Responses to Reviewers' Comments

We are sincerely grateful to the editor and reviewers 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**).

Reviewer #2:

This manuscript focuses on aerosol-driven precipitation modification over four major megacity clusters in China (BTH, YRD, YRM, PRD), systematically analyzing the spatiotemporal heterogeneity of precipitation microphysics and vertical structures using integrated datasets such as GPM DPR, MERRA-2, and ERA5. The research topic is highly relevant to regional hydrological cycles and climate model refinement, as aerosol-precipitation interactions in densely populated, polluted urban agglomerations remain a key uncertaintyin atmospheric science. Overall, this manuscript is well organized: it investigates precipitation structural parameters, microphysical processes (e.g., coalescence, break-up), and the regulatory role of meteorological factors (RH, CAPE), providing a comprehensive framework for cross-regional comparisons. The conclusions regarding "regional precipitation disparities exceeding seasonal variations" and "aerosols mitigating regional differences in spring/summer" offer valuable insights for improving urban climate models. However, the manuscript has notable limitations that need to beaddressed, including insufficient quantification of aerosol type contributions, lack of analysis on joint meteorological factor interactions, and minor issues in details (e.g., figures). With appropriate modifications to strengthen mechanistic analysis and technical rigor, the manuscript will likely meet the publication standards.

Response:

Thank you for your thorough review and constructive feedback on our manuscript titled *"Aerosol-Driven Precipitation Modification: Spatiotemporal Heterogeneity in Precipitation Microphysics and Vertical Profiles over China's Megacity Clusters"*. We appreciate the time and effort you have invested in understanding our work and for providing us with clear directions for improvement. We confirm that all your earlier concerns were addressed in detail in our initial point-by-point response letter (submitted with the revised manuscript) and implemented in both the tracked-changes and clean versions of the manuscript. Below are our point-by-point responses:

Major comments:

[1]. Quantitative contribution of different types of aerosols to precipitation lacks clarity: The manuscript claims that BTH's convective precipitation is dominated by dust aerosols (semi-direct

effect), YRD/PRD by hygroscopic sea salt, and YRM by fine particles. However, it fails to provide quantitative data on the composition of aerosol types (DU, SS, SO_4, BC, OC from MERRA-2) across seasons and regions. For example:No temporal-spatial maps of aerosol type proportions (e.g., the proportion of dust column mass concentration in spring over BTH) are provided to support the "dust-dominated semi-direct effect" conclusion.

Response:

We thank you for this critical comment and fully agree that a more quantitative analysis is essential for attributing precipitation effects to specific aerosol species.

In sincere response to your valuable suggestion, we have significantly enhanced our manuscript to provide a more quantitative foundation. Specifically, we have supplemented our analysis with seasonal/regional distribution data of MERRA-2 aerosol type proportions/ and conducted correlation analyses between specific individual aerosol types and key precipitation parameters. These additions directly address your primary concerns and substantially strengthen the mechanistic interpretation of our results. **A detailed point-by-point explanation of how we have implemented these specific analyses is provided in our response to Comment #2 (Major) below, where we elaborate on the new tables and figures incorporated into the revised manuscript.**

We are profoundly grateful for the constructive comment again, which have been instrumental in improving the rigor and clarity of our work.

[2]. I strongly recommend the authors supplement (1) seasonal/regional distribution maps of MERRA-2 aerosol type proportions; (2) correlation analyses between individual aerosol types (e.g., DU in BTH, SS in PRD) and precipitation parameters (e.g., RR, Dm); (3) absorption aerosol optical depth (AAOD) data to distinguish the role of absorbing (BC, DU) vs. scattering (SO_4, SS) aerosols in microphysical processes. This will clarify the mechanism of aerosol type-specific impacts.

Response:

We sincerely thank you for these specific and constructive suggestions to quantitatively clarify the mechanisms of aerosol type-specific impacts. We fully agree that providing (1) seasonal/regional distribution maps of aerosol type proportions, (2) correlation analyses between individual aerosol types and precipitation parameters, and (3) utilizing AAOD and SAOD data to distinguish absorbing vs. scattering aerosols, would significantly strengthen our findings. In response, we have undertaken a comprehensive enhancement of our analysis:

(1) Seasonal/Regional Distribution of Aerosol Type Proportions and AOD Concentrations:

While our original analysis and SI did include some foundational data on aerosol type contributions (Fig S.2), we acknowledge that its presentation was insufficient to robustly support our mechanistic interpretations. Therefore, following your suggestion, we have now created and included detailed seasonal spatial distribution maps of both the average AOD and the proportional contributions of the seven MERRA-2 aerosol types (BC, DU, OC, SS, SO_4, absoring, and scattering) for each urban agglomeration (**now included as Figs. S3-S8 in the revised SI**).

The comparative analysis of both AOD concentration and proportional contribution maps reveals that the BTH region consistently exhibits the highest DUA burden among the four clusters (Figs. S3(b)-S8(b)), especially during spring. This regional specificity provides robust evidence for the proposed prominence of DUA and their associated semi-direct effect in shaping precipitation patterns in the BTH. Similarly, the figures show that SSA register the most pronounced signals in the PRD compared to the other regions (Figs. S3(d)-S8(d)), especially during spring and summer, firmly establishing the primary role in influencing local microphysics.

The corresponding figure citations and discussions for these findings have been incorporated into the main text of the revised manuscript. For instance:

"The spatial and seasonal distributions of aerosol composition over China's megacity clusters, are detailed in Figs. S3-S8. Overall, the BTH region is characterized by a high burden of DUA (Figs. S3-S8b), particularly during spring. In contrast, the PRD region shows a pronounced signal of SSA, especially in spring and summer (Figs. S3-S8d). Figs. S3-S8 (f-g) show that loadings of both absorbing and scattering aerosols are markedly elevated in the BTH region, in contrast to the discernibly lower concentrations observed in the PRD. These characteristic distributions provide a fundamental basis for interpreting the region-specific aerosol-precipitation mechanisms discussed in subsequent sections"(Section 2.3, Lines 198-206)

"In the BTH region, which is characterized by a high concentration of DUA(Figs. S2-8). Sun and Zhao (2021) attributed similar phenomena to the radiative effect of aerosols enhancing atmospheric instability and triggering earlier precipitation." (Section 3.3, Lines 406-409)

