radiation, and physics schemes) in a self-contained manner. This will improve the clarity and reproducibility of the study.***

Response: We sincerely appreciate the reviewer's suggestion regarding the organization of the iAMAS model description. We have added more descriptions of iAMAS's critical components in the revised Section 2.1 to improve the clarity and reproducibility of our study as follows:

"In this study, we employed the integrated Atmospheric Model Across Scales (iAMAS) (Feng et al., 2023; Gu et al., 2022). The iAMAS model is a non-hydrostatic global variable-resolution atmospheric modeling system featuring online integrated aerosol feedbacks. The model is also designed for the supercomputer with heterogeneous many-core architecture such as China's Sunway supercomputer.

iAMAS's dynamic core is adapted from the Model for Prediction Across Scales – Atmosphere (MPAS-A) (Skamarock et al., 2012), which discretizes the computational domain horizontally on a C-grid staggered unstructured Voronoi mesh using finite-volume formation (Skamarock et al., 2012). The fully compressible non-hydrostatic equations are casted in terms of geometric-height hybrid terrain-following coordinate, and the solver applies the split-explicit time integration scheme. The time-integration scheme employs the 3rd-order Runge-Kutta (RK3) method and the explicit time-splitting technique (Wicker and Skamarock, 2002).

For physics suite, iAMAS incorporates a comprehensive suite of microphysical parameterization schemes, including the Predicted Particle Properties (P3) scheme (Morrison and Milbrandt, 2015), the Morrison double-moment scheme (Morrison et al., 2005), and the Thompson scheme (Thompson et al., 2008) , the WRF Single-Moment 6-class scheme (WSM6) (Hong and Lim, 2006), and the basic warm-rain Kessler scheme (Kessler, 1969). On convective processes, iAMAS implements multiple parameterization options: the sophisticated multi-scale Kain-Fritsch (MSKF) scheme (Zheng et al., 2016), the original Kain-Fritsch (KF) scheme (Kain, 2004), the original and new Tiedtke mass-flux schemes (Tiedtke, 1989; Zhang et al., 2011), and the modified version of the scale-aware Grell-Freitas scheme (Grell and Freitas, 2014). The surface layer physics options include the classical Monin-Obukhov similarity theory scheme (Monin and Obukhov, 2009) and the Mellor-Yamada-Nakanishi-Niino (MYNN) scheme (Nakanishi and Niino, 2006, 2009). For planetary boundary layer (PBL) processes, both the Yonsei University (YSU) scheme (Hong et al., 2006) and MYNN scheme are implemented. The land-atmosphere interactions are represented through the Noah land surface model with four soil layers (Chen and Dudhia, 2001). Radiative transfer processes are parameterized using either the Rapid Radiative Transfer Model for GCMs (RRTMG) for both shortwave and longwave radiation (Iacono et al., 2000; Mlawer et al., 1997) or the Community Atmosphere Model (CAM) radiation scheme.

For aerosol related suite, iAMAS includes the processes of online emission, advection, diffusion, vertical turbulent mixing, dry deposition, gravitational settling, and wet scavenging. In the experiments conducted for this study, only dust aerosols are included to isolate their effects from those of other aerosols. iAMAS uses sectional approach to represent a 10-bin size distribution of aerosol particles ranging from ~0.04 to 40 µm. Each size bin is assumed to be internally mixed so that all particles within a size bin have the same properties. The dust emission scheme of iAMAS is adapted from the Goddard Chemistry Aerosol Radiation and Transport (GOCART) scheme (Ginoux et al., 2001). The dry deposition of aerosols is calculated based on Peters and Eiden, (1992) in iAMAS and wet deposition of aerosols both in-cloud and below-cloud are also treated in the model.

