Response to Reviewer Comments

Dear Reviewer and Editors:

We are sincerely grateful to the editor and reviewer for their valuable time for reviewing our manuscript. The comments are very helpful and valuable, and we have addressed the issues raised by the reviewer in the revised manuscript. Please find our point-by-point response (in blue text) to the comments (in black text) raised by the reviewer. We have revised the paper according to your comments (highlighted in blue text of the revised manuscript).

Sincerely yours,

Dr. Yuanjian Yang, representing all co-authors

#Review 1#

The manuscript presents a comprehensive analysis of how different aerosol types affect the microphysical properties and precipitation patterns of shallow precipitation systems in South China. Utilizing a comprehensive dataset that includes GPM DPR data, MERRA-2, and ERA5, the study finds that coarse aerosols generally enhance rainfall by promoting collision-coalescence processes, leading to larger raindrop sizes and higher rainfall rates. In contrast, fine aerosols tend to suppress rainfall through increased raindrop breakup and reduced coalescence efficiency. The study's findings are particularly relevant for understanding regional precipitation patterns and aerosol-cloud-precipitation interactions. Overall, this manuscript is well-organized and of clear scientific significance. I want to offer the following minor suggestions:

1. The MERRA-2 aerosol data product may have certain uncertainties in its representation of aerosol species and concentrations. It would be beneficial to include a brief introduction to the known limitations of the MERRA-2 product, as well as acknowledging the potential impacts of these uncertainties.

Response: Thank you.

(1) In Section '2.1 Data', a detailed analysis of the accuracy of the MERRA-2 AOD has been added (Lines 127-139): **'Previous studies have shown a relatively good consistency of the AOD of MERRA-2 and ground-based observations, ie AERONET, Sun sky radiometer observation network (SONET) (Ou et al., 2022; Buchard et al., 2015; Sun et al., 2019a). The correlation coefficient between MERRA-2 AOD and AERONET could reach 0.92 in summer China (Sun et al., 2019a). However, there is a slight underestimation of MERRA-2 AOD compared to in situ observations. Ou et al. (2022) revealed that the MERRA-2 AOD is underestimated by approximately 0.1 compared to a SONET station over South China. This is mainly because MERRA-2 lacks nitrate aerosols, leading to underestimations in the estimation of total AOD and fine aerosols (Sun et al., 2019b; Ou et al., 2022). The fine and coarse aerosol environment is defined by not only the AOD thresholds but also the AOD fractions to the total AOD, which can reduce uncertainties caused by underestimating AOD to some extent. '**

(2) In the section of 'Conclusion and Discussion', the uncertainties introduced by MERRA-2 are discussed (lines 674-681): **'Furthermore, MERRA-2 shows a slight underestimation of approximately 0.1 compared to in-situ observations in South China (Ou et al., 2022), probably due to the absence of nitrate aerosols in the MERRA-2 dataset. Consequently, the fine aerosol-polluted environments examined in this study may not fully capture conditions with high nitrate loading. There is an urgent need for long-term observational data on aerosol concentrations with high spatiotemporal resolution and accuracy to fully capture**

the samples of high aerosol loading and more effectively capture fine-scale processes in aerosol-cloud interactions. '

References:

Buchard, V., da Silva, A. M., Colarco, P. R., Darmenov, A., Randles, C. A., Govindaraju, R., Torres, O., Campbell, J., and Spurr, R.: Using the OMI aerosol index and absorption aerosol optical depth to evaluate the NASA MERRA Aerosol Reanalysis, Atmos. Chem. Phys., 15, 5743-5760, 10.5194/acp-15-5743-2015, 2015.

Fan, J., Rosenfeld, D., Zhang, Y., Giangrande, S. E., Li, Z., Machado, L. A. T., Martin, S. T., Yang, Y., Wang, J., Artaxo, P., Barbosa, H. M. J., Braga, R. C., Comstock, J. M., Feng, Z., Gao, W., Gomes, H. B., Mei, F., Pöhlker, C., Pöhlker, M. L., Pöschl, U., and de Souza, R. A. F.: Substantial convection and precipitation enhancements by ultrafine aerosol particles, Science, 359, 411-418, 10.1126/science.aan8461, 2018.

Ou, Y., Li, Z., Chen, C., Zhang, Y., Li, K., Shi, Z., Dong, J., Xu, H., Peng, Z., Xie, Y., and Luo, J.: Evaluation of MERRA-2 Aerosol Optical and Component Properties over China Using SONET and PARASOL/GRASP Data, Remote Sensing, 14, 821, 2022.

Pan, Z., Mao, F., Rosenfeld, D., Zhu, Y., Zang, L., Lu, X., Thornton, J. A., Holzworth, R. H., Yin, J., Efraim, A., and Gong, W.: Coarse sea spray inhibits lightning, Nat Commun, 13, 4289, 10.1038/s41467-022-31714-5, 2022.