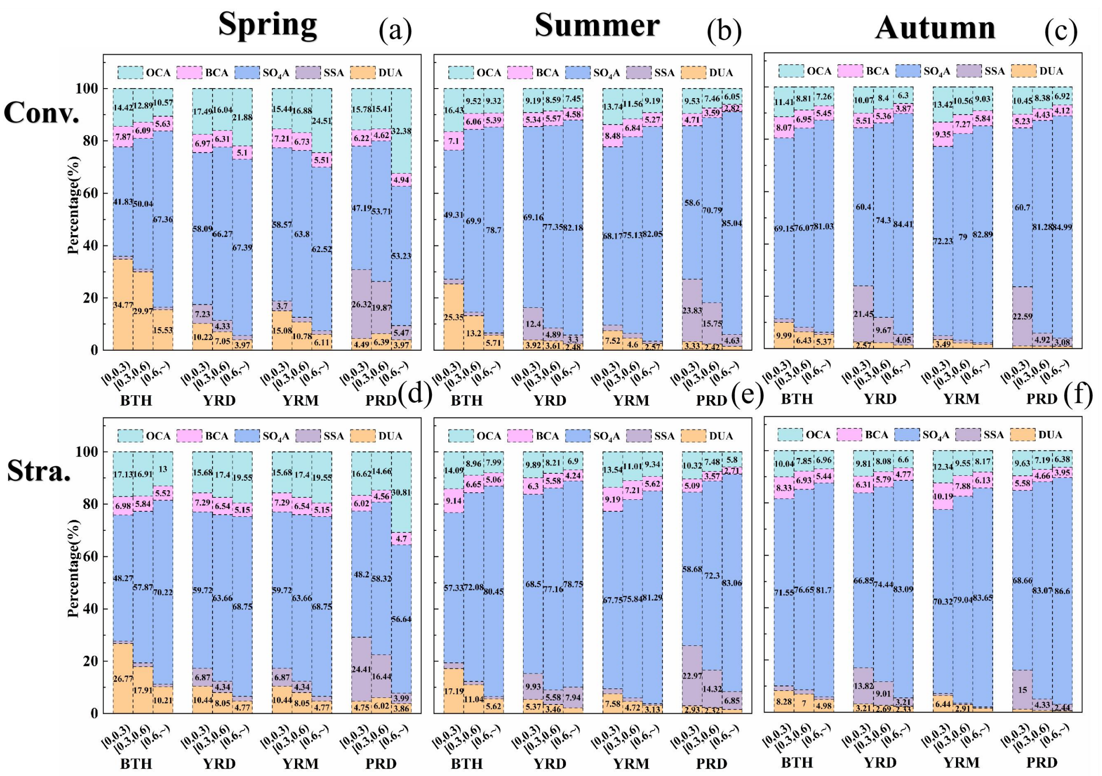

Fig. S2. Proportion of AOD in convective precipitation and stratiform precipitation under different

AOD loads in spring, summer, and autumn in the four regions.

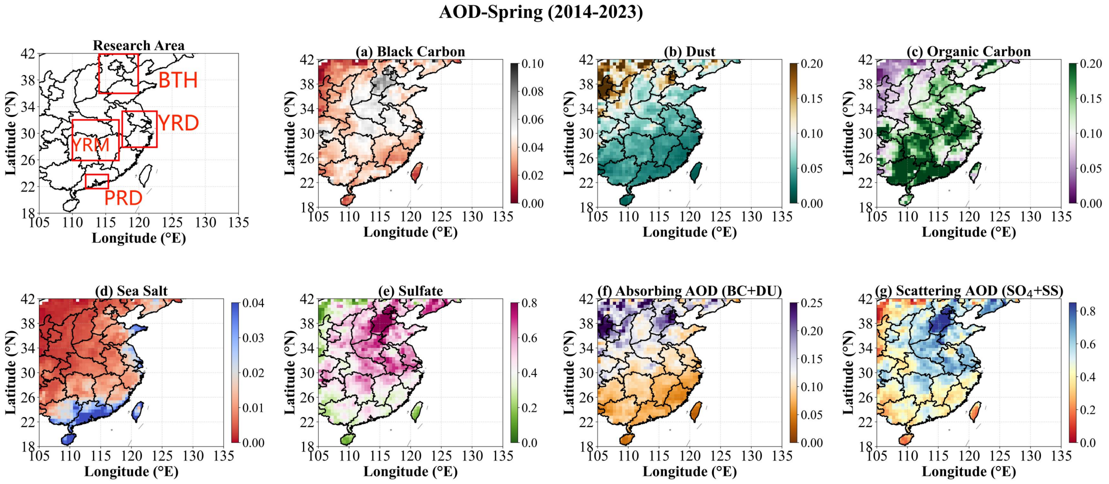

Fig. S3. Spatial distribution map of seven types (BC, DU, OC, SS, SO_4, absoring, and scattering) of average aerosols in spring from 2014 to 2023 over China's Megacity Clusters (BTH, YRD, YRM, and PRD).

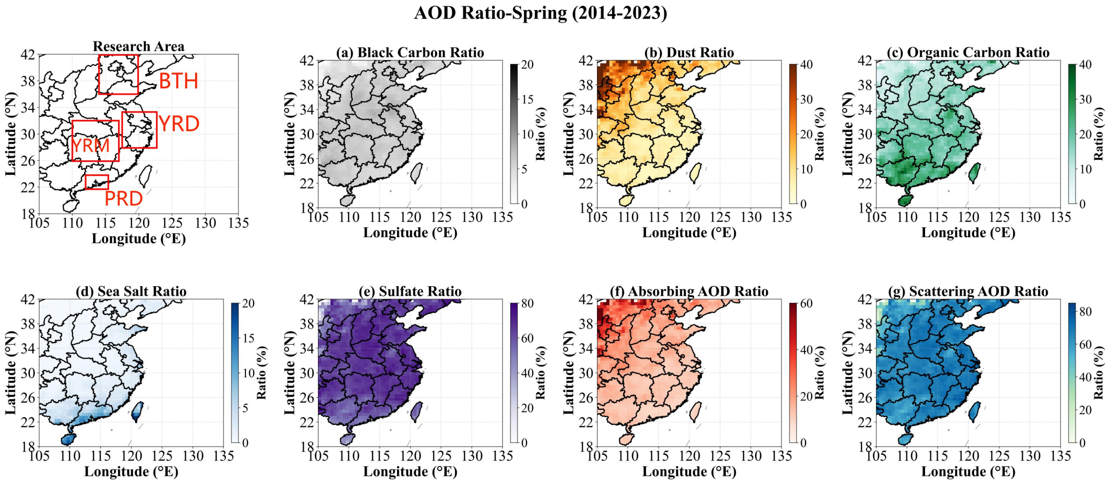

Fig. S4. Spatial distribution map of seven types (BC, DU, OC, SS, SO_4, absoring, and scattering) of aerosol type proportions in spring from 2014 to 2023 over China's Megacity Clusters (BTH, YRD, YRM, and PRD).

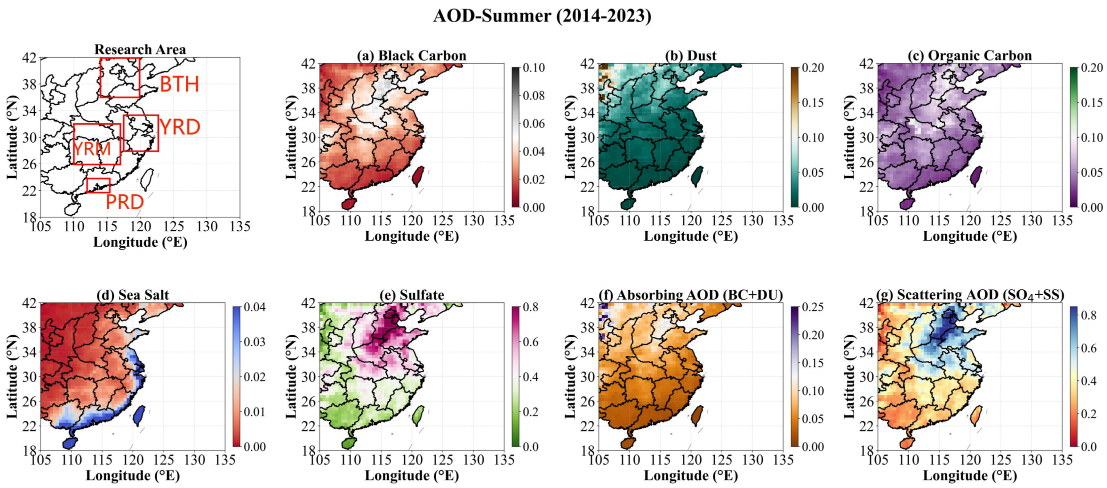

Fig. S5. Spatial distribution map of seven types (BC, DU, OC, SS, SO_4, absoring, and scattering) of average aerosols in summer from 2014 to 2023 over China's Megacity Clusters (BTH, YRD, YRM, and PRD).

