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Aerosol-Driven Precipitation Modification: Spatiotemporal Heterogeneity in Precipitation Microphysics and Vertical Structures over China's Megacity Clusters

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ABSTRACT

As crucial atmospheric components, aerosols influence precipitation through complex microphysical mechanisms and exhibit spatiotemporal heterogeneity. This study investigates aerosol effects on precipitation vertical structures and microphysical characteristics across four Chinese urban clusters (the Beijing–Tianjin–Hebei (BTH), Yangtze River Delta (YRD), Yangtze River Middle Reaches (YRM), and Pearl River Delta (PRD)), including sensitivities to meteorological factors. Initially, the principal findings elucidate three fundamental attributes of precipitation differences: regional disparities surpass seasonal variations in magnitude; heightened aerosol concentrations mitigate regional precipitation

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discrepancies, particularly during the spring and summer seasons; convective precipitation exhibits greater regional and seasonal variability than stratiform precipitation. Furthermore, the findings indicate that aerosols exert an influence on precipitation through microphysical processes, encompassing the growth via condensation on cloud condensation nuclei, coalescence growth, semi-direct effect, and moisture competition. These phenomena exhibit distinct variations that are influenced by spatial and temporal factors, as well as the particular type of aerosols present. Specifically, convective precipitation in the BTH region is dominated by the semi–direct effect of dust aerosols, whereas the YRD and PRD are more influenced by hygroscopic sea salt aerosols and the YRM by fine aerosol particles. Furthermore, RH promotes condensation and coalescence processes by replenishing water vapor, particularly under low aerosol loading. However, CAPE plays a dual role: it enhances precipitation by intensifying cloud development and suppresses it through particle break-up driven by dynamics. The present study elucidates the mechanisms of spatio–temporal modulation underlying aerosol–precipitation interactions, offering a scientific foundation for the refinement of climate models within urban agglomerations.

Key words: GPM DPR, MERRA–2, Aerosols, Precipitation Structure, Urban Agglomerations

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1. Introduction

Aerosols modulate clouds and precipitation primarily through Aerosol–Radiation Interactions (ARI) and Aerosol–Cloud Interactions (ACI). These mechanisms affect the intensity, frequency, and spatiotemporal distribution of precipitation (Rosenfeld et al., 2008). These processes involve complex multiscale, multi–factor coupling effects with profound implications for regional hydrological cycles, extreme weather events, and climate systems (Li et al., 2016, 2019; Ramanathan et al., 2001). Therefore, one of the most important problems facing atmospheric research is the clarification of aerosol–driven precipitation mechanisms (IPCC, 2013; IPCC, 2021). In this framework, the ACI describes the mechanism by which aerosols function as ice nuclei (IN) and cloud condensation nuclei (CCN), modifying cloud microphysical processes to indirectly modify the type and distribution of precipitation intensity (Gettelman, 2015). These include cloud droplet spectrum distribution, phase transition efficiency, and precipitation formation pathways (Xie et al., 2013). Known as the Twomey Effect (the First Indirect Effect), higher aerosol concentrations increase the number of cloud droplets, while decreasing their effective radius (r_e) and increasing cloud albedo (Twomey, 1974). In addition, the Cloud Lifetime Effect (Second Indirect Effect), aerosol-induced reduction in $r_{e,}$ suppresses precipitation initiation, whereas prolonging cloud lifetime (Albrecht, 1989). The Semi-Direct Effect is another way in which absorptive aerosols can shorten cloud lifetime by heating the atmosphere through the absorption of shortwave radiation, which accelerates droplet evaporation (Ackerman et al., 2000; Huang et al., 2014). There are still many unknowns

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surrounding the measurement of aerosol impacts on precipitation, even though the primary mechanisms of aerosol–precipitation interactions are documented. This is due to the diversity and highly nonlinear characteristics of aerosol–precipitation responses (Chang et al., 2015), which are jointly regulated by aerosol concentration, type, vertical distribution, and local meteorological conditions (Fan et al., 2007; Storer et al., 2010), leading to pronounced regional variations (Xiao et al., 2025). Furthermore, external synoptic conditions modulate the ACI process (Chen et al., 2025; Sun et al., 2023; Zhao et al., 2024).

Significant research in recent years has focused on aerosol–induced modifications of precipitation structures in key regions of China. Major urban agglomerations, Beijing–Tianjin–Hebei (BTH), Yangtze River Delta (YRD), Pearl River Delta (PRD), and Yangtze River Middle Reaches (YRM)–represent China's most economically vibrant and densely populated areas while also experiencing severe aerosol pollution (Guo et al., 2018; Sun and Zhao, 2021; Zhao et al., 2025), thus providing critical entry points for investigating regional manifestations of aerosol effects. Although previous research has been conducted on 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), analysis of specific seasons or precipitation types is frequently limited without considering meteorological drivers. Moreover, numerical models show substantial instability in precipitation capture (Zhang et al., 2024), and simulation capabilities exhibit inherent asymmetries (Snively and Gallus, 2014). In summary, methodological divergences and data source variations across studies have

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yielded divergent conclusions with persistent controversies, precluding robust cross–regional comparisons of aerosol impacts on precipitation structures. Therefore, it is essential to develop consistent techniques for the collection and interpretation of aerosol–precipitation data.

The Global Precipitation Measurement (GPM) mission extends and advances the Tropical Rainfall Measuring Mission (TRMM). Compared with TRMM's single–frequency Precipitation Radar (PR), the Dual–frequency Precipitation Radar (DPR) onboard the GPM core observatory demonstrates higher sensitivity and provides more accurate three–dimensional precipitation structure. This increase markedly enhances precipitation detection capabilities at mid-to high latitudes (Hou et al., 2014). Furthermore, comparisons between GPM DPR precipitation data and observations from ground–based radars and meteorological stations (Chandrasekar and Le, 2015; Lasser et al., 2019; Sun et al., 2020) validated the substantial agreement across all three platforms. Moreover, a robust concordance in surface precipitation patterns and brilliant band height was noted between DPR data and the high–resolution NICAM 3.5 km model (Kotsuki et al., 2023), hence reinforcing data dependability.

Additionally, Modern–Era Retrospective Analysis for Research and Applications Version 2 (MERRA–2) significantly improves the accuracy of aerosol vertical distributions and optical properties through assimilation of multi–source satellite and ground–based observations (Buchard et al., 2017; Chang et al., 2015). Building on the reliable precipitation data from GPM DPR, researchers analyzed aerosol impacts on

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precipitation vertical structure, microphysical characteristics, and extreme hydrometeorological events using integrated MERRA–2 aerosol and DPR precipitation datasets (Ji and Tian, 2024; Jiang et al., 2023; Sun et al., 2022). Furthermore, compared with the ECMWF Re–Analysis–Interim (ERA–Interim), the European Centre for Medium–Range Weather Forecasts Reanalysis Version 5 (ERA–5) offers significantly improved spatiotemporal resolution, yielding superior environmental parameters(Zhao et al., 2021). This enhancement facilitates its widespread utilization in research investigating the impact of aerosol on precipitation structure(Dong et al., 2018; Guo et al., 2018; Pravia-Sarabia et al., 2023).

Peng et al. (2025) conducted a focused investigation into the effects of fine and coarse aerosols on summer precipitation processes within the YRD region. The results indicated that coarse aerosols suppress convective precipitation by competing for moisture, whereas fine aerosols enhance precipitation by forming small droplet clusters with condensational and coalescence growth. However, precipitation characteristics vary significantly across different regions and seasons, which can be attributed to differences in aerosol types, concentrations, and meteorological conditions. Therefore, this study integrates precipitation, aerosol, and environmental data from four major urban agglomerations (the BTH, YRD, YRM, and PRD) between 2014 and 2023. A multi–source DPR–MERRA–2–ERA5 dataset was constructed to systematically analyze the impact of aerosol on precipitation properties and microphysical processes. In addition, the interactions between aerosol and precipitation structures are further investigated under varying thermodynamic and

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dynamic conditions. This unified methodology facilitates a comprehensive examination of aerosol effects on the precipitation structure and cloud microphysics across China's major urban agglomerations, enabling cross–regional comparative assessments.

