Responses to Reviewers' Comments

We are sincerely grateful to the editor and reviewers for their valuable time spent on reviewing our manuscript. The comments are constructive and valuable, and we have tried our best to address the issues raised by the reviewers in revised manuscript. Please find our item-by-item response (in bold) to the comments (in black) raised by the reviewers, and the paragraphs added in the revised manuscript (in red).

Reviewer #2

General Comments: This manuscript investigates the impact of dust aerosols on the three-dimensional structure of precipitation systems of different sizes using a variety of observational data and reanalysis data. The authors employed a clustering method to group satellite precipitation radar profiles into organized precipitation systems, which is a novel and valuable approach. Studying precipitation from the system perspective provides deeper insights into aerosol–precipitation interactions and their coupling with environmental conditions. However, there remain a few minor issues that need further clarification and refinement, as outlined below.

Reply: We thank the reviewer for the encouragement and the valuable comments to improve our manuscript. All the comments have been addressed in the revised manuscript.

Major Comments:

Q1: In section 2.1, since MODIS cannot detect aerosols below clouds, the authors used a spatiotemporal interpolation and extrapolation method to estimate the dust concentration. It is noted that the spatial extent of the extrapolation varies with the size of PSs, and the size of PSs can reflect cloud coverage to some extent. However, this manuscript does not evaluate the impact of cloud coverage. I believe sensitivity experiments should be added.

Reply: We appreciate this insightful question. We agree that the cloud coverage may influence the estimation of dust concentration. To address this issue, we have included the following discussion about sensitivity experiments in the supplementary materials:

"We have conducted sensitivity tests using Modern-Era Retrospective Analysis for Research and Applications for version 2 (MERRA-2) data. Specifically, we artificially removed varying proportions of valid data to simulate different cloud cover conditions. For each precipitation system (PS), the averaged MERRA-2 AOD in the PS region was taken as the "true" AOD. Then, these AOD data were removed (white blocks in Fig. S1), and additional values were randomly removed from surrounding areas (gray blocks) to represent different cloud fractions. Our

interpolation algorithm was then applied to the AOD data under varying cloud cover conditions, and compared with the true values. Figures S2 and S3 summarize the results.

Across different missing data fractions, the interpolated AOD agrees well with the "true" AOD, with root mean square error (RMSE) remaining low and correlation coefficients exceeding 0.8. Although performance slightly decreases with increasing missing data (e.g., declining correlation and slightly higher RMSE), the overall impact remains minor. This result is likely because the frequent Saharan dust outbreaks in the study region, which persist for several days. Thus, even under high cloud cover condition, valid data from surrounding grids and adjacent days still provide sufficient information to estimate dust aerosol conditions of PSs.