Sun, E., Xu, X., Che, H., Tang, Z., Gui, K., An, L., Lu, C., and Shi, G.: Variation in MERRA-2 aerosol optical depth and absorption aerosol optical depth over China from 1980 to 2017, Journal of Atmospheric and Solar-Terrestrial Physics, 186, 8-19, https://doi.org/10.1016/j.jastp.2019.01.019, 2019a.

Sun, E., Che, H., Xu, X., Wang, Z., Lu, C., Gui, K., Zhao, H., Zheng, Y., Wang, Y., Wang, H., Sun, T., Liang, Y., Li, X., Sheng, Z., An, L., Zhang, X., and Shi, G.: Variation in MERRA-2 aerosol optical depth over the Yangtze River Delta from 1980 to 2016, Theoretical and Applied Climatology, 136, 363-375, 2019b.

2. The different datasets, including GPM DPR data, MERRA-2, and ERA5, have different spatial resolutions, which might not fully capture the fine-scale processes in aerosol-cloud interactions. The authors may discuss the consistency of different products to strengthen the conclusions.

   Response: Thank you. We agree that the coarser resolutions of MERRA-2 (0.5° × 0.625°, approximately 50 km) and ERA5 (0.25°, approximately 27 km) make it challenging to capture fine-scale processes in aerosol-cloud interactions directly.

To ensure consistency among the DPR, MERRA-2, and ERA5 datasets, we applied linear interpolation to adjust them to a resolution of 0.05 degrees in the manuscript. The interpolation process may introduce errors and not fully reflect the true conditions. Following your nice suggestions, we have added some discussions in the 'Discussion and Conclusion': ' **However, it is important to note that the spatial resolution of MERRA-2 and ERA5 is much coarser than that of DPR. The interpolation methods employed in the present study may introduce errors and may not fully capture the true conditions, making it challenging to accurately assess fine-scale processes in aerosol-cloud interactions …. There is an urgent need for long-term observational data on aerosol concentrations with high spatiotemporal resolution and accuracy to fully capture the samples of high aerosol loading and more effectively capture fine-scale processes in aerosol-cloud interactions.'** (Lines 670-681) in the revised manuscript.

3. The study focuses primarily on the microphysical processes within shallow precipitation systems. The authors may discuss whether it is possible to extend the approach from shallow to deep convection or mixed-phase cloud regime.

   Response: Thank you. Your suggestion is promising for fully understanding aerosol-cloud-precipitation interactions across different cloud types. The methods introduced in this study, along with the merged data set (which includes shallow and deep convection clouds), may be valuable to further analyze these interactions in deep convection scenarios. In the revised manuscript, we have added these comments to suggest future work: **'This study primarily elucidates the microphysical processes within shallow precipitation systems under varying aerosol conditions. However, the methods and data utilized have broad application potential. Future research could extend these approaches to explore the relationship between deep convection or mixed-phase clouds and aerosols. Such investigations could reveal the complex effects of aerosols on the precipitation process and further enhance our scientific understanding of the**

physical connections between aerosols and precipitation microphysics.' (Lines 664-670).

For your reference, we conducted a preliminary study on deep convective clouds (storm top height > 10 km). Unfortunately, there are only about 660 deep convective samples under coarse aerosol-polluted environments, which is a small sample size. In the future, longer-term observations are needed to accumulate more deep convection samples to further advance research in this area.

4. The authors may clarify the methodology for aerosol classification, particularly the choice of thresholds for defining polluted and clean environments. Is it possible to have some sensitive test for the threshold to ensure the representation of the conclusions?

Response: Thank you for the good suggestions.

(1) The thresholds are primarily based on the PDFs of the AOD for total aerosols, fine aerosols, and coarse aerosols, as illustrated in Figure 1b in the manuscript. For example, a clean environment is classified when the total AOD is below 0.225 (the lowest 30%). A fine (or coarse) aerosol-polluted environment must not only exceed 60% quantiles across all sampled data but also have the AOD of fine (or coarse) particles exceeding 50% of the total aerosol AOD. This approach ensures that in fine (or coarse) aerosol-polluted environments, fine (or coarse) particles are the primary influencing factor.