The remainder of this paper is organized as follows. Section 2 introduces the data and methods. Section 3 examines aerosol influences on precipitation structure and properties. Section 4 conducts an analysis of aerosol effects on the microphysical processes of precipitation. Section 5 investigates meteorological effects on aerosol-precipitation interactions. Section 6 summarizes the conclusions of this study and Section 7 discusses the limitations and shortcomings of this research.

2. Data and Methods

2.1 Study area

The YRM urban cluster (Fig. 1a) is situated between 26°N–32.5°N and 110.5°E–118.3°E, inside a humid subtropical monsoon region characterized by concentrated summer precipitation. The BTH region (36°N–41.6°N, 113.5°E–119.9°E; Fig. 1b) exhibits a temperate semi–humid continental monsoon climate, with summer comprising over 67% of the annual precipitation and spring characterized by numerous dust events (Zhai et al., 2022). The PRD cluster (21.7°N–23.8°N, 112°E–115.4°E; Fig. 1c) exhibits a South Asian tropical marine monsoon climate, characterized by the 85% of annual precipitation occurring from April to September, frequently exacerbated by typhoons (Guo et al., 2018). Dominated by the Taihu Plain

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(27.9°N–33.3°N, 117.5°E–122.7°E; Fig. 1d), the YRD exhibits a humid subtropical monsoon climate characterized by concentrated spring–summer precipitation, including prolonged June–July Meiyu–front rainfall (Liu et al., 2017). Fig. 1 shows the spatial distribution of all four urban agglomerations.

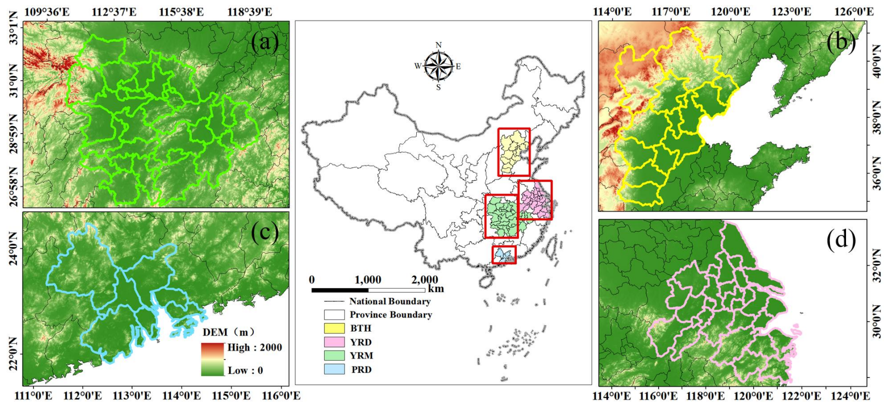

Fig. 1. Geographical location and elevation map of the Yangtze River Middle Reaches (a), Beijing–Tianjin–Hebei (b), Pearl River Delta (c), and Yangtze River Delta (d) urban agglomeration (source: GS(2024) 0650). Publisher’s remark: please note that the above figure contains disputed territories.

2.2 GPM DPR Precipitation Data

Mounted on the core satellite, the DPR transmits at the Kuband (13.6 GHz) and Kaband (35.5 GHz) frequencies, achieving a nadir horizontal resolution of 5 km to detect three–dimensional precipitation structures from the surface to an altitude of 22 km (Hou et al., 2014). This study utilized the GPM Level 2 DPR (2ADPR) standard product, Version 07, which employs two unique antenna scanning modes: the High–Sensitivity Scan (HS) and the Full Scan (FS). A significant alteration in Version 07, compared to Version 06, entails a shift in the KaPR scanning pattern from the

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inner swath to the outer swath configuration. This change aligns the KaPR scanning mode with that of KuPR.

Given the relatively low frequency of winter precipitation events and frequent occurrence of solid precipitation in northern regions, this study focuses on precipitation data during spring (March–May), summer (June–August), and autumn (September–November) from 2014 to 2023. The parameters analyzed in this study include: The near–surface Rain Rate (nsRR), Rain Rate (RR), Storm Top Height (STH), Liquid Water Path (LWP), Ice Water Path (IWP), DSD, and radar reflectivity factor (Z_e). The DSD includes two parameters: mass–weighted diameter (D_m) and normalized DSD intercepts (N_w).

2.3 MERRA–2 Aerosol Data

This study utilized the MERRA–2 atmospheric reanalysis dataset, updated in 2017 and released by NASA's Global Modeling and Assimilation Office (GMAO). By assimilating multi–source observations with numerical modeling techniques, this dataset characterizes the column mass concentrations of five aerosol types: dust (DU), sea salt (SS), sulfate (SO4), black carbon (BC), and organic carbon (OC), and their corresponding AOD. The data feature a global spatial coverage at a horizontal grid resolution of 0.625°×0.5° (longitude×latitude), with temporal products available at hourly intervals.

It is noteworthy that the aerosol data matched are those prior to precipitation events.

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2.4 ERA–5 Data

Environmental data for this study were acquired from the ERA5 reanalysis dataset. Through the coupled assimilation of multi–source satellite observations, ground–based measurements, and numerical forecasting systems, this product provides multidimensional climate parameters that span the surface–to–stratopause column (Hersbach et al., 2020). This investigation utilizes two key parameters: Relative Humidity (RH) at 850hPa and Convective Available Potential Energy (CAPE).

2.5 Classification Methods

Prior to data analysis, the DPR, MERRA–2, and ERA5 datasets were subjected to spatiotemporal matching using the best–proximity method. Subsequently, precipitation pixels were screened using the connectivity method (Hu et al., 2022), applying a minimum threshold of four contiguous pixels to define valid precipitation systems. This study categorized precipitation into stratiform and convective types based on the 2ADPR classification criteria, excluding shallow convection events from convective precipitation (Liu and Zipser, 2015). Aerosol classification followed the total AOD thresholds: Low AOD, [0, 0.3); Medium AOD, [0.3, 0.6); and High AOD, [0.6, ~). In terms of aerosol classification, BCA, OCA, and SO_{4A} were categorized as fine aerosol particles, whereas SSA and DUA were classified as coarse aerosol particles.

Fig. S1 illustrates the cumulative distribution functions (CDFs) of the RH and CAPE throughout the four urban agglomerations for meteorological conditioning.

Given the higher similarity in RH distributions among the YRD, YRM, and PRD versus distinct BTH characteristics, the YRD–YRM–PRD RH data were unified (red dashed line; Fig. S1a–c). Conversely, the BTH–YRD–YRM exhibited comparable CAPE distributions, and the PRD showed significantly higher values. Thus, the BTH–YRD–YRM CAPE data were combined (red dashed line; Fig. S1d–f). To balance methodological consistency with regional specificity, the classification strategy implemented distinct groupings: RH was classified separately for the BTH region, whereas the YRD, YRM, and PRD shared a unified RH classification. Similarly, CAPE maintained independent classification for the PRD, whereas BTH, YRD, and YRM employed combined CAPE classification, as visualized by the red dashed lines in Fig. S1. Moreover, to prevent feature ambiguity from adjacent samples, three percentile tiers were defined using the CDFs thresholds: low (0%–30%), medium (35%–65%), and high (70%–100%), with 30–35% and 65–70% as buffer zones to avoid adjacent–sample ambiguity.