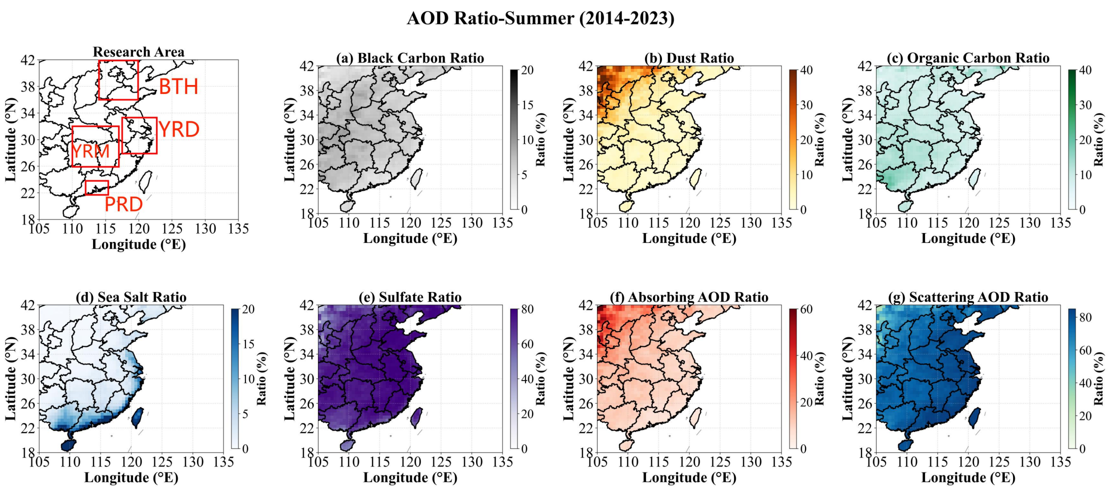

Fig. S6. Spatial distribution map of seven types (BC, DU, OC, SS, SO_4, absoring, and scattering) of aerosol type proportions in summer from 2014 to 2023 over China's Megacity Clusters (BTH, YRD, YRM, and PRD).

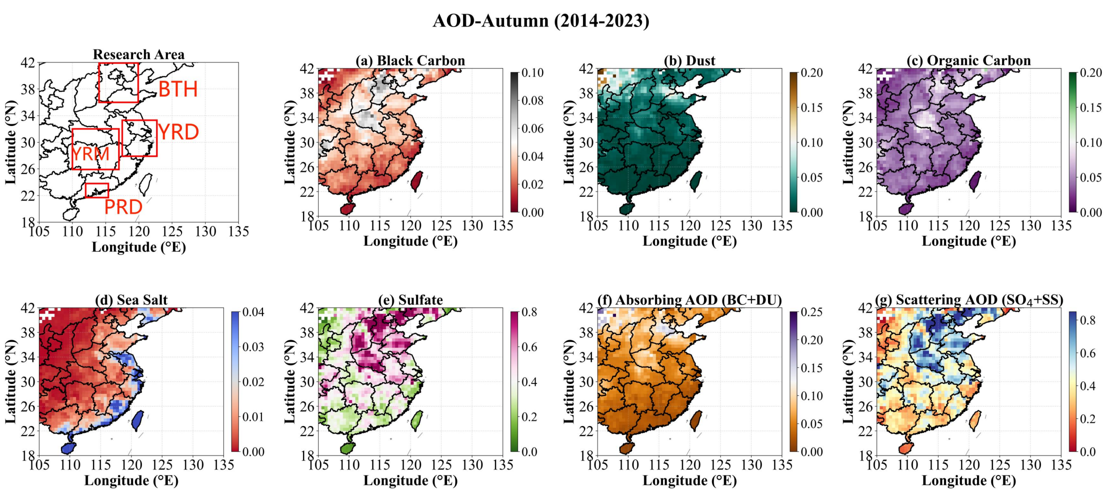

Fig. S7. Spatial distribution map of seven types (BC, DU, OC, SS, SO_4, absoring, and scattering) of average aerosols in autumn from 2014 to 2023 over China's Megacity Clusters (BTH, YRD, YRM, and PRD).

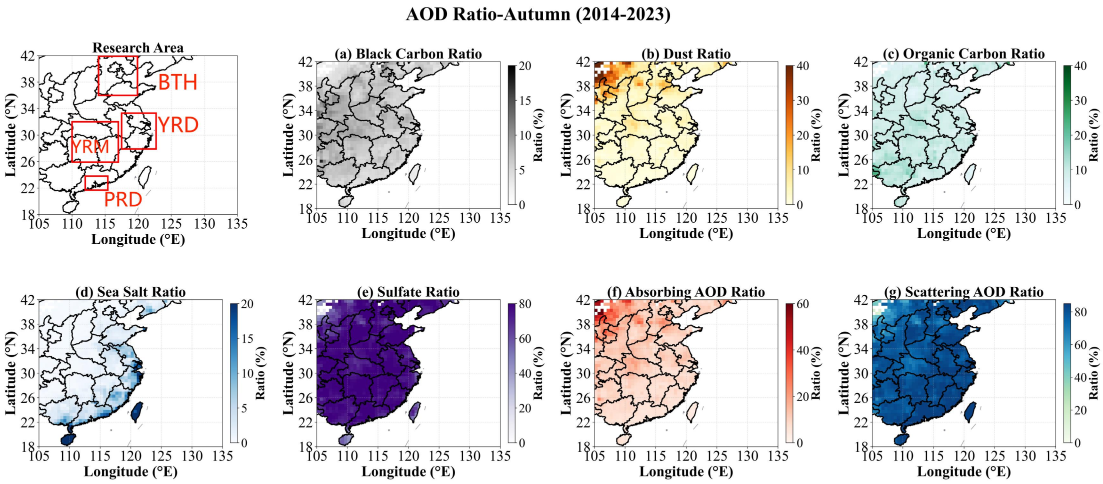

Fig. S8. Spatial distribution map of seven types (BC, DU, OC, SS, SO_4, absoring, and scattering) of aerosol type proportions in autumn from 2014 to 2023 over China's Megacity Clusters (BTH, YRD, YRM, and PRD).

(2) Correlation Analyses between Individual Aerosol Types and Precipitation Parameters:

We have conducted and now present in the revised manuscript (Section 3.3) the results of Spearman correlation analyses between the concentrations of key aerosol types (DU in BTH, SS in PRD) and critical precipitation parameters (RR, D_m, and N_w). Specifically, for RR, N_w and D_m, we adopted the mean values within the 1–3 km altitude range as the core indicators.

The newly added correlation analyses figure (Fig. S12) further elucidate the distinct seasonal and precipitation type dependent roles of key aerosol species. We have added the sentence to specify that: **"Despite a complex influence that varies with season and precipitation type, DUA in the BTH region exhibit a consistent negative correlation with N_w (Fig. S12b-e). This negative correlation could be attributed to the semi-direct effect of DUA, whereby the absorption of solar radiation heats the atmosphere, thus promoting cloud droplet evaporation and suppressing droplet concentrations. The negative relationship with RR and D_m is particularly evident in stratiform precipitation under low-to-medium aerosol loadings (Fig. S12d). For convective precipitation, the influence of DUA is seasonally modulated, showing a negative correlation in summer but a positive correlation in spring and autumn. Meanwhile, in the PRD region (Fig. S12g-l), SSA during spring and summer are consistently positively correlated with precipitation parameters. These statistically significant relationships further corroborate the proposed type-specific mechanisms." (Section 3.3. Lines 391-402)**

For completeness, we conducted an extensive analysis encompassing all five individual aerosol species **(below the Fig. S12)**. To maintain clarity and conciseness in the main narrative, we have presented the analysis for the most regionally representative types as a paradigm.