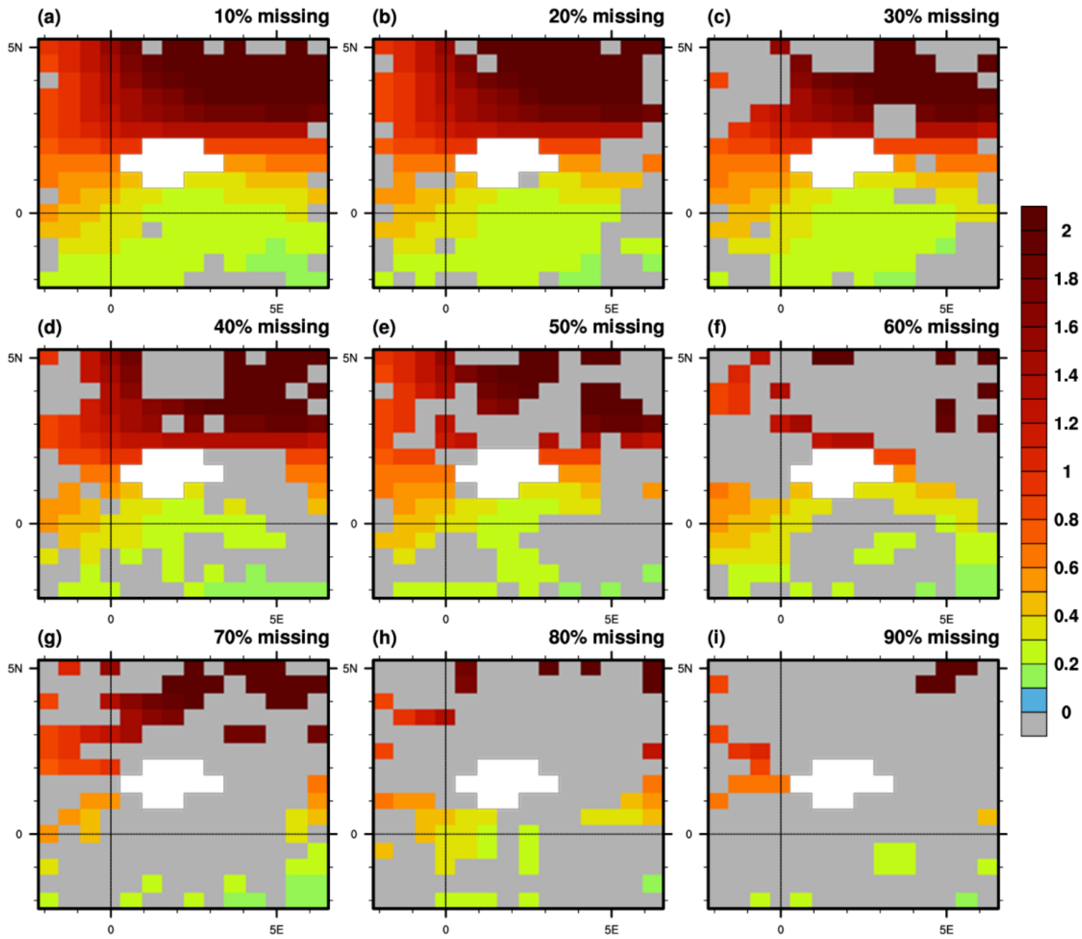

Figure S1. Spatial distribution of AOD for a PS case under varying proportions of artificially removed data. White blocks denote removed AOD data in PS region, and grey blocks denote additional removed data with different proportions from surrounding area.