2.6 Normalized difference calculation

In order to quantify regional and seasonal differences in precipitation parameters, the BTH region and spring season were set as the benchmark for normalizing variations. The fractional changes ($DIFF_{region}$, in %) for each parameter in the YRD, YRM, and PRD regions relative to BTH were calculated as follows:

$$DIFF_{region} = \frac{X_{region} - X_{BTH}}{X_{BTH}} * 100\% \qquad (1)$$

Beyond regional differences, the fractional seasonal changes ($DIFF_{season}$, in %) for precipitation parameters were calculated as:

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$$DIFF_{season} = \frac{X_{season} - X_{spring}}{X_{spring}} * 100\% \quad (2)$$

where $DIFF_{region}$ represents the normalized differences for the YRD, YRM, and PRD relative to BTH, respectively; $DIFF_{season}$ denotes the normalized seasonal differences when comparing summer and autumn to spring. X_{BTH} and X_{spring} represent the reference value of the target precipitation parameter in the BTH and spring, respectively. X_{region} denotes the precipitation parameter values for the YRD, YRM, and PRD regions, respectively, and X_{season} represents the precipitation parameter values in the seasons being compared to spring.

3 Influence of aerosols on precipitation structure and properties

3.1 Correlation changes of precipitation parameters with aerosols

To investigate aerosol impacts on convective and stratiform precipitation characteristics across the four urban agglomerations, five precipitation parameters were selected: nsRR, STH, LWP, IWP, and the precipitation efficiency index (PEI). A correlation heat map of the convective precipitation between AOD and these parameters is shown in Fig. 2. The PEI is a crucial metric for measuring the efficiency of precipitation formation in clouds, indicating the effectiveness of converting cloud water into precipitation. Higher PEI values indicate enhanced precipitation efficiency, which is characterized by a greater conversion of cloud water into rainfall. Following Hu et al. (2022) and scaled by 1000 for enhanced readability, PEI is defined as:

$$PEI = \frac{nsRR}{CWP} = \frac{nsRR}{(LWP + IWP)} * 1000 \quad (3)$$

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In the resulting heat map of convective precipitation (Fig. 2), individual cells exhibit Spearman correlation coefficients that quantify the relationship between AOD and key meteorological parameters. For spring convective precipitation (Fig. 2a–c), the BTH exhibits significant negative correlations with the STH and IWP under low aerosol loading, whereas showing a significant positive correlation with PEI. The YRD displays patterns similar to those of the BTH: negative correlations at low aerosol loading shift to positive correlations with precipitation parameters as aerosol loading increases. In contrast, both the YRM and PRD show consistently positive correlations under low aerosol loading (Fig. 2a). However, the PRD demonstrates pronounced negative correlations at moderate loading, whereas the YRM maintains positive correlations at high aerosol loading. Summer (Fig. 2d–g): Under low (high) AOD conditions, consistent positive (negative) correlations prevail across all study regions (Fig. 2d). At moderate aerosol loading levels, the PRD shifts to a negative correlation, whereas the other three regions retain a positive correlation (Fig. 2e). Autumn (Fig. 2g–i): the YRD exhibits pronounced negative correlations under low–to–moderate AOD thresholds. Conversely, the BTH and YRD (PRD) demonstrate positive (negative) correlations under high AOD levels. Overall, the precipitation under varying aerosol loading exhibits pronounced seasonal and regional disparities, demonstrating nonlinear characteristics in their relationships.

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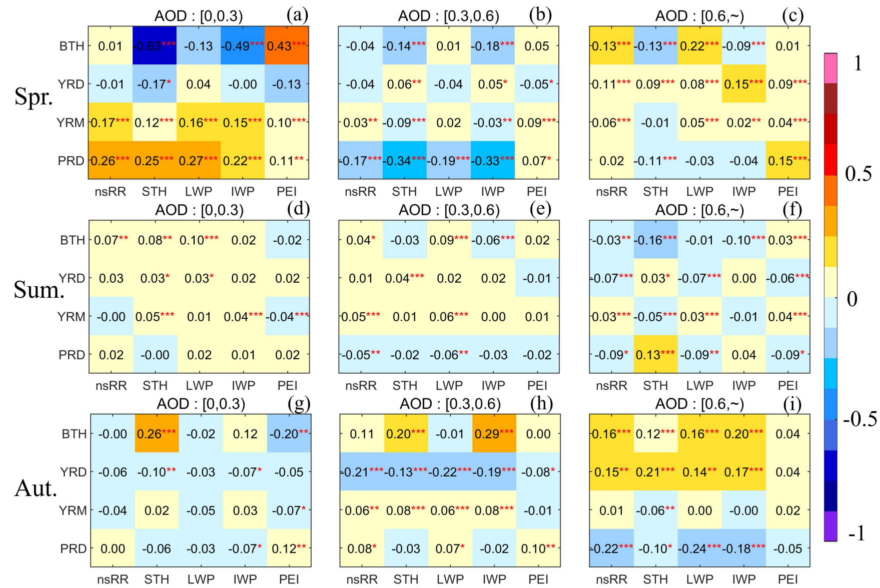

Fig. 2. Spearman correlation coefficients between AOD and precipitation parameters for convective precipitation across regions and seasons under the three AOD regimes. Color gradients (from yellow to blue) encode the correlation strength and direction, and asterisks denote statistical significance (*：p<0.05, **：p<0.01, ***：p<0.001).

Spearman correlation coefficients are computed to characterize the precipitation parameters in stratiform precipitation (Fig. S3), similar to that of convective precipitation (Fig. 2). Overall, the PRD exhibits the strongest similarity between the stratiform and convective precipitation parameters in the correlation with AOD. In contrast, the BTH, YRD, and YRM resemble convective precipitation characteristics under moderate to high aerosol loading, but show reduced similarity under low aerosol loading, particularly in the BTH.

3.2 Changes in the structural characteristics of precipitation parameters associated with aerosols

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Fig. 3 illustrates the seasonal mean values of the convective precipitation parameters for nsRR, STH, LWP, IWP, and PEI across AOD intervals. During spring (Fig. 3a–e), the BTH and YRD regions exhibit similar responses, with nsRR, STH, LWP, and PEI demonstrating persistent enhancement as the aerosol burden increases. In contrast, the YRM and PRD manifest nonlinear features: nsRR, LWP, and IWP experience initial suppression before rebounding at elevated AOD levels. Summer observations (Fig. 3f–j) reveal predominantly linear positive relationships between aerosol loading and precipitation parameters in the BTH, YRD, and YRM regions. However, the PRD diverges sharply, displaying inverted V–shaped responses in the nsRR, STH, LWP, and PEI. Autumn analysis (Fig. 3k–o) reveals consistent increases in the YRM and PRD with aerosol enhancement, whereas the BTH and YRD exhibit a pattern of initial decline followed by a subsequent increase.

The regional comparisons indicate that the differences of the precipitation parameters are mitigated under moderate to high aerosol loading conditions (Table 1). For instance, at low aerosol loading, the fractional changes in spring nsRR reach $DIFF_{PRD}$=613% and $DIFF_{YRM}$=247.33%, whereas high aerosol loading reduces these to $DIFF_{PRD}$=155% and $DIFF_{YRM}$=49.6% (Table 1). These results highlight that increasing aerosol loading can moderately alleviate regional disparities in precipitation characteristics. Furthermore, the BTH exhibits notably higher IWP and PEI values, indicating enhanced ice-phase processes and superior precipitation conversion efficiency, as evidenced by the negative $DIFF_{YRD}$, $DIFF_{YRM}$, and $DIFF_{PRD}$ values.