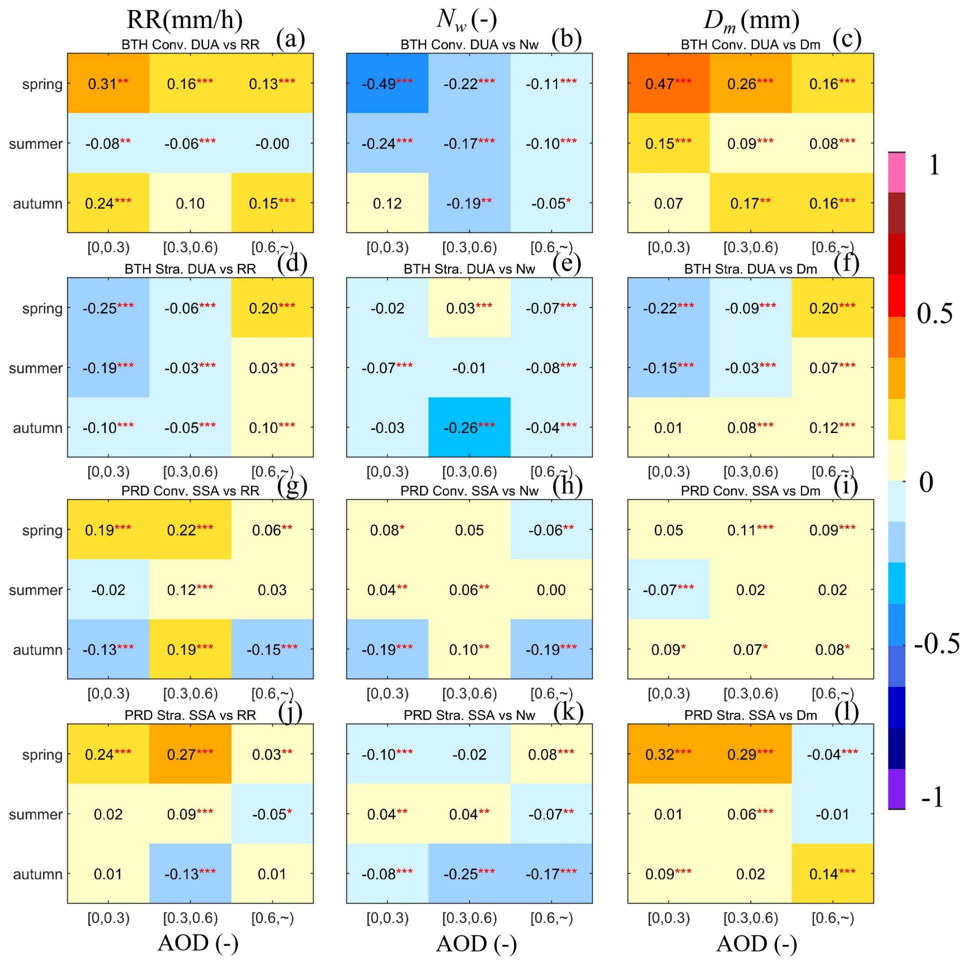

Fig. S12. Spearman correlation coefficients between key aerosol types (DUA for the BTH and SSA for the PRD) and precipitation parameters (RR, N_w and D_m) across regions and seasons under the three AOD regimes. Color gradients (from yellow to blue) encode the correlation strength and direction, and asterisks denote statistical significance (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

Furthermore, in direct response to a related point raised by Reviewer Comment#1: ***<u>"While the authors emphasize the importance of the semi-direct effect of dust in the BTH region, dust is also a major source of ice nuclei, which could substantially influence cold-toppedprecipitation formation."</u>***, we have conducted an additional analysis to specifically investigate the role of DU as ice nuclei (IN) in the BTH region. This involved examining the correlations between DUA and both the Ice Water Path (IWP) and Storm Top Height (STH).

The results reveal a notable dual role of dust aerosols: **"Given the dominant roles of DUA in BTH and SSA in PRD (Figs. S2-S8), this study further investigated how these key aerosol types distinctly modulate precipitation. Correlation analyses reveal that DUA is significantly positively correlated with both IWP and STH in the convective precipitation (Fig. S10), indicating an invigoration of ice-phase processes. This suggests that DUA, acting as efficient IN, promote the glaciation and vertical development of convective clouds, consistent with the invigoration effect (Rosenfeld., 2008). In contrast, the impact of DUA on stratiform precipitation is substantially weaker and more variable. This promotional mechanism, facilitated by ice-nucleating ability of DUA, stands in contrast to precipitation-suppressing semi-direct effect, highlighting the complex and multi-faceted nature of DUA impacts on different precipitation types." (Section 3.1. Lines 306-316)**

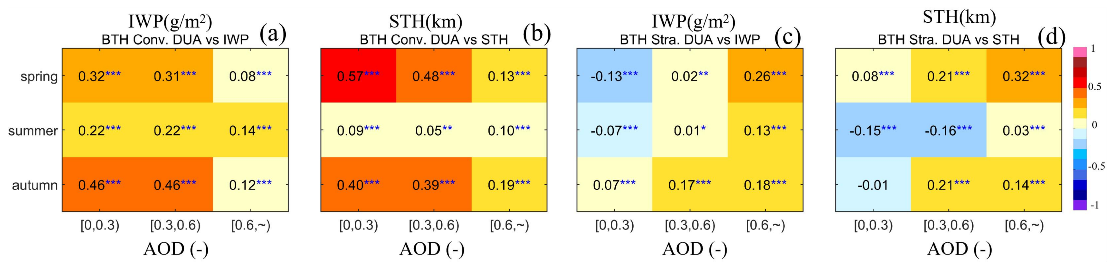

Fig. S10. Spearman correlation coefficients between DUA and precipitation parameters (STH, and IWP) in BTH for convective and stratiform precipitation under three AOD regimes and seasons.

(3) Consideration of Absorbing Aerosols and Scattering Aerosols:

We deeply appreciate the insightful recommendation to use Absorption Aerosol Optical Depth (AAOD) and Scattering Aerosol Optical Depth (SAOD). Firstly, we categorized the aerosols as absorbing (BC, DU) and scattering (SO_4, SS) based on their fundamental radiative properties (Section 2.3). Secondly, detailed seasonal spatial distribution maps of both the average AOD and the proportional contributions are now visualized in the new supplement information(Figs. S3-S8). **"Figs. S3-S8 (f-g) show that loadings of both absorbing and scattering aerosols are markedly elevated in the BTH region, in contrast to the discernibly lower concentrations observed in the PRD." (Section 2.3, Lines 202-204)** Finally, we explicitly attribute the observed precipitation modifications to the fundamental processes associated with specific aerosol types and conditions. The revised manuscript highlights the following physical mechanisms through which aerosols modify precipitation:

- The semi-direct effect for strongly absorbing aerosols (e.g., dust in BTH).
- The Twomey and cloud lifetime effects for predominantly scattering aerosols (e.g., sulfate).
- The convective invigoration effect, particularly for dust aerosols acting as efficient IN, which enhances ice-phase processes and deepens convective clouds.
- The hygroscopic growth and coalescence-enhancement effect associated with coarse-mode aerosols (e.g., sea salt in PRD).