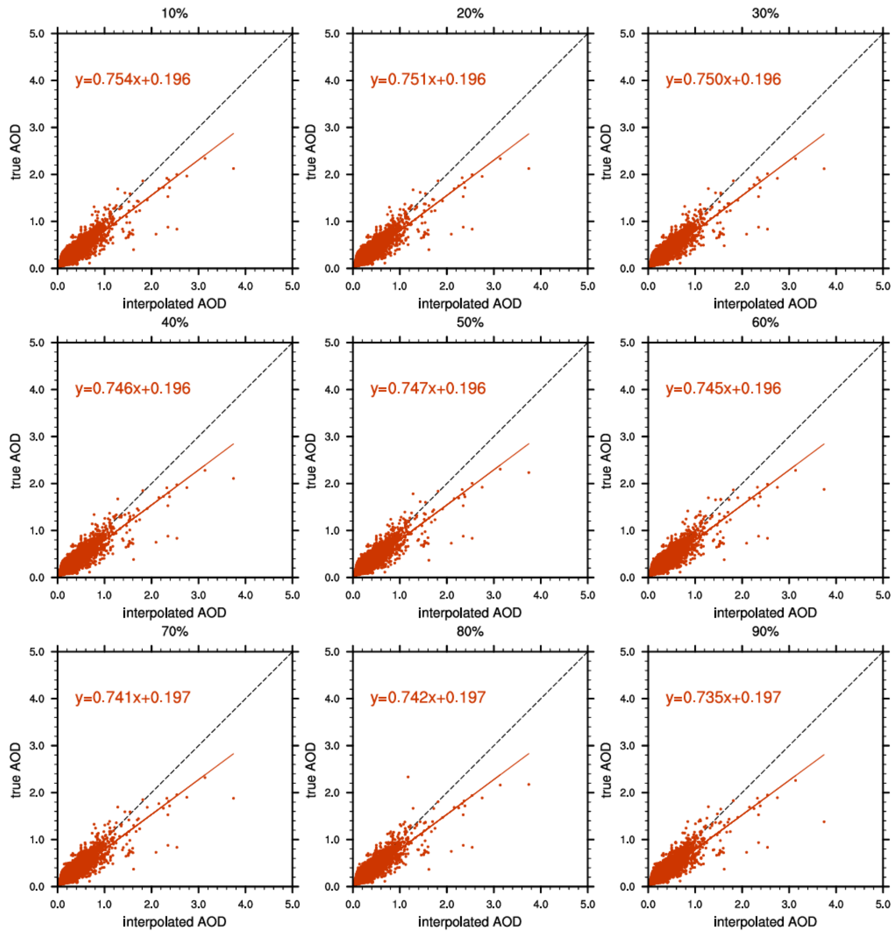

Figure S2. Scatter plots of interpolated AOD (y-axis) versus true AOD (x-axis) for different proportions of artificially removed data.

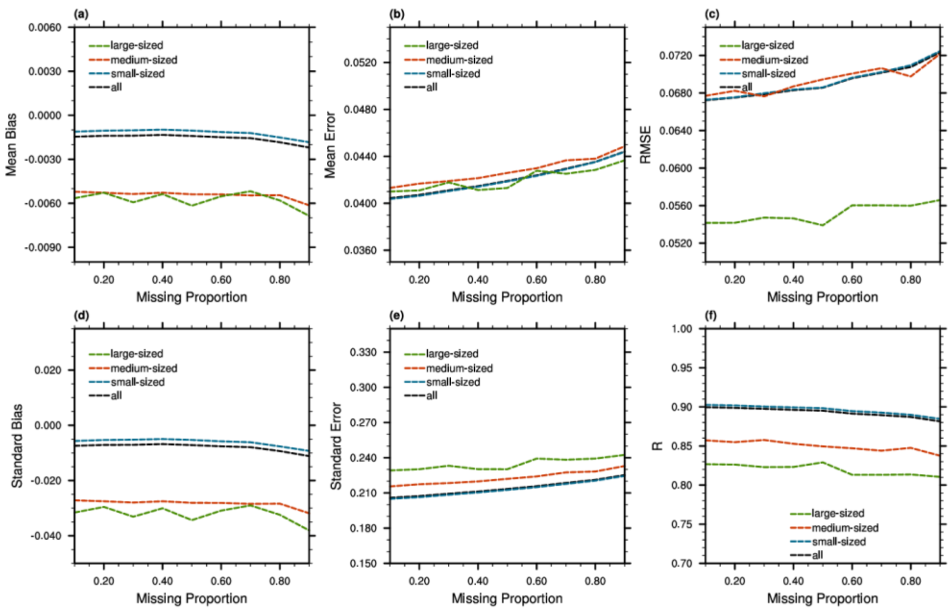

Figure S3. Variations in (a) mean bias, (b) mean error, (c) RMSE, (d) standard bias, (e) standard error, and (f) correlation coefficient of the interpolated AOD relative to the true values for PSs of different sizes, as a function of the proportion of missing data. "

Q2: In section 3.2,the authors analyzed the influence of meteorological conditions on dust effects and found that CAPE plays a significant role. The author did not explain why CAPE emerges as a more prominent factor compared to other dynamic and moisture conditions(e.g., vertical wind shear, relative humidity).Such an explanation is critical for understanding of the complex interactions between precipitation, aerosols, and meteorology.

Reply: Thank you for your valuable comment. CAPE measures the convective instability energy, and is one of the most representative parameters of atmospheric dynamic conditions. CAPE can directly influence the vertical development of precipitation. It is expected that stronger CAPE conditions typically correspond to more vigorous convective processes, leading to higher precipitation rates and deeper cloud structures (Zhu et al., 2023).

Zhu, H., Li, R., Yang, S., Zhao, C., Jiang, Z., and Huang, C.: The impacts of dust aerosol and convective available potential energy on precipitation vertical structure in southeastern China as seen from multisource observations, Atmos. Chem. Phys., 23, 2421-2437, doi:10.5194/acp-23-2421-2023, 2023.

Q3: In section 4, although the radiative effect of dust can cause warming of the midtroposphere and cooling of the near surface, thereby suppressing convection, the influence of dust radiative effects cannot be ruled out. This manuscript provides a rather limited introduction to dust radiative effects, which requires further elaboration.