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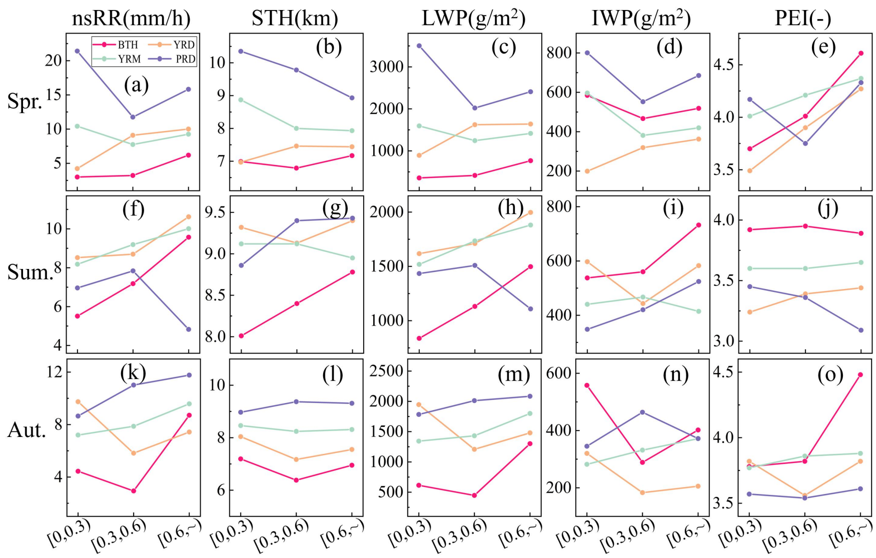

Fig. 3. Average point line plots of nsRR, STH, LWP, IWP, and PEI under three AOD conditions for convective precipitation across the four regions and seasons. Each subplot employs color–coding (BTH–red, YRD–yellow, YRM–green, and PRD–purple) with the x–axis denoting AOD bins ([0,0.3), [0.3,0.6), [0.6, ~)) and the y–axis representing parameter magnitudes.

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Table 1. Normalized regional differences in convective precipitation during the spring season. Units: nsRR (mm/h), STH (km), LWP (g/m^2), IWP (g/m^2).

	AOD	BTH	YRD $DIFF_{YRD}$	YRM $DIFF_{YRM}$	PRD $DIFF_{PRD}$
nsRR	[0,0.3)	3	4.23+41.00%	10.42+247.33%	21.4+613.33%
	[0.3,0.6)	3.23	9.1+181.73%	7.75+139.94%	11.76+264.09%
	[0.6,~)	6.19	10.01+61.71%	9.26+49.60%	15.82+155.57%
	[0,0.3)	6.99	6.97-0.29%	8.87+26.90%	10.35+48.07%
STH	[0.3,0.6)	6.79	7.46+9.87%	8+17.82%	9.78+44.04%
	[0.6,~)	7.17	7.44+3.77%	7.93+10.60%	8.93+24.55%
	[0,0.3)	355.11	892.42+151.31%	1593.58+348.76%	3501.97+886.16%
LWP	[0.3,0.6)	414.57	1622.99+291.49%	1242.87+199.80%	2019.85+387.22%
	[0.6,~)	765	1639.19+114.27%	1415.35+85.01%	2407.82+214.75%
	[0,0.3)	584.6	199.12-65.94%	596.38+2.02%	800.57+36.94%
IWP	[0.3,0.6)	466.54	319.12-31.60%	381.24-18.28%	552.17+18.35%
	[0.6,~)	518.72	362.2-30.17%	419.48-19.13%	685.27+32.11%
	[0,0.3)	3.7	3.49-5.68%	4.01+8.38%	4.17+12.70%
PEI	[0.3,0.6)	4.01	3.9-2.74%	4.21+4.99%	3.75-6.48%
	[0.6,~)	4.61	4.27-7.38%	4.37-5.21%	4.33-6.07%

To further characterize the stratiform precipitation parameters (nsRR, STH, LWP, IWP, and PEI), the seasonal mean values across aerosol loading levels are presented in Fig. S4 through point–line plots that were formatted consistently with those in Fig. 3.

For spring (Fig. S4a–e), the BTH, YRD, and YRM exhibit continuously increasing trends in nsRR, LWP, and IWP with increasing aerosol loading. Conversely, the PRD shows overall decreasing trends across most precipitation parameters. In summer (Fig. S4f–j), the BTH, YRD, and YRM demonstrate linear increases in nsRR and LWP means as aerosol loading rises. However, the PRD exhibits nonlinear trends: initial increases followed by decreases in nsRR, STH, LWP, and IWP means, a pattern consistent with its convective precipitation behavior. In autumn (Fig. S4k–o): monotonically rising trends in nsRR, LWP, and IWP are shown

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by the YRD and YRM, whereas the BTH and PRD display decreasing and then increasing trends in nsRR, IWP, and PEI, indicating an increase in aerosol loading. Additionally, the fractional changes in stratiform precipitation indicate that an increase in aerosol loading moderately reduces regional disparities during regional normalized difference comparisons, particularly in the spring and summer (Tables .S3-5). For instance, in the PRD region during spring (Table .S3), the $DIFF_{PRD}$ values for IWP are 208.16%, 141.06%, and 34.13%, corresponding to AOD ranges of [0, 0.3), [0.3, 0.6), and [0.6, ~), respectively. The seasonal normalized differences indicate significant ice-phase processes but weak liquid-phase processes across various regions during spring.

To summarize, aerosols influence the average values of precipitation parameters, displaying characteristics that differ across spatiotemporal scales and precipitation types. Furthermore, precipitation parameters exhibit greater regional than seasonal variation. In particular, within the 270 $DIFF_{region}$ samples, 41 (constituting 15.2%) exhibited values exceeding 100%, whereas among the 240 $DIFF_{season}$ samples, only 10 (representing 4.2%) demonstrated such a phenomenon (Tables S.1-7). Additionally, convective precipitation shows larger magnitude changes across seasons and regions than stratiform precipitation.

3.3 Changes in the vertical structure of precipitation associated with aerosols

To further investigate the vertical structure of precipitation, Fig. 4 presents the vertical distributions of the mean Z_e, D_m, N_w, and RR for convective precipitation under varying AOD loadings and seasons. Overall, the mean Z_e, N_w, and RR values

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generally increase with decreasing height, whereas D_m exhibits an initial decrease followed by an increase. In addition, the PRD displays a markedly higher RR than the BTH, YRD, and YRM in spring, but lower RR in summer. This seasonal contrast may be attributed to the abundant moisture supply during the pre–rainy season in South China, versus significant precipitation suppression in summer caused by hygroscopic aerosol–induced moisture competition. Furthermore, Chen et al. (2015) observed that a moderate CAPE in the PRD summer may lead to diminished precipitation.

As shown in Fig. 5a, in spring, the RR and Z_e of BTH, YRD, YRM, and PRD have obvious similarities with the variation in AOD. The RR and Z_e increase linearly with aerosol loading in the BTH and YRD but display non–monotonic trends (initial suppression followed by enhancement) in the YRM and PRD, consistent with Fig. 4a–e. This discrepancy may arise from the predominant influence of DUA on the spring AOD composition of the BTH region (Fig. S1a), whereby their semi–direct effect promotes cloud droplet evaporation, reduces moisture availability, and triggers earlier precipitation(Sun and Zhao, 2021). Although the rising proportion of fine–mode aerosols mitigates dust–induced precipitation suppression as AOD increases, persistently low moisture availability in the BTH maintains precipitation levels below those of the other regions. The YRD exhibits a more abundant water vapor supply (Fig. S1a): Increased aerosol concentrations supply additional CCN and IN, providing more condensation nuclei for cloud droplet formation and thereby enhancing precipitation. With increasing AOD, the YRM transitions from low–concentration coarse particles to high–concentration fine particles (Fig. 4c–d).