In summary, your comments have been instrumental in driving a significant upgrade to our manuscript. The new figures and correlation analyses provide the clear, quantitative evidence needed to solidify our conclusions regarding aerosol type-specific impacts.

Rosenfeld, D., Lohmann, U., Raga, G. B., O'Dowd, C. D., Kulmala, M., Fuzzi, S., Reissell, A., and Andreae, M. O.: Flood or Drought: How Do Aerosols Affect Precipitation?, Science, 321, 1309–1313, https://doi.org/10.1126/science.1160606, 2008.

Sun, Y. and Zhao, C.: Distinct impacts on precipitation by aerosol radiative effect over three different megacity regions of eastern China, Atmos. Chem. Phys., 21, 16555–16574, https://doi.org/10.5194/acp-21-16555-2021, 2021.

[3].Ambiguity in precipitation type classification: The manuscript excludes "shallow convection" from convective precipitation based on 2ADPR criteria but does not specify the 2ADPR threshold for shallow convection and report the proportion of shallow convection in total precipitation across regions/seasons. This will affect sample representativeness and undermine the robustness of the findings.

Response:

We thank you for the insightful comment regarding the precipitation type classification. We agree that clarity on this point is crucial for the robustness of our findings. We provide a detailed clarification of our methodology, which is firmly based on the GPM DPR (2ADPR V07) Algorithm Theoretical Basis Document (ATBD).

(1) Definition of Precipitation Based on GPM DPR Criteria:

In our study, precipitation types were classified using GPM DPR products (2ADPR V07). Shallow convection was identified as a subset of the convective precipitation using the following criterion:

$$index\_Shallow = (heightZeroAll - STHAll > 1)\ \&\ (typeAll == 2)$$

Similarly, the classification of the stratiform and convective precipitation in our study were as follows:

$$inde\_Stra = (STHAll > heightZeroAll)\ \&\ (typeAll == 1)$$

$$index\_Conv = (STHAll > heightZeroAll)\ \&\ (typeAll == 2)$$

Here, $heightZeroAll - STHAll > 1$ indicates that the storm top is more than 1 km below the freezing level,which threshold is consistent with the ATBD (See figure below). The typeAll is the precipitation type flag from 2ADPR, where 1 denotes stratiform and 2 denotes convective. The condition $STHAll > heightZeroAll$ was applied to both types to ensure we focused on sufficiently developed precipitating systems.

(c) **Shallow rain and small cell-size rain**

Detection of shallow rain is also made independently of the above mentioned methods of rain type classification. When the following condition is satisfied, it is judged as shallow rain, which will be marked by an internal flag:

$$\texttt{heightStormTop} < \texttt{heightZeroDeg} - \text{margin}$$

where margin is currently 1000 m.

Shallow rain is separated out into shallow isolated and shallow non-isolated by examining the horizontal extent of shallow rain. In the rain type unification, both shallow isolated and shallow non-isolated are classified as convective. (It should be noted that in the TRMM PR rain type classification algorithm 2A23 V7, all the shallow isolated is convective, but shallow non-isolated can be either stratiform or convective.)

Detection of rain having small cell size is also made independently. The rain having small cell size is classified as convective in the unification of rain type.

Definition and Classification of Shallow Rain in the GPM DPR Algorithm. (https://gpm.nasa.gov/resources/documents/gpmdpr-level-2-algorithm-theoretical-basis-document-atbd)

(2) Proportion of Shallow Convection in Total Precipitation:

As suggested, we have calculated the seasonal and regional proportions of shallow convection relative to total convective precipitation. The results are summarized below (as a percentage of total precipitation events):

Table. S1 Shallow convection statistics: event counts and percentage contributions to convective and total precipitation (analyzed in this study) across regions and seasons

Region	Season	Shallow Counts	Shallow/Conv. (%)	Shallow/Total (%)
BTH	Spring	570	13.60	1.01
	Summer	7860	30.27	5.83

	Autumn	1904	44.95	5.23
	Spring	9575	57.32	8.62
YRD	Summer	23268	53.74	13.92
	Autumn	4860	68.78	14.59
	Spring	23945	41.69	6.78
YRM	Summer	63536	51.58	13.16
	Autumn	18959	69.89	13.23
	Spring	2765	37.08	9.47
PRD	Summer	6961	46.29	20.15
	Autumn	2349	49.02	17.19

These proportions reveal significant regional and seasonal variations in the shallow convection precipitation. While shallow convection represents a relatively small fraction in some regions and seasons (e.g., 13.60% in BTH Spring), it constitutes a substantial portion of total convective precipitation in others (e.g., 69.89% in YRM Autumn). This heterogeneity underscores the importance of our methodological approach in excluding shallow convection to ensure physical consistency across our analysis. Importantly, the convective sample sizes across all regions and seasons exceed 2,000 events, providing robust statistical power for our analyses.

We have revised the manuscript to include a clear specification of the classification criteria for all precipitation types, including the shallow convection threshold, in the Data and Methods section. **"This study categorized precipitation into stratiform and convective types based on the 2ADPR classification criteria, excluding shallow convection events (defined by the 0°C isotherm attitude below STH more than 1 km) from convective precipitation (Liu and Zipser, 2015). It is noteworthy that shallow convection precipitation constitutes a non-negligible proportion of the convective events in our dataset (Table S1). This prevalence underscores the necessity of our methodological decision to exclude these events. " (Section 2.5. Lines 220-226)**

We believe this clarification fully addresses your concern and underscores the methodological rigor of our study.

Liu, C. and Zipser, E. J.: The global distribution of largest, deepest, and most intense precipitation systems, Geophysical Research Letters, 42, 3591–3595, https://doi.org/10.1002/2015gl063776, 2015.

[4].It is well acknowledged that favorable meteorological conditions are indispensable for the formation and evolution of precipitation, thereby inevitably making it elusive to disentangle the aerosol effect on precipitation. This manuscript analyzes RH (thermodynamic) and CAPE (dynamic) separately but ignores their synergistic or antagonistic effects on aerosol-precipitation interactions. The readers are more willing to see does aerosol-induced coalescence strengthen more than in single-factor conditions under the high RH (sufficient moisture) + high CAPE (strong updrafts) conditions. The authors may conduct a two-factor crossed analysis (e.g., 3 RH levels × 3 CAPE levels) to quantify aerosol impacts on precipitation parameters under different

combined meteorological scenarios. This will reveal the regulatory mechanism of thermodynamic-dynamic synergy, improving the comprehensiveness of the conclusion.

Response:

We sincerely thank you for this insightful comment regarding the potential synergistic or antagonistic effects of meteorological factors on aerosol-precipitation interactions. We fully agree that a two-factor crossed analysis could provide a more nuanced understanding of how thermodynamic and dynamic conditions jointly modulate aerosol impacts.