In the revised manuscript, we have provided a further explanation of the classification methods in the manuscript: '**There are three types of aerosol conditions discussed in the present study: clean environment, fine aerosol-polluted environment, and coarse aerosol-polluted environment.**' (lines 201-203). '**A fine (or coarse) aerosol-polluted environment must not only exceed 60% quantiles across all sampled data but also have the AOD of fine (or coarse) particles exceeding 50% of the total aerosol AOD. This approach ensures that**

in fine (or coarse) aerosol-polluted environments, fine (or coarse) particles are the primary influencing factor. ' (Lines 211-215)

(2) Sensitivity Test:

Following your nice suggestions, we have conducted a sensitivity test by changing the PDF thresholds. In the sensitivity test, a clean environment is classified when the total AOD is below 0.235 (the lowest 33% quantiles). A fine (or coarse) aerosol-polluted environment must not only fall within the top 67% quantiles across all sampled data, but also have the AOD of fine (or coarse) particles exceeding 50% of the total aerosol AOD. The new thresholds and sample sizes are shown in Table R1.

Similarly, the box plots of RR, N_w, D_m, and Z_e near the surface at 2.5 km altitude, as well as LWP and STH for shallow precipitation under different aerosol conditions in South China are shown in Figure R1. DSDs at 2.5 km altitude for shallow precipitation clouds over southern China under three aerosol conditions are illustrated in Figure R2. Sensitivity tests show conclusions similar to those of the previous thresholds (results in Figure 2 and Figure 3 in the manuscript). For example, compared to clean environments, RR, N_w, D_m, LWP, and Z_e decrease slightly in fine aerosol-polluted environments but increase in coarse aerosol-polluted environments.

Sensitivity tests indicate that different thresholds do not significantly affect the conclusions of our paper. Therefore, the previously set threshold design to classify different environmental conditions is reasonable. In Data and Methods (Lines 219-222): **'A sensitivity test was conducted with different thresholds to ensure the robustness of the present study. The results indicate that varying the thresholds does not significantly affect the conclusions of the work.'** Thank you again.

Table R1 Sensitivity test: Definitions of clean conditions, fine and coarse aerosol-polluted environments in southern China during the summers of 2014-2021.

Environment	Definition	Samples
Clean	Total AOD < 0.235	10090
Polluted_Fine	Fine AOD > 0.355 & Fine AOD ratio>50%	8330
Polluted_Coarse	Coarse AOD > 0.0495 & Coarse AOD ratio>50%	2557

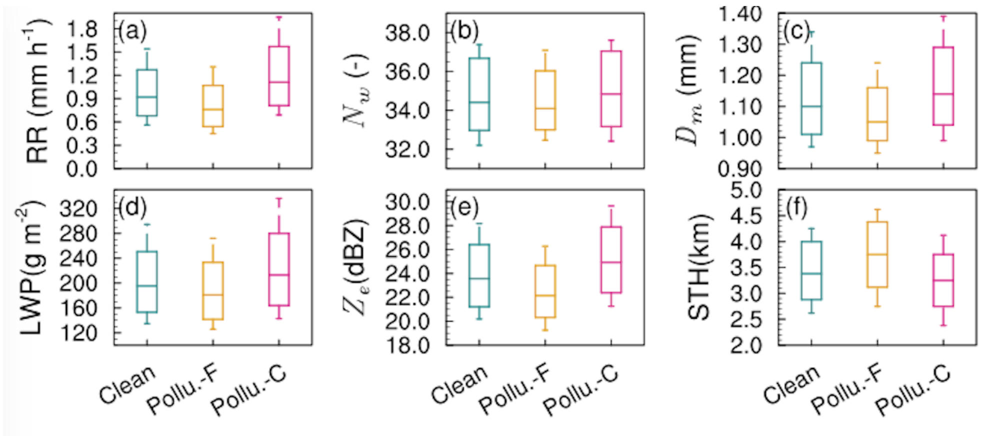

Figure R1 Similar to Figure 2 in the manuscript, but for new AOD thresholds presented in Table R1.

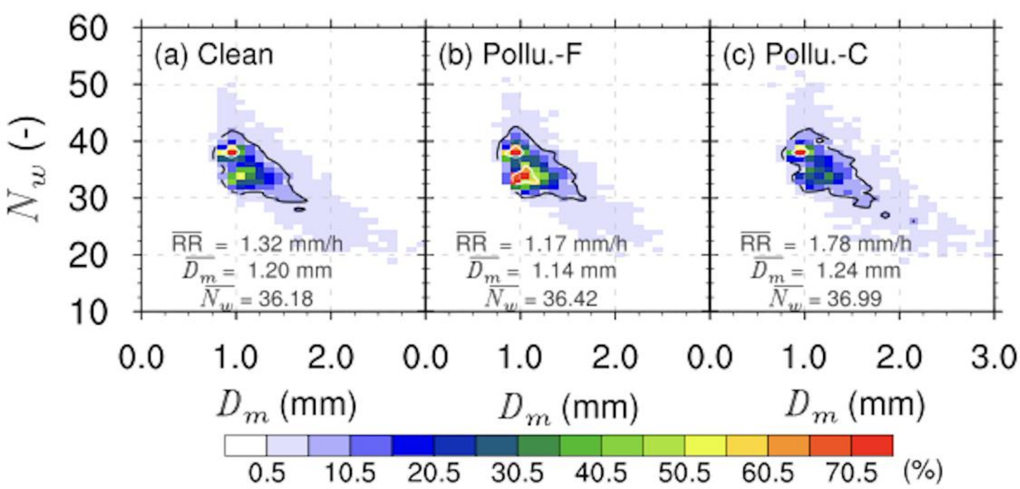

Figure R2 Similar to Figure 3 in the manuscript, but for new AOD thresholds presented in Table R1.