Inadequate moisture supply triggers the Twomey effect through competition for cloud water; however, extended cloud longevity and enhanced collision–coalescence (Fig. 5a) subsequently cause precipitation to initially decline and then rise. The PRD precipitation patterns resemble those of the YRM, although hygroscopic SSA exert a stronger influence (Fig. S2a). At low AOD (with an SSA proportion of 26.32%), moisture from South China's pre–rainy season and hygroscopic giant CCN derived from sea salt promote spring precipitation growth (Guo et al., 2022). As AOD increases, the SSA contribution declines rapidly, weakening its precipitation–promoting effect. However, with further AOD growth, the proportion of fine (notably hygroscopic OCA) aerosols rises (Fig. S2a), supplying more effective CCN to enhance the precipitation. Additionally, under low AOD conditions, the lower atmosphere in the YRD (YRM) is dominated by high concentrations of smaller (larger) particles. As aerosol loading increases, the Twomey effect emerges in the YRM, whereas the BTH and YRD exhibit the anti–Twomey effect.

During the summer (Fig. 4e–h), average vertical profiles of RR and Z_e in the BTH, YRD, and YRM generally exhibit increasing linear trends with rising aerosol loading. Conversely, the PRD shows an initial increase followed by a decrease, which is consistent with the findings in Fig. 3f–j. Within the BTH, YRD, and YRM, low proportions of hygroscopic giant CCN (SSA) mean increasing aerosols boost N_w and D_m, supplying more CCN and IN for cloud droplet formation. Coupled with ample summer moisture supply and dynamic forcing, cloud droplets are transported to higher altitudes (Fig. 3g), enhancing precipitation. During summer in the PRD, ample

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moisture is derived from the Indian Ocean. With low aerosol loading, the proportion of sea salt particles is elevated (23.83%). An increase in giant sea salt CCN loading triggers an anti–Twomey effect, characterized by a rise in D_m and a decline in N_w, leading to intensified precipitation. Nevertheless, as aerosol loading escalates further, fine–mode particles predominate (93.9%; Fig. S2b), resulting in moisture competition becoming the principal mechanism inhibiting precipitation.

Consistent with the conclusions in Fig. 3k–o, autumn trends (Fig. 4i–l) show that precipitation in the BTH and YRD initially decreased and then increased with increasing aerosol loading, although the magnitude of the increase is increasing with rising aerosol loading, though the increase magnitude is larger in the BTH than in the YRD. Conversely, RR exhibits monotonically increasing trends in the YRM and PRD. The underlying mechanisms are as follows. The BTH and YRD: Initial aerosol increase elevates N_w while reducing D_m (Fig. 4k–l), suppressing precipitation via the Twomey effect. However, prolonged cloud lifetime promotes further cloud development (Fig. 3l–m). Consequently, when aerosol loading continues rising, abundant CCN and IN become available for cloud–precipitation processes, ultimately enhancing precipitation. The YRM and PRD: The monotonic trends stem from greater autumn moisture availability versus the BTH and YRD (Fig. S1c), which supports cloud droplet condensational growth (Fig. 4k–l) and enhances collision–coalescence (Fig. 5a), collectively facilitating precipitation.

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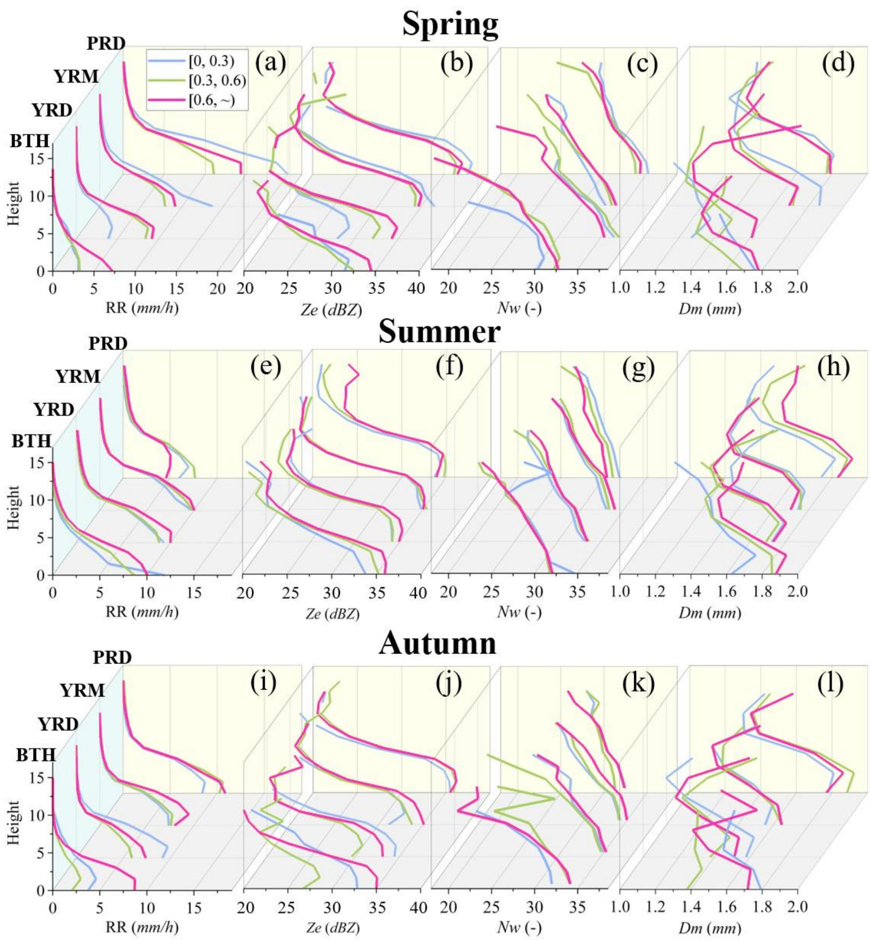

Fig .4. Vertical profiles of the average convective precipitation parameters Z_e, D_m, N_w and RR for different regions in different seasons under three AOD conditions ([0,0.3)–blue lines; [0.3,0.6)–green lines; [0.6, ~)–magenta lines). Within each subplot, line profiles are categorized into four regions: BTH, YRD, YRM, and PRD.

To enhance the characterization of the vertical structure and microphysical processes of stratiform precipitation, Fig. S5 displays the mean vertical profiles of Z_e, D_m, N_w, and RR, similar to those in Fig. 4. A notable Z_e peak at an altitude of 5 km

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corresponds to the 0 °C bright band signature, which is a distinctive indicator of the hydrometeor phase transition and stratiform precipitation. Fig. S5a illustrates that the PRD exhibits declining trends in RR and Z_e, diverging from the characteristics of convective precipitation depicted in Fig. 4a–b. In the PRD, increasing aerosol loading induces a Twomey effect: N_w increases, accompanied by a decrease in D_m (Fig. S5c–d). This dominance of particle competition mechanisms at higher AOD loadings aligns with increasing OCA contributions (Fig. S2c–d), as light–absorbing OCAs suppress precipitation via semi–direct effects of shortwave radiation absorption.

During summer (Fig. S5 e–h), the BTH region displayed distinct patterns compared to the other three regions: RR decreases with increasing aerosol loading, whereas Z_e and D_m increase simultaneously. This suggests that higher aerosol loads enhance particle albedo, thereby intensifying the evaporation of smaller particles and the processes of break–up (Fig. 5b), such that while N_w remains stable, the PEI declines (Fig. S4j). Concurrently, the increased abundance of hygroscopic SO_4A further depletes the atmospheric moisture. These combined effects lead to a notable reduction in precipitation within the BTH region. The summer stratiform precipitation responses of the PRD to aerosol loading resemble those of convective precipitation, whereas the YRD and YRM show negligible alterations in the vertical profiles, suggesting a low sensitivity of stratiform precipitation to aerosol loading.