However, conducting a comprehensive two-factor crossed analysis (3 RH × 3 CAPE) within the existing framework (which already encompasses four regions, three seasons, two precipitation types and three AOD levels), would lead to a substantial fragmentation of the sample size into numerous sub-groups. Many of these sub-groups, especially those representing specific combinations of high RH and high CAPE under certain AOD regimes in particular regions and seasons, would contain an insufficient number of samples. This would severely compromise the statistical significance and robustness of the results, potentially introducing considerable uncertainty rather than providing clear mechanistic insights. The bubble chart below depicts the sample distribution across these RH-CAPE combinations (The classification of RH and CAPE values in the figure is consistent with the three conditions used in the original manuscript, though without further subdivision by precipitation type or AOD level):

"As shown in Fig. 6 a–d, an increase in RH generally enhances the near-surface rain rate (nsRR), and the combination of high RH × high CAPE (indicated by ☆) tends to produce heavier precipitation. However, as the CAPE values (Fig. 6 e–h) continue to rise beyond 4000 J/kg, the nsRR shows a decreasing trend. Moreover, extremely high CAPE values are most often observed alongside moderate to low RH (indicated by ○ and △) conditions." (Section 5.1. Lines 527-532)

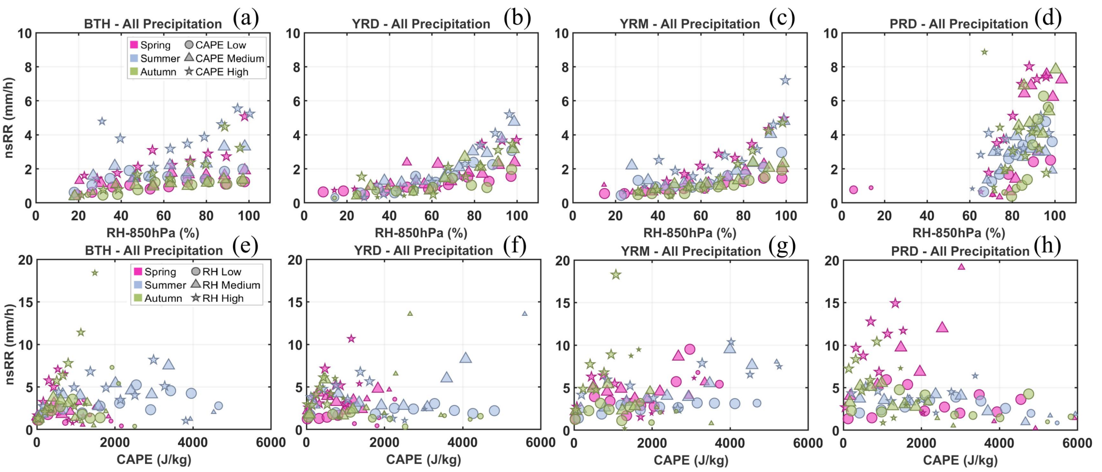

Fig. 6. nsRR as a function of RH-850 hPa (CAPE), stratified by season (color) and CAPE (RH) level (symbol), for all precipitation types (convective and stratiform) in the four regions. The symbol size is proportional to the sample size ([0,20), [20,45), [45,90), [90,~)).

In our current study, we have systematically analyzed the individual influences of RH and CAPE across different regions, seasons, and aerosol loadings (in Section 5). This approach has already yielded significant insights. For instance, we found that elevated RH generally promotes coalescence and enhances precipitation parameters, whereas increased CAPE can enhance cloud development but also intensify break-up processes, suppressing precipitation under certain conditions.

Therefore, while we acknowledge the limitation of not performing the specific synergistic analysis suggested, we believe that our detailed separate analyses of RH and CAPE, combined with the investigation of microphysical processes, have effectively captured the primary individual and indirect roles of these key meteorological factors. We have explicitly acknowledged this aspect as a scope for future work in the revised Discussion section: **"Additionally, a more complete understanding of aerosol-precipitation interactions must account for the complex synergies among environmental factors, leveraging advanced statistical or modeling methods in a multi-factor analytical framework." (Section 7. Lines 793-796)**

We are grateful for this valuable suggestion again, which provides a clear and important direction for our subsequent researches.

[5].In Results and discussion part: I recommend adding one or two paragraphs to focus on key findings and providing a comparative discussion on how these findings align with or diverge from previous studies on aerosol-precipitation interaction. This will help more effectively highlight the study's unique contributions to the community.

Response:

We sincerely thank you for this insightful suggestion. Therefore, we have now added dedicated paragraph in the Results and Discussion section to synthesize the key findings and explicitly compare them with previous studies:

“Building on the findings of Peng et al. (2025), which investigated the effects of fine and coarse aerosols on summer precipitation structure and microphysics in the YRD region, the present study expands the scope of analysis to examine aerosol impacts on precipitation vertical profiles and microphysical processes across multiple regions and seasons in China. This expanded scope, combined with a unified analytical methodology, enables a systematic cross-regional and cross-seasonal comparison that mitigates inconsistencies often associated with disparate data sources or methods, yielding the following key findings: (1)Enhanced aerosol loading reduces regional precipitation disparities, most pronounced in spring and summer. (2)Precipitation exhibits stronger regional than seasonal variability. (3)The BTH precipitation is dominated by dust aerosols, whereas the YRD and PRD are influenced by sea salt aerosols. These conclusions are primarily derived from analyses of satellite-based datasets, which provide extensive spatial coverage, high spatiotemporal resolution, and continuous temporal monitoring.” (Section 7. Lines 743-756)

“The results provide further evidence for several established mechanisms: The dominant role of dust aerosols in the BTH region aligns with existing research (Xi et al.,

2024; Xiao et al.,2025), manifesting as impacts on precipitation through ARI (Sun and Zhao, 2022) and semi-direct effects, and also serving as effective IN to promote convective cloud development (Xi et al.,2025). Furthermore, the precipitation-enhancing effect of sea salt aerosols in the PRD region is consistent with prior observations (Guo et al., 2022; Chen et al.,2025). (Section 7. Lines 757-763)

However, as noted by Stier et al. (2024) and Zhao et al. (2025), aerosol impacts on precipitation remain highly complex, and their net effects are still subject to considerable uncertainty across different scales. Multiple factors are known to modulate precipitation processes, such as vertical wind shear (Kim et al., 2003; Guo et al.,2018), cloud properties (Shao and Liu, 2005; Zhao et al., 2012), and latent heating (Zhu et al., 2025). Therefore, a critical challenge for future research lies in better disentangling the influence of such environmental meteorological factors from the overall aerosol effect." (Section 7. Lines 764-771)

We believe these additions significantly strengthen the discussion by directly addressing the interplay between our new findings and the established body of knowledge, thereby clarifying unique value of our research. We are grateful for this constructive suggestion.

Chen, F., Yang, Y., Yu, L., Li, Y., Liu, W., Liu, Y., and Lolli, S.: Distinct effects of fine and coarse aerosols on microphysical processes of shallow-precipitation systems in summer over southern China, Atmos. Chem. Phys., 25, 1587–1601, https://doi.org/10.10194/acp-25-1587-2025, 2025.

Guo, J., Luo, Y., Yang, J., Furtado, K., and Lei, H.: Effects of anthropogenic and sea salt aerosols on a heavy rainfall event during the early-summer rainy season over coastal Southern China, Atmospheric Research, 265, 105923, https://doi.org/10.1016/j.atmosres.2021.105923, 2022.

Guo, J., Liu, H., Li, Z., Rosenfeld, D., Jiang, M., Xu, W., Jiang, J. H., He, J., Chen, D., Min, M., and Zhai, P.: Aerosol-induced changes in the vertical structure of precipitation: a perspective of TRMM precipitation radar, Atmos. Chem. Phys., 18, 13329–13343, https://doi.org/10.5194/acp-18-13329-2018, 2018.

Peng, H., Hu, X., Ai, W., Qiao, J., and Zhao, X.: Effects of fine and coarse aerosols on the summer precipitation structure and microphysics over the yangtze river delta region, Atmospheric Research, 326, 108277, https://doi.org/10.1016/j.atmosres.2025.108277, 2025.

Shao, H. and Liu, G.: Why is the satellite observed aerosol's indirect effect so variable?, Geophysical Research Letters, 32, https://doi.org/10.1029/2005GL023260, 2005.