Reply: We fully agree with the reviewer that the radiative effects of dust should be discussed more thoroughly. We have added the following paragraph in the section of "Discussion" of the revised manuscript:

"Although the microphysical effects are considered to play a dominant role, the possible contribution of radiative effects cannot be excluded. A few modeling studies (e.g., Cheng et al., 2019) have shown that dust radiative effects can delay convection initiation, allowing for energy accumulation, which may ultimately lead to more intense convective development once triggered. This highlights the complexity of dust radiative effects, thus it is difficult to quantify their impact using observational data. Future modeling studies will be needed to conduct sensitivity experiments to disentangle the contributions of dust radiative and microphysical effects.

Cheng, C.-T., Chen, J.-P., Tsai, I. C., Lee, H.-H., Matsui, T., Earl, K., Lin, Y.-C., Chen, S.-H., and Huang, C.-C.: Impacts of Dust–Radiation versus Dust–Cloud Interactions on the Development of a Modeled Mesoscale Convective System over North Africa, Monthly Weather Review, 147, 3301-3326, 10.1175/mwr-d-18-0459.1, 2019. "

Q4: The PSs selected for this study primarily consist of deep convective cloud systems that exceed 6 km in height. This selection criterion may affect the statistical results. Therefore, this should be highlighted in the conclusion section, so readers are aware of its potential influence on the findings.

Reply: We appreciate this suggestion. The selection criterion of PSs may influence the statistical results and should be clearly emphasized. We have added the following paragraph in the section of "Conclusions" of the revised manuscript:

"Our study primarily focuses on deep convective PSs with vertical development exceeding 6 km. Whether these conclusions can be extended to other types of PSs requires further investigation."

Minor Comments:

Q1: In line 38, 'with a temperature of between -5 and +2 ℃' should be corrected to 'with temperatures between -5 and +2 ℃'.

Reply: Done!

Q2: In Table 5, the sample sizes of large-sized PSs across different CAPE bins appear too small, which raises concerns about the statistical reliability of the results.

Reply: Thanks for pointing this out. We agree with the reviewer that the small sample sizes of large-sized PSs across different CAPE bins may affect the statistical reliability of the results. We have added the following paragraph in the revised manuscript when presenting Table 5:

"It is noted that the sample sizes for large-sized PSs across different CAPE bins are relatively small in Table 5. This is mainly due to the lower frequency of large-sized PSs compared to smaller ones, and the limitations of the PR swath, as only untruncated PSs were selected for analysis. While significance tests were applied to the data, the limited sample sizes may affect the statistical robustness of the results, which should be interpreted with caution."

Q3: In Figure 3, it would be more accurate to replace 'area' with 'near-surface precipitation area', since it is defined as the number of pixels with near-surface precipitation rates greater than 0 mm/h multiplied by the pixel area.

Reply: We have replaced 'area' with 'near-surface precipitation area' in Fig. 3, Fig. 7, and Fig. 8, and throughout the manuscript.