4 Influence of aerosols on precipitation microphysical processes

To validate the aforementioned microphysical processes, this study assesses near-surface precipitation mechanisms below the melting layer. The melting layer

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refers to the region where the ice phase of the hydrometeors transitions to the liquid phase during precipitation(Hu et al., 2024), and the analysis employs the categorization approach established by Kumjian and Prat (2014). This approach employs radar reflectivity (ΔZ_e=Z_e^{1km}-Z_e^{3km}) and raindrop size (ΔD_m=D_m^{1km}-D_m^{3km}) differences between 1 km and 3 km above ground level. These metrics classify processes into four categories: size sorting evaporation, coalescence, break-up, and break-up coalescence balance. The extensive application of this methodology demonstrates that coalescence and break-up processes dominate cloud microphysics (Chen et al., 2025; Hu et al., 2022; Wen et al., 2023; Zhou et al., 2022). Consequently, this analysis focuses exclusively on these two mechanisms. Fig. 5 displays the coalescence and break-up processes for convective and stratiform precipitation across regions and seasons.

In convective precipitation (Fig. 5a), coalescence consistently dominates over break-up across all regions, particularly during spring and autumn. With rising AOD concentrations, the YRD, YRM, and PRD exhibit enhanced coalescence in spring, whereas the PRD shows a decreasing-then-increasing trend in coalescence. In summer, the proportions of coalescence and break-up remain comparable, whereas autumn exhibits nonlinear responses in the BTH and YRD.

In stratiform precipitation (Fig. 5b), break-up generally exceeds coalescence, with distinct seasonal patterns: in spring, the BTH exhibits increasing-then-decreasing coalescence, whereas the PRD shows the opposite trend (aligning with divergent RR patterns in Fig. S5a). During summer and autumn, BTH consistently shows notably

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lower break-up than coalescence, which is one of the reasons why precipitation continues to decline with increasing AOD loading in summer. The specific microphysical influence process is explained in detail in Section 3.

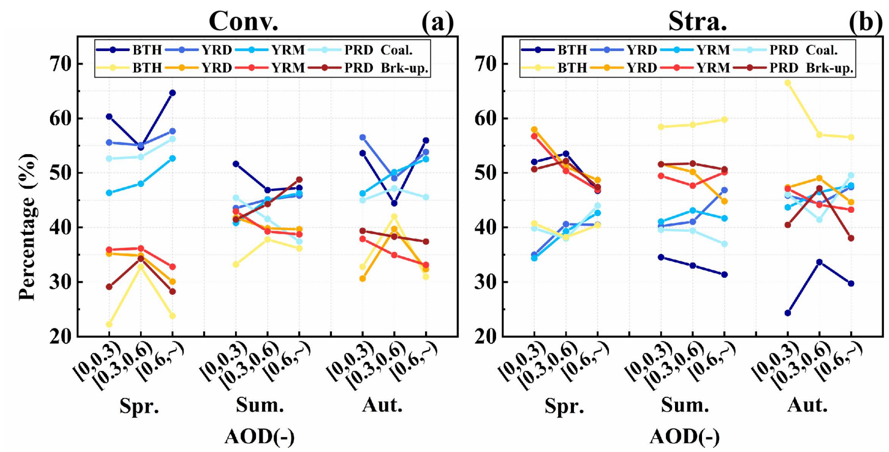

Fig. 5. Average point line plots of coalescence and break-up processes in precipitation across different regions and seasons (Spr.-Spring, Sum.-Summer, and Aut.-Autumn) under three AOD conditions. Here, (a) represents convective precipitation, and (b) represents stratiform precipitation.

5 Meteorological effects

5.1 Sensitivity analysis of aerosols to meteorological factors in precipitation parameters

Since precipitation processes are equally influenced by thermodynamic and dynamic environments, this study employs RH at 850hPa as a thermal influence factor and CAPE as a dynamic influence factor to examine aerosol sensitivity to these meteorological elements. Following the classification criteria established in Section

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2.5, RH and CAPE values were categorized into low, medium, and high levels.

Following the format of Fig. 3, Fig. 6 displayed point-line plots of convective precipitation parameters across regions under different RH and aerosol loading conditions. Notably, higher RH values consistently enhance mean precipitation parameters (nsRR, LWP, PEI) across all regions, whereas STH and IWP show inconsistent seasonal and regional variations. This suggests that elevated RH supplies additional moisture, thereby mitigating moisture competition effects.

In spring (Fig. 6a–e), rising RH values do not interfere with the established trends of the BTH across varying aerosol levels: nsRR and LWP continue to rise with aerosol loading, yet STH and IWP exhibit persistent decrease-then-increase trajectories. Precipitation parameters in the YRD and YRM remain consistent with the characteristics observed in Fig. 3a–e. By contrast, the PRD displays distinct characteristics under moderate RH conditions. This indicates that aerosols exhibit greater sensitivity to RH in the spring convective precipitation of the PRD, whereas aerosol effects dominate over RH influences in the BTH, YRD, and YRM.

Summer patterns (Fig. 6f–j) show modified the BTH responses under high RH; however, other regions remain consistent with prior trends in Fig. 3f–j. In autumn, observations (Fig. 6k–o) highlight inconsistent aerosol–precipitation relationships across the RH levels in the PRD. By contrast, the BTH, YRD, and YRM maintain nearly identical parameter responses.

The results indicate that RH sensitivity significantly influences aerosol-precipitation effects on convective precipitation in the PRD, whereas aerosol loading is the main factor affecting precipitation parameters in the other three regions.

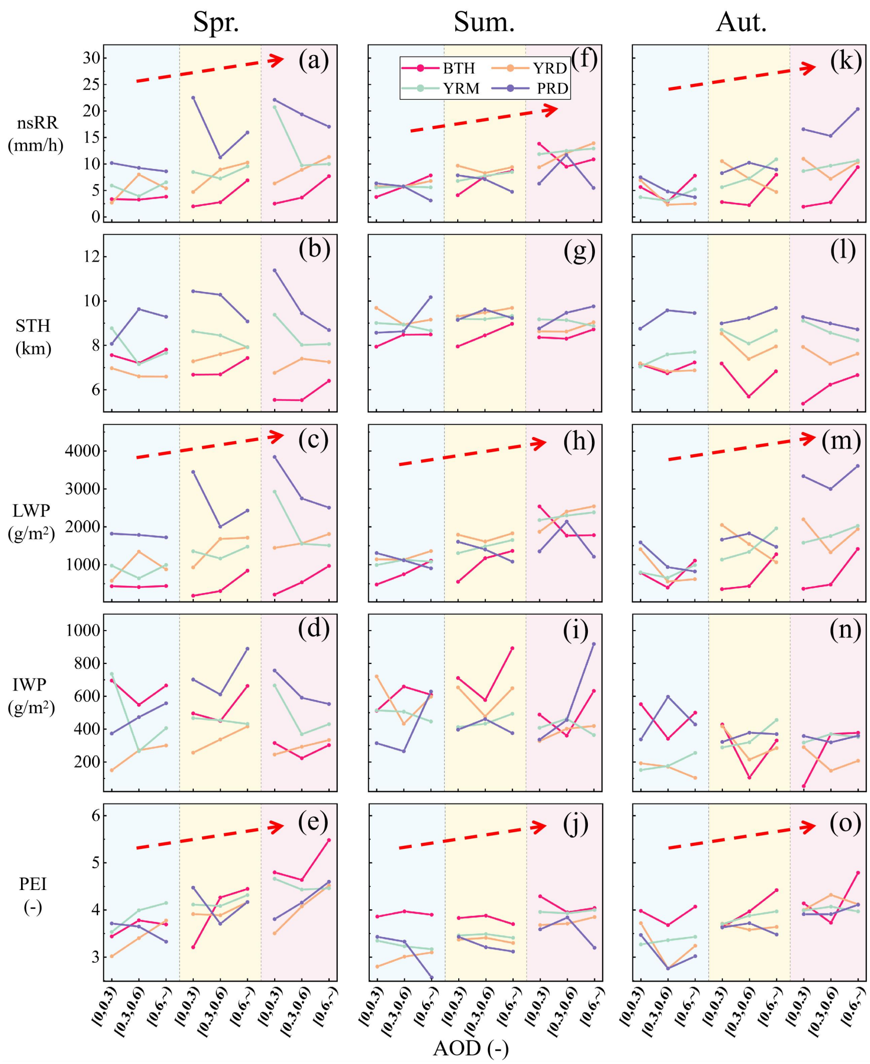

Fig. 6. Point-line graphs of mean values for convective precipitation parameters (nsRR, STH, LWP, IWP, and PEI) across seasons and regions. The analysis is based on three AOD intervals and various RH conditions. Each subpanel displays RH gradients from left to right: low RH (blue background), medium RH (yellow background), and high RH (red background). The red dashed arrow represents the