5. In addition to the CAPE, the authors may acknowledge the contribution of other meteorological factors, as well as their potential role in affecting aerosol-precipitation relationships.

Response: Thank you. Precipitation is a complex process influenced by multiple meteorological factors, such as instability, moisture, temperature, and wind vectors. In the manuscript, only CAPE and relative humidity are used due to the limitations of the length of the article. We also analyzed the near-surface RR, N_w, D_m, LWP, Z_e, and STH under different aerosol and surface air temperature (TM) conditions, as illustrated in Figure R3. Based on the terciles of the TM values during precipitation events in southern China, the samples are grouped into three groups: TM1 < 299 K, TM2: 299~301 K, and TM3: > 301K. The result shows that the suppression of RR in fine aerosol-polluted environments and the invigoration of RR in coarse aerosol-polluted environments are independent of the temperature conditions. Similarly to the conclusion for various CAPE and RH conditions at 850hPa (Figure 6 and Figure 7), the amplitudes of invigoration and suppression are related to the conditions of surface air temperature. Invigoration and suppression effects are more significant under low surface air temperature conditions (TM1). These comments have been added in lines (637-642): **'The effects of fine and coarse aerosols on the suppression and enhancement of RR are independent of CAPE and humidity, consistent with the findings by Liu et al. (2022). However, our results show that the extent of suppression or enhancement varies with CAPE and humidity. Additionally, the analysis of aerosol-precipitation interactions under different surface air temperatures yields results similar to those observed for CAPE and RH at 850 hPa (figures not shown).'**

Furthermore, following your nice suggestions, we have stated more about the role of meteorological factors in aerosol-precipitation relationships in the “Conclusion and Discussion” (Lines 659-663): **'It is important to note that precipitation is a complex**

process influenced by multiple meteorological factors, including instability, moisture, and temperature. Other factors such as wind vectors and pressure may also affect the impact of aerosols on precipitation, which is worthy of further study.'

Reference:

Liu, F., Mao, F., Rosenfeld, D., Pan, Z., Zang, L., Zhu, Y., Yin, J., and Gong, W.: Opposing comparable large effects of fine aerosols and coarse sea spray on marine warm clouds, Communications Earth & Environment, 3, 232, 10.1038/s43247-022-00562-y, 2022.

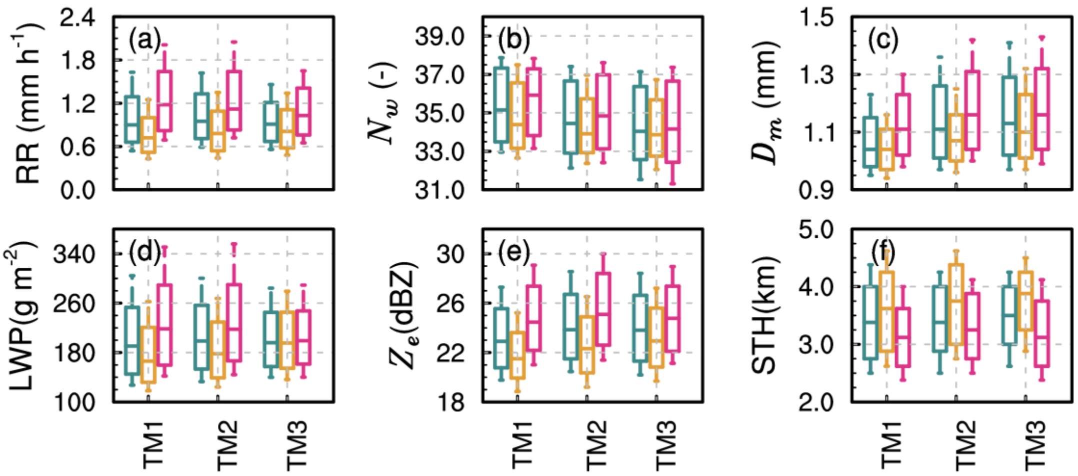

Figure R3 Box plot of the near-surface rain rate (a), N_w (b), D_m (c), LWP (d), Z_e (e), and STH (f) under different aerosol and surface air temperature conditions for shallow precipitation over southern China during the summers of 2014-2021.