Aerosol-cloud interaction (ACI) is implemented in the model based on the method described by (Gustafson et al., 2007) for calculating the activation and resuspension between dry aerosols and cloud droplets. Aerosol activation (or droplet nucleation) is based on a maximum supersaturation determined from a Gaussian spectrum of updraft velocities, similar to the methodology used in (Ghan et al., 2001). The activated droplet number is then coupled with the Thompson microphysics scheme. In this way, aerosols can affect cloud droplet number, and clouds can also alter aerosol concentration through aqueous processes and wet scavenging. The hygroscopicity of dust aerosols are assumed to be 0.10 in this study. Within the Thompson cloud microphysics scheme, the number of ice nucleation (IN) in mixing-phase clouds from dust is calculated following the formula proposed by DeMott et al.(DeMott et al., 2010). This study only considers the wet scavenging process of activated dust aerosols into cloud droplet, ignoring the conversion of dust into IN because the IN feedback calculations are not fully evaluated in iAMAS at this stage.

iAMAS also incorporates the aerosol-radiation interaction (ARI). Following the new method proposed by Feng et al., (2025), aerosol optical properties are computed and coupled with the RRTMG radiation scheme for both shortwave and longwave bands. For dust aerosols, this study utilizes the Optical Properties of Aerosols and Clouds (OPAC) dataset (Hess et al., 1998) to provide their shortwave and longwave refractive indices.”

- ***3. The manuscript lacks clarity on aerosol treatment, especially dust. Please specify:***
  - ✓ ***Whether both direct (radiative) and indirect (cloud) effects are included. If only direct effects (ARI) are used, this should be clearly stated and justified.***
  - ✓ ***Whether aerosol-cloud interactions (ACI) are active, and if not, why.***
  - ✓ ***Whether aerosols are internally or externally mixed, and what assumptions are made regarding their optical and hygroscopic properties.***

I recommend that the authors include a dedicated subsection or an expanded paragraph in Section 2 covering these aerosol processes in sufficient detail.

Response: We sincerely appreciate the reviewer's insightful suggestions regarding aerosol process specification. As addressed in our prior response, we have expanded Section 2.1 to detailed document our treatment of aerosols. To directly answer the reviewer's queries: 1. The ACI and ARI are both used in this study. 2. ACI is active but the IN feedbacks are deactivated because these calculations in iAMAS are not fully evaluated at this stage. 3. Aerosols are internally mixed and the optical and hygroscopic properties are also described in the revised text. Please refer to the Methodology of revised text for details.

- ***4. The choice to simulate only 20 days during the early monsoon season (June 10–30, 2016) warrants further justification. This short time frame captures only the monsoon onset and not the full seasonal evolution, intraseasonal variability, or withdrawal phase. While the period may have been chosen to isolate certain synoptic features or reduce computational cost, the manuscript should explicitly state the scientific rationale for selecting this specific window. Additionally, it would strengthen the study to discuss how representative this period is of broader monsoon-dust interactions. If this is intended as a case study, that should be clearly stated to avoid overgeneralization of the results.***

Response: Thanks a lot for this critical point. We have clarified in the revised Section 2 text as: "The simulations covered the period from June 10 to June 30, 2016, focusing on a specific intense rainfall period occurring during the 2016 Indian summer monsoon season. To be clarified, this period does not cover the entire dust-ISM interactions throughout the monsoon season or across different years. We selected this specific period as it features a monsoon onset period with monsoon depression system that is particularly sensitive to aerosol impacts, making it suitable for investigating physical and chaotic effects. This approach also balances computational costs (necessitated by the large number of ensemble experiments) with scientific objectives, though we recognize that longer-term simulations would be valuable for future work to capture the full range of dust-ISM interaction."

Besides, we have added additional discussions in the revised Introduction section as: "While substantial progress has been made in characterizing dust-monsoon interactions, most previous studies have focused on the mature monsoon season (July-August), during which atmospheric circulation is more stable and convective systems are already well established. In contrast, the onset phase is dynamically transitional and thus more sensitive to radiative and thermodynamic perturbations. During this transition, atmospheric circulation is dynamically unstable, the Intertropical Convergence Zone (ITCZ) and low-level jets are reorganizing, and synoptic systems such as monsoon depressions are forming. Under such complex conditions, dust-induced heating may exert outsized influence. Furthermore, to investigate the influence of chaotic effects of dust impacts, we plan to conduct a large ensemble of experiments with 50 members, which demands substantial computational resources. Given that dust may exert a pronounced influence during the onset period and to manage the computational resource constraints, we select only the onset period of the ISM in 2016 (June 10–30) as our simulation period."