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overall variation trend of precipitation parameters with the increase of RH. Fig. S6 presents point-line plots illustrating mean precipitation parameters associated with stratiform precipitation. Increased RH consistently enhances these parameters, particularly nsRR, LWP, and PEI, in BTH, YRD, and YRM. However, the PRD exhibits differing parameter responses across seasons under varying relative humidity conditions, similar to convective precipitation, as aerosol loading rises.

In addition to the thermodynamic conditions, CAPE was selected as a dynamic factor. Similar to the RH, the precipitation parameter characteristics across regions were investigated under varying CAPE conditions. As indicated by the red dashed arrows in Fig. 7, increasing CAPE values provide favorable dynamic conditions for convective precipitation, leading to rising STH, increased IWP, and enhanced ice-phase processes.

Spring (Fig. 7a–e) shows that in the PRD, the characteristics of nsRR, LWP, and PEI under varying AOD loading remain consistent across different CAPE conditions. In contrast, the BTH, YRD, and YRM exhibit distinct variations in these parameters under different CAPE levels. Summer (Fig. 7f–j) reveals that aerosol effects in the BTH region demonstrate heightened sensitivity to CAPE variations. However, during autumn convective precipitation (Fig. 7k–o), aerosols across the four regions exhibit substantial sensitivity to CAPE, indicating different seasonal response mechanisms to atmospheric instability in these areas.

Fig. S7 presents point-line plots of the mean precipitation parameters for stratiform precipitation. Increasing CAPE enhances the STH and IWP parameters,

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which is consistent with the convective precipitation patterns in Fig. 6.

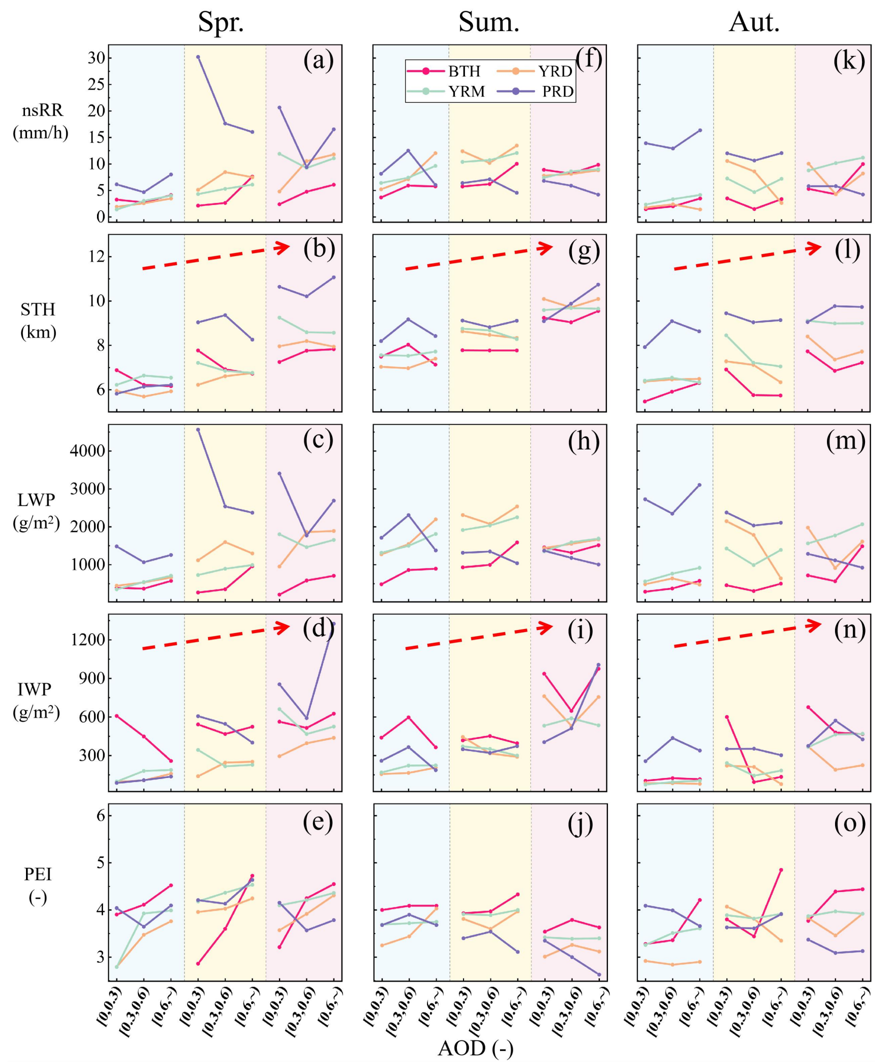

Fig. 7. Point-line graphs of mean values for convective precipitation parameters across seasons and regions. The analysis is based on three AOD intervals and varying CAPE scenarios. The form of this expression is similar to that shown in Fig. 6.

5.2 Sensitivity analysis of aerosols to meteorological factors in the vertical structure of precipitation

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Furthermore, to examine aerosol sensitivity to thermodynamic conditions and their effects on the vertical profiles of precipitation components, mean vertical profiles of precipitation parameters (Z_e, D_m, N_w, RR) at varying RH levels are illustrated, according to the technique shown in Fig. 4. Notably, as the parameter profile variations in Fig. 5 are concentrated within 0–10 km, the vertical coordinate range is limited to 0–10 km to emphasize the core precipitation processes. Moreover, where the curves intersect, dashed lines are employed to distinguish the selected profiles while maintaining the same representational integrity as the solid lines.

Spring convective precipitation (Fig. 8a–l) exhibits region-specific responses to RH, and in the BTH and YRD, increasing RH from low to medium ranges significantly elevates precipitation under high aerosol loading but suppresses it under medium loading (Fig. 8a). This discrepancy arises because abundant particles under elevated RH conditions undergo accelerated condensational growth, which increases D_m (Fig. 8f). In contrast, the YRM and PRD show that RH enhancement primarily boosts precipitation, under low aerosol loading (blue curves). This is because in the YRD and YRM, particle competition continues to dominate at high loading, whereas added moisture at low loading facilitates condensational growth and enhances N_w (Fig. 8g).

For the stratiform precipitation (Fig. 8m–x), the BTH, YRD, and YRM show consistent rightward shifts in RR curves across aerosol gradients as RH increases. This suggests that RH enhances moisture availability without modifying microphysical competition mechanisms. The PRD exhibits a response analogous to its

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convective precipitation feature.