Stier, P., van den Heever, S. C., Christensen, M. W., Gryspeerdt, E., Dagan, G., Saleeby, S. M., Bollasina, M., Donner, L., Emanuel, K., Ekman, A. M. L., Feingold, G., Field, P., Forster, P., Haywood, J., Kahn, R., Koren, I., Kummerow, C., L'Ecuyer, T., Lohmann, U., Ming, Y., Myhre, G., Quaas, J., Rosenfeld, D., Samset, B., Seifert, A., Stephens, G., and Tao, W.-K.: Multifaceted aerosol effects on precipitation, Nat. Geosci., 17, 719–732, https://doi.org/10.1038/s41561-024-01482-6, 2024.

Sun, Y., Wang, Y., Zhao, C., Zhou, Y., Yang, Y., Yang, X., Fan, H., Zhao, X., and Yang, J.: Vertical Dependency of Aerosol Impacts on Local Scale Convective Precipitation, Geophysical Research Letters, 50, https://doi.org/10.1029/2022gl102186, 2023.

Sun, Y. and Zhao, C.: Distinct impacts on precipitation by aerosol radiative effect over three different megacity regions of eastern China, Atmos. Chem. Phys., 21, 16555–16574, https://doi.org/10.5194/acp-21-16555-2021, 2021.

Xi, J., Li, R., Fan, X., and Wang, Y.: Aerosol effects on the three-dimensional structure of organized precipitation systems over Beijing-Tianjin-Hebei region in summer, Atmospheric Research, 298, 107146, https://doi.org/10.1016/j.atmosres.2023.107146, 2024.

Xi, J., Wang, Y., Li, R., Wu, B., Fan, X., Ma, X., and Meng, Z.: The impact of Sahara dust aerosols on the three-dimensional structure of precipitation systems of different sizes in spring, EGUsphere, 1–30, https://doi.org/10.5194/egusphere-2025-2799, 2025.

Xiao, Y., Zhang, J., Zhu, J., and Dai, Q.: Exploration of aerosol-precipitation relationships under different climate regimes in China, GIScience & Remote Sensing, 62, https://doi.org/10.1080/15481603.2025.2457992, 2025.

Zhao, C., Klein, S. A., Xie, S., Liu, X., Boyle, J. S., and Zhang, Y.: Aerosol first indirect effects on non-precipitating low-level liquid cloud properties as simulated by CAM5 at ARM sites, Geophysical Research Letters, 39, https://doi.org/10.1029/2012GL051213, 2012.

Zhao, X., Zhao, C., Chi, Y., Yang, J., Sun, Y., Yang, Y., and Fan, H.: Different Impacts of Aerosols on Cloud Development over Land and Ocean Regions in East China, Adv. Atmos. Sci., 42, 731–743, https://doi.org/10.1007/s00376-024-4165-z, 2025.

Zhu, H., Zhao, H., Yang, S., Zhou, R., Wang, Y., Zou, Y., Zhao, C., and Li, R.: Smoke aerosols elevate precipitation top and latent heat to the upper atmosphere globally, npj Clim Atmos Sci, 8, https://doi.org/10.1038/s41612-025-01047-3, 2025.

Minor comments

[1] Lines 71-73: Except for the external synoptic conditions that can modulate the ACI process, entrainment, and other in-cloud meteorological factors, particularly that surrounding clouds and challenging to be measured, can affect the aerosol effect on clouds and precipitation.

Response:

We thank you for this insightful comment. In the revised manuscript, we have acknowledged this point in the Introduction to provide a more comprehensive background: "**Furthermore, external synoptic conditions, entrainment, and other in-cloud meteorological factors, particularly that surrounding clouds and challenging to be measured, can affect the aerosol effect on clouds and precipitation (Lee et al.,2008; Stevens and Feingold,2009; Chen et al., 2025; Sun et al., 2023; Zhao et al., 2024)**. **" (Lines 71-75)**

Chen, F., Yang, Y., Yu, L., Li, Y., Liu, W., Liu, Y., and Lolli, S.: Distinct effects of fine and coarse aerosols on microphysical processes of shallow-precipitation systems in summer over southern China, Atmos. Chem. Phys., 25, 1587–1601, https://doi.org/10.5194/acp-25-1587-2025, 2025.

Lee, S. S., Donner, L. J., Phillips, V. T. J., and Ming, Y.: The dependence of aerosol effects on clouds and precipitation on cloud-system organization, shear and stability, Journal of Geophysical Research: Atmospheres, 113, https://doi.org/10.1029/2007JD009224, 2008.

Stevens, B. and Feingold, G.: Untangling aerosol effects on clouds and precipitation in a buffered system, Nature, 461, 607–613, https://doi.org/10.1038/nature08281, 2009.
Sun, Y., Wang, Y., Zhao, C., Zhou, Y., Yang, Y., Yang, X., Fan, H., Zhao, X., and Yang, J.: Vertical Dependency of Aerosol Impacts on Local Scale Convective Precipitation, Geophysical Research Letters, 50, https://doi.org/10.1029/2022gl102186, 2023.
Zhao, C., Sun, Y., Yang, J., Li, J., Zhou, Y., Yang, Y., Fan, H., and Zhao, X.: Observational evidence and mechanisms of aerosol effects on precipitation, Science Bulletin, 69, 1569–1580, https://doi.org/10.1016/j.scib.2024.03.014, 2024.

[2]. Line 75: the citations are not correctly placed. Actually, these references are used to support "Significant research in recent years has focused on aerosol–induced modifications of precipitation structures in key regions of China".

Response:

Sorry for the careless error in the previous manuscript. Thank you! We have corrected the citation placement to properly support the statement on recent research in key Chinese regions. **"Recent research has extensively examined aerosol-induced modifications of precipitation structures in major urban clusters across China (Guo et al., 2018; Sun and Zhao, 2021; Zhao et al., 2025)." (Lines 76-78)**

Guo, J., Liu, H., Li, Z., Rosenfeld, D., Jiang, M., Xu, W., Jiang, J. H., He, J., Chen, D., Min, M., and Zhai, P.: Aerosol-induced changes in the vertical structure of precipitation: a perspective of TRMM precipitation radar, Atmos. Chem. Phys., 18, 13329–13343, https://doi.org/10.5194/acp-18-13329-2018, 2018.
Sun, Y. and Zhao, C.: Distinct impacts on precipitation by aerosol radiative effect over three different megacity regions of eastern China, Atmos. Chem. Phys., 21, 16555–16574, https://doi.org/10.5194/acp-21-16555-2021, 2021.
Zhao, X., Zhao, C., Chi, Y., Yang, J., Sun, Y., Yang, Y., and Fan, H.: Different Impacts of Aerosols on Cloud Development over Land and Ocean Regions in East China, Adv. Atmos. Sci., 42, 731–743, https://doi.org/10.1007/s00376-024-4165-z, 2025.