And we have avoided overgeneralization of the results by adding: "To be clarified, our results on precipitation response patterns reflect this specific meteorological situation (Jun 10 to Jun 30, 2016), and the large effect we document here specifically applies to dust's role during the monsoon onset period in modulating the formation of monsoon depression systems during favorable meteorological conditions, rather than representing a general dust-monsoon interaction magnitude that could be extrapolated to seasonal or climatological time scales." in the revised text in Section 3 (Line 350) and "It is crucial to emphasize that the ensemble size requirements discussed here are specific to the analysis of synoptic-scale processes within this 20-day simulation during the monsoon onset period. Studies focusing on longer-term climatological means (e.g., seasonal averages or multi-year averages) inherently integrate over more weather events. This temporal smoothing might accelerate the convergence towards a robust physical effect in function of ensemble size, which is a promising hypothesis that warrants systematic investigation in future studies. Our findings on the necessity of larger ensembles therefore primarily apply to dust aerosol impacts on synoptic events, where the stochastic component of variability remains dominant and unresolved by temporal averaging." in Section 3 (Line 457).

- ***5. Figure 3c (AOD from the "Sensitive" simulation) appears to show nearly no aerosol loading over much of South Asia, including the Indo-Gangetic Plain — a region known for high anthropogenic aerosol concentrations even during the monsoon period. Since the "Sensitive" case only excludes Arabian dust emissions, anthropogenic aerosol emissions should still be present in the simulation or was it only dust emissions enabled?***

Response: Sorry for the confusion. Actually, only dust emissions are enabled in this study. We have clarified this point in the revised manuscript's methodology section as: "In the experiments conducted for this study, only dust aerosols are included to isolate their effects from those of other aerosols."

- ***6. Figure 10 suggests that ensemble sizes beyond 30 members yield only marginal improvements in the convergence of dust-induced precipitation responses. Given the computational cost associated with running large ensembles, could the authors clarify whether they consider 30 members as an optimal threshold for similar studies? Additionally, do they recommend any specific criteria or diagnostics to determine when further increases in ensemble size (e.g., to 40 or more) are justified?***

Response: Thank you for this insightful question regarding optimal ensemble sizes. We would like to clarify that the threshold of 30 members suggested by Figure 10 should not be interpreted as a universally optimal value for all aerosol impacts studies. Rather, our analysis demonstrates a scale-dependent relationship between required ensemble size and the meteorological phenomena being studied.

Our results indicate that different atmospheric processes require different minimum ensemble sizes to achieve robust results:

For mesoscale weather systems like the monsoon depression examined in our case study, we found that ensembles with fewer than 30 members could produce substantially different or even opposing dust-induced impacts. With approximately 30 members, the spatial patterns of responses showed much better convergence, with differences mainly in magnitude rather than sign.

In contrast, for larger-scale processes such as general monsoon circulation and precipitation along India's western coast and the southern slopes of the Himalayas, reasonable convergence was achieved with as few as 5 ensemble members.
This scale-dependence reflects the inherent predictability differences between large-scale and mesoscale atmospheric processes. Smaller-scale phenomena generally exhibit greater sensitivity to initial conditions and thus require larger ensembles to robustly characterize their responses to aerosol forcing.

We also explicitly state in the revised manuscript as: "Please note that our findings of 30 members for mesoscale systems and 5 members for larger-scale processes are specific to our case study of dust effects on the ISM during June 10-30, 2016, and may vary for different aerosol types, regions, or seasons. The optimal ensemble size ultimately depends on the specific research questions, phenomena of interest."

- ***7. Would the authors expect similar sensitivity and ensemble size requirements if the primary response variable were temperature rather than precipitation? Could temperature fields, given their typically lower chaotic variance, be used to isolate aerosol radiative effects with smaller ensemble sizes?***

Response: Thank you for this insightful question about temperature fields as response variables. You raise an important point that highlights the variable sensitivity of different meteorological parameters to chaotic effects.

As shown in Figure R2 below, temperature fields indeed exhibit considerably less chaotic variance compared to precipitation fields. This aligns with fundamental atmospheric dynamics - temperature fields tend to be more spatially coherent and temporally stable than precipitation.