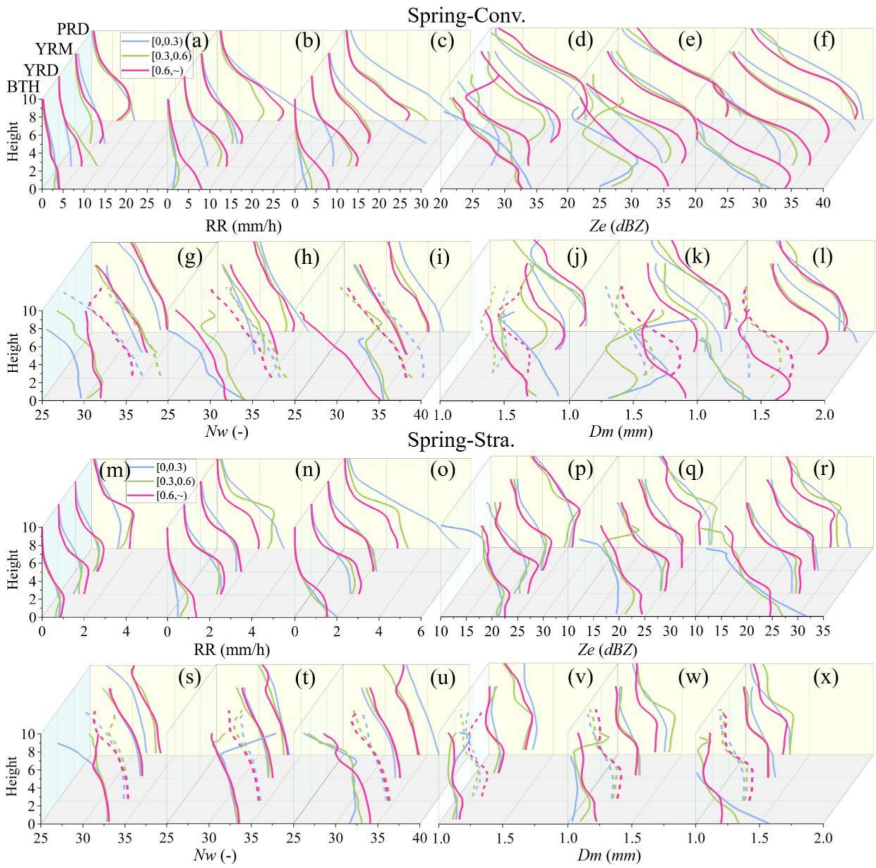

Fig. 8. Vertical profiles of mean precipitation parameters for convective (a–l) and stratiform (m–x) precipitation in spring across four regions. The profiles are shown under three AOD scenarios and RH conditions (arranged left to right as low, medium, high RH; e.g., panels a–c correspond to low, medium, high RH, respectively). To differentiate overlapping curves, selected profiles are plotted as dashed lines while retaining the same representational validity as solid lines.

Additionally, similar characteristics are observed in convective and stratiform precipitation during summer (Figs. S8) and autumn (Figs. S9) with variations in RH.

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In general, increasing RH provides moisture conditions, accelerates cloud particle condensational growth, and simultaneously increases both D_m and N_w, thereby enhancing precipitation. However, this process also depends on the content of CCN and various physical competition mechanisms.

Similarly, vertical profiles of precipitation parameters under varying CAPE conditions are presented. Fig. S10 illustrates consistent patterns between convective and stratiform precipitation during spring, echoing the fundamental characteristics in Fig. 8. This consistency suggests that RH and CAPE exert analogous influences on precipitation across aerosol loading gradients during spring.

Summer convective precipitation (Fig. S11a–l) reveals distinct regional responses. In the BTH region, CAPE elevation significantly enhances low-AOD precipitation, likely driven by improved dynamic forcing that promotes cloud development (red point line in Fig. S7g). In contrast, the PRD exhibits pronounced precipitation suppression, most evident under moderate aerosol loading, where heightened CAPE intensifies particle break-up processes (Fig. S13h). These findings indicate that RH and CAPE exert divergent influences across regions. For RH, increasing moisture availability promotes particle growth via condensation under suited particle concentrations, but the Twomey effect dominates under high AOD loading, where particle competition for cloud water prevails. CAPE provides favorable dynamic conditions for cloud development, but simultaneously intensifies particle break-up through dynamic forces, which hinders the constant growth of cloud droplets and suppresses precipitation.

5.3 Sensitivity analysis of aerosols to meteorological factors in precipitation microphysical processes

To validate the aforementioned inferences, the proportions of break-up and coalescence processes in convective and stratiform precipitation are further investigated. Fig. S13 reveals that in convective precipitation, an increase in RH generally correlates with enhanced coalescence (white-green bars in the upper half; the trend is shown by the blue arrows) and reduced break-up (white-green bars in the lower half). Conversely, increasing CAPE is associated with decreased coalescence (green line in the upper half) and intensified break-up (yellow line in the lower half; the trend is shown by the red arrows), particularly in summer and the PRD region. As illustrated in Fig. S14, stratiform precipitation demonstrates similarities to convective precipitation, and the increase in RH makes the enhancement of coalescence processes more universal.

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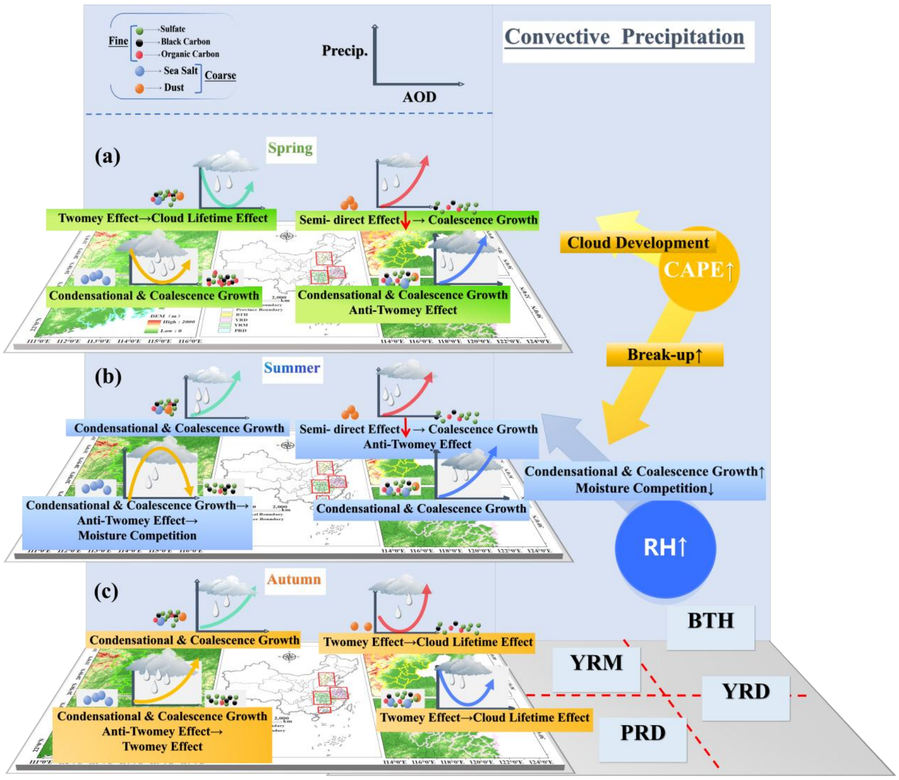

Fig. 9. Theoretical framework of aerosol impact on convective precipitation in the BTH, YRD, YRM, and PRD: (a) spring, (b) summer, and (c) autumn. Symbol conventions, ↑: Enhancement of process; ↓: Weakening of process; →: Transition from left-side process dominance to right-side process dominance; Right-side CAPE arrows: ↗ promotes precipitation; ↘ suppresses precipitation; Right-side RH arrows: ↗ enhances precipitation processes. Arrow length reflects the relative process intensity.

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