[3]. The argument "analysis of specific seasons or precipitation types is frequently limited" is not correct. To my knowledge, the following references have investigated the aerosol effect on precipitation types, such as https://doi.org/10.1073/pnas.1715386115; https://doi.org/10.1029/2019GL085442

Response:

We sincerely thank you for correcting this argument and for providing the relevant literature. We have revised the statement in the Introduction (Lines 82-85) to more accurately reflect the existing research landscape: **"Previous research has been conducted on aerosol-driven precipitation patterns in more general areas, such as the North China Plain (Sun et al., 2023),**

South China (Chen et al., 2025), and East China (Wen et al., 2023) under different seasonal and precipitation type conditions (Day et al., 2018; Guo et al., 2019). These studies have consistently confirmed that the modulation effects of aerosols on clouds and precipitation exhibit pronounced regional heterogeneity (Guo et al., 2017, 2019; Li et al., 2019; Sun and Zhao, 2021). However, the underlying physical mechanisms, particularly the cloud microphysical processes responsible for these disparate regional responses, are not yet fully understood." (Lines 82-90)

Chen, F., Yang, Y., Yu, L., Li, Y., Liu, W., Liu, Y., and Lolli, S.: Distinct effects of fine and coarse aerosols on microphysical processes of shallow-precipitation systems in summer over southern China, Atmos. Chem. Phys., 25, 1587–1601, https://doi.org/10.5194/acp-25-1587-2025, 2025.

Day, J. A., Fung, I., and Liu, W.: Changing character of rainfall in eastern China, 1951–2007, Proceedings of the National Academy of Sciences, 115, 2016–2021, https://doi.org/10.1073/pnas.1715386115, 2018.

Guo, J., Su, T., Li, Z., Miao, Y., Li, J., Liu, H., Xu, H., Cribb, M., and Zhai, P.: Declining frequency of summertime local-scale precipitation over eastern China from 1970 to 2010 and its potential link to aerosols, Geophysical Research Letters, 44, 5700–5708, https://doi.org/10.1002/2017GL073533, 2017.

Guo, J., Su, T., Chen, D., Wang, J., Li, Z., Lv, Y., Guo, X., Liu, H., Cribb, M., and Zhai, P.: Declining Summertime Local-Scale Precipitation Frequency Over China and the United States, 1981–2012: The Disparate Roles of Aerosols, Geophysical Research Letters, 46, 13281–13289, https://doi.org/10.1029/2019GL085442, 2019.

Li, Z., Wang, Y., Guo, J., Zhao, C., Cribb, M. C., Dong, X., Fan, J., Gong, D., Huang, J., Jiang, M., Jiang, Y., Lee, S.-S., Li, H., Li, J., Liu, J., Qian, Y., Rosenfeld, D., Shan, S., Sun, Y., Wang, H., Xin, J., Yan, X., Yang, X., Yang, X., Zhang, F., and Zheng, Y.: East asian study of tropospheric aerosols and their impact on regional clouds, precipitation, and climate (EAST-AIRCPC), Journal of Geophysical Research: Atmospheres, 124, 13026–13054, https://doi.org/10.1029/2019JD030758, 2019.

Sun, Y. and Zhao, C.: Distinct impacts on precipitation by aerosol radiative effect over three different megacity regions of eastern China, Atmos. Chem. Phys., 21, 16555–16574, https://doi.org/10.5194/acp-21-16555-2021, 2021.

Sun, Y., Wang, Y., Zhao, C., Zhou, Y., Yang, Y., Yang, X., Fan, H., Zhao, X., and Yang, J.: Vertical Dependency of Aerosol Impacts on Local Scale Convective Precipitation, Geophysical Research Letters, 50, https://doi.org/10.1029/2022gl102186, 2023.

Wen, L., Chen, G., Yang, C., Zhang, H., and Fu, Z.: Seasonal variations in precipitation microphysics over East China based on GPM DPR observations, Atmospheric Research, 293, 106933, https://doi.org/10.1016/j.atmosres.2023.106933, 2023.

[4]. "Aerosol loading" and "aerosol concentration" are used interchangeably. The authors may unify to one terminology. And "vertical structures" and "vertical profiles" (used for Ze, Dm) can be unified to "vertical profiles" for consistency.

Response

We appreciate this suggestion for improving terminological consistency. We have revised the manuscript accordingly: using "**aerosol loading**" and "**vertical profiles**" consistently.

[5]. The discussion mentions EarthCARE's potential for aerosol-cloud vertical profiling but does not specify how its data (ATLID lidar aerosol profiles, CPR cloud profiles) will address the current study's limitation of "inadequate 3D aerosol matching". I recommend adding 1–2 sentences on future research directions (e.g., combining EarthCARE's aerosol vertical distribution with GPM DPR's precipitation profiles to analyze aerosol-altitude-dependent impacts on cloud microphysics), enhancing the discussion's innovations.

Response:

This is an excellent suggestion. Thank you! We have expanded the Discussion to specify the future application of EarthCARE data: **"However, the successful launch and stable operation of EarthCARE now facilitates accurate three-dimensional vertical profiling of clouds and aerosols via lidar (ATLID) and cloud profiling radar (CPR) (Irbah et al., 2023). The integration of high-precision vertical profiles from ATLID (aerosols), CPR (clouds), and GPM DPR (precipitation) will enable future researchers to quantify how aerosol layers at different altitudes modulate cloud microphysics and precipitation formation (Li et al., 2025b)." (Lines 781-787)**

Irbah, A., Delanoë, J., Van Zadelhoff, G.-J., Donovan, D. P., Kollias, P., Puigdomènech Treserras, B., Mason, S., Hogan, R. J., and Tatarevic, A.: The classification of atmospheric hydrometeors and aerosols from the EarthCARE radar and lidar: the A-TC, C-TC and AC-TC products, Atmos. Meas. Tech., 16, 2795–2820, https://doi.org/10.5194/amt-16-2795-2023, 2023.

Li, Z., Ge, S., Hu, X., Ai, W., Tang, J., Qiao, J., Hu, S., Zhao, X., Wu, H., Li, Z., Ge, S., Hu, X., Ai, W., Tang, J., Qiao, J., Hu, S., Zhao, X., and Wu, H.: Preliminary analysis of a novel spaceborne pseudo tripe-frequency radar observations on cloud and precipitation: EarthCARE CPR-GPM DPR coincidence dataset, Remote Sens., 17, https://doi.org/10.3390/rs17152550, 2025b.

[6]. Figure 1 caption can be rephrased as "Geographical distribution of four urban agglomerations over (a) the Yangtze River Middle Reaches, (b) Beijing–Tianjin–Hebei, (c) Pearl River Delta, and (d) Yangtze River Delta (d), which is superimposed with elevation."

Response:

Done! Thank you for your good suggestions. **(Lines 166-170)**

[7]. Fig. 3's y-axis for PEI lacks clarity—specify that "-" indicates dimensionless (after scaling by 1000). Also, "across the FOUR regions and seasons." is not correct, I only saw three seasons corresponding to three rows of line plots.

Response:

Sorry for the careless. Done! Thank you. And the sentence has been modified to: **"Average point line plots of nsRR, STH, LWP, IWP, and PEI under three AOD conditions for convective precipitation across the four regions and three seasons." (Lines 342-343)**

[8].Figure 5's title for X-axis lacks clarity—specify that "-" indicates dimensionless or directly delete "-" (as we all know AOD is dimensionless).

Response:

Done! Thank you. We have specified that **"-" indicates dimensionless.**

[9].Figures 2-3, 5-7: Spr. Sum. and Aut. are not standard abbreviation for three different seasons.

Response:

Thank you. We have replaced "Spr.", "Sum.", "Aut." with names: **"Spring", "Summer", "Autumn"** in all figures (Figs. 2-9; Figs .S9,11,13-22).

[10]."Conclusion" -> "Conclusions"

Response:

Done! Thank you.

We sincerely thank you for their insightful and constructive feedback, which has been invaluable in improving the quality and clarity of our manuscript. The revisions made in response to these comments have significantly strengthened the paper's methodological transparency, analytical depth, and conceptual framing. We believe that the revised manuscript now presents a more robust and compelling analysis of aerosol-precipitation interactions across China's megacity clusters. We look forward to your further feedback.