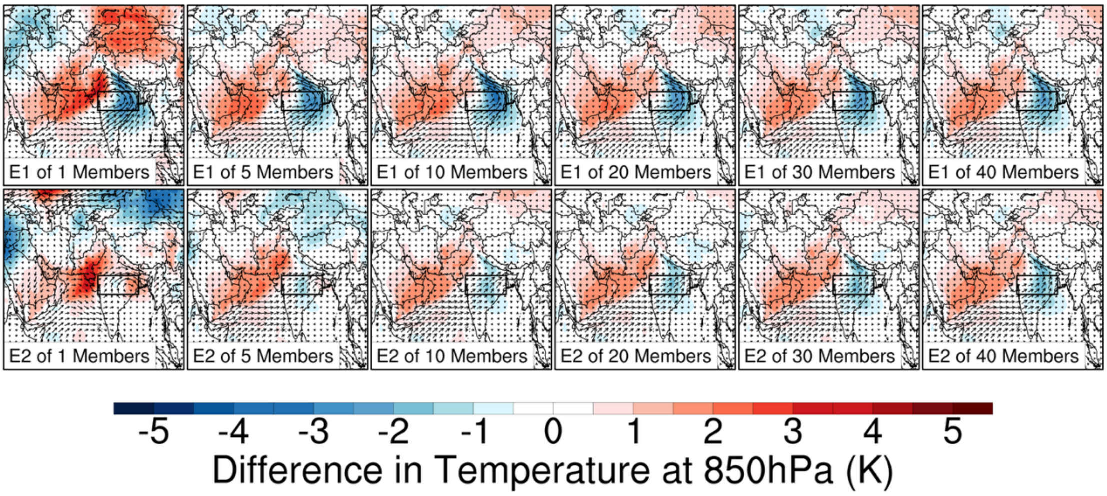

Figure R2. The spatial distribution of dust-induced temperature at 850hPa impacts for two extreme cases selected from possible combinations of 1, 5, 10, 20, 30, and 40-member ensembles, representing the maximum (E1 in top panels) and minimum (E2 in bottom panels) area-averaged responses.

Given these results, we would expect temperature responses to dust aerosol forcing to converge with smaller ensemble sizes compared to precipitation responses. While we did not explicitly test convergence thresholds for temperature in this study, our results suggest that temperature fields could likely be used to isolate aerosol radiative effects with smaller ensemble sizes - perhaps around 10 members or even fewer for robust characterization of the temperature response.

This supports your suggestion that temperature fields could be a more computationally efficient way to isolate certain aerosol radiative effects. Temperature responses directly reflect the radiative perturbation from dust, whereas precipitation responses involve additional complex processes including cloud microphysics, convective dynamics, and boundary layer interactions, all of which amplify the influence of chaotic variability.

In our current study, we tend to focused on precipitation as one of the most challenging variables to characterize robustly, providing an estimate of required ensemble sizes. For comprehensive aerosol impact studies targeting multiple variables and processes, ensemble size requirements would likely be dictated by the most chaotically sensitive variables of interest.

This differential sensitivity across variables is an interesting avenue for future work, and we appreciate your suggestion to consider how ensemble requirements might be optimized depending on the specific response variables being investigated.

We have added some discussions in the revised manuscript as: "We extend a similar analysis to dust impacts on 850 hPa temperature following Figure 10. The results (as shown in Figure S11) indicate that temperature responses to dust aerosol forcing may converge with smaller ensemble sizes compared to precipitation responses. While we did not focus on temperature in this study, the observed patterns suggest that temperature fields could be used to isolate aerosol radiative effects with relatively modest ensemble sizes. This likely reflects that temperature responses more directly reflect the radiative perturbation from dust, whereas precipitation involves additional complex processes such as cloud microphysics, convective dynamics, and boundary layer interactions, which amplify the influence of chaotic variability. The role of chaotic effects in modulating dust aerosol impacts across different climate variables and processes represents a compelling avenue for future research."

- ***8. Since the study focuses predominantly on dust aerosols and specifically targets the Indian Summer Monsoon, I recommend the review title to more accurately reflect this focus.***

Response: Thanks a lot for reviewer's insightful recommendation to emphasize the specific role of dust aerosols in the Indian Summer Monsoon. The new title now directly reflects this core focus: "Dust impacts on Indian summer monsoon: chaotic or physical effect?".