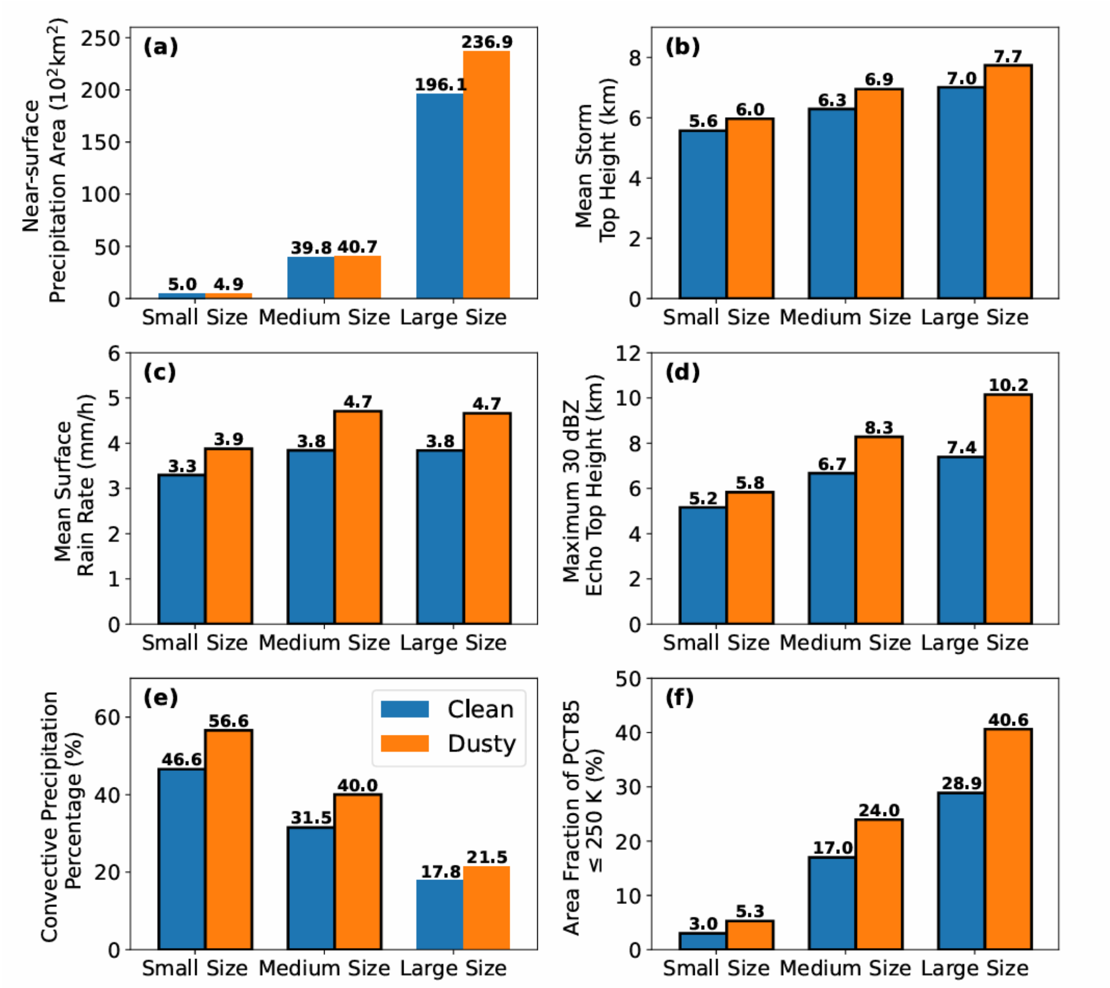

Figure 3. The averages of general characteristics of PSs of different sizes, including (a) near-surface precipitation area (km ²), (b) mean storm top height (km), (c) mean surface rain rate (mm/h), (d) maximum 30 dBZ echo top height (km), (e) convective precipitation percentage (%) and (f) area fraction of PCT85 ≤ 250 K (%) under clean and dusty conditions. The average values of these properties are labeled on the data bars. The black border around the data bar indicates that the difference between clean and dusty conditions is statistically significant at the 95% confidence level using a Student's t-test.

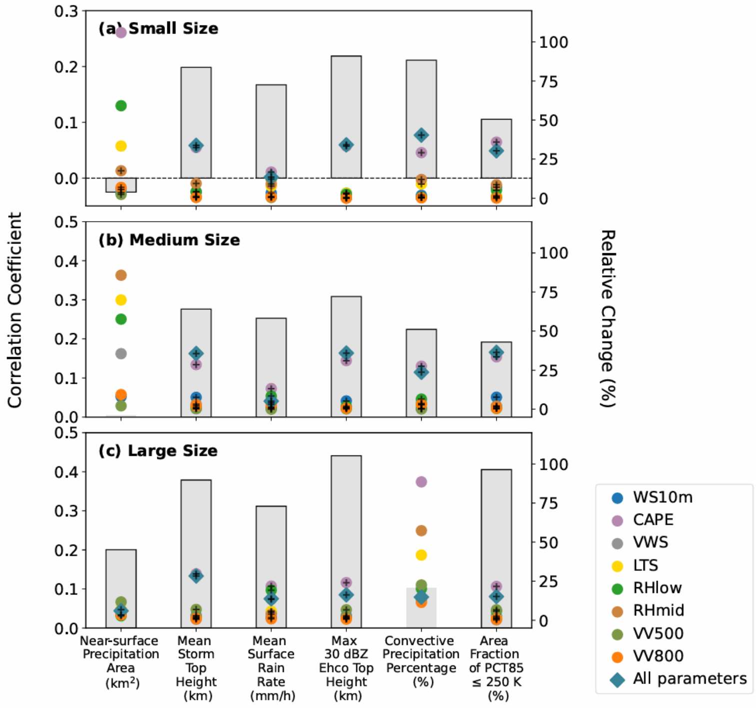

Figure 7. Total correlations between AOD and PS properties (bars, left y-axis), and the relative changes in partial correlations with the effects of 8 meteorological parameters eliminated individually (colored circular markers) and totally (diamond-shaped markers), compared with total correlations (right y-axis) for (a) small-sized, (b) medium-sized and (c) large-sized PSs. The black border around grey data bar and the black cross on the marker indicate that the total correlation and the partial correlation are statistically significant at the 95% confidence level, individually.

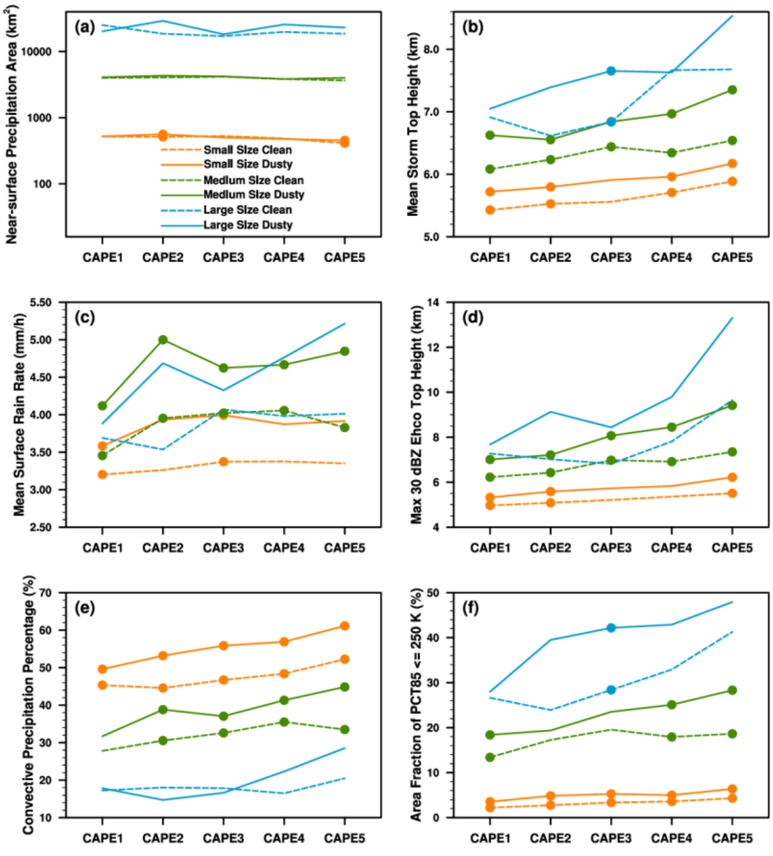

Figure 8. Variations in PS properties, including (a) near-surface precipitation area (km^2), (b) mean storm top height (km), (c) mean surface rain rate (mm/h), (d) maximum 30 dBZ echo top height (km), (e) convective precipitation percentage (%) and (f) area fraction of PCT85 ≤ 250 K (%), as a function of CAPE, for different sizes of PSs under clean and dusty conditions. The orange, green, and blue lines represent small-, medium- and large-sized PSs, respectively. The dashed and solid lines represent clean and dusty conditions, respectively. The circular marker indicates that the difference between clean and dusty conditions is statistically significant at the 95% confidence level using a Student's t-test.

Q4: The expression 'meteorology conditions' should be replaced with 'meteorological conditions' throughout the manuscript for grammatical accuracy and consistency.

Reply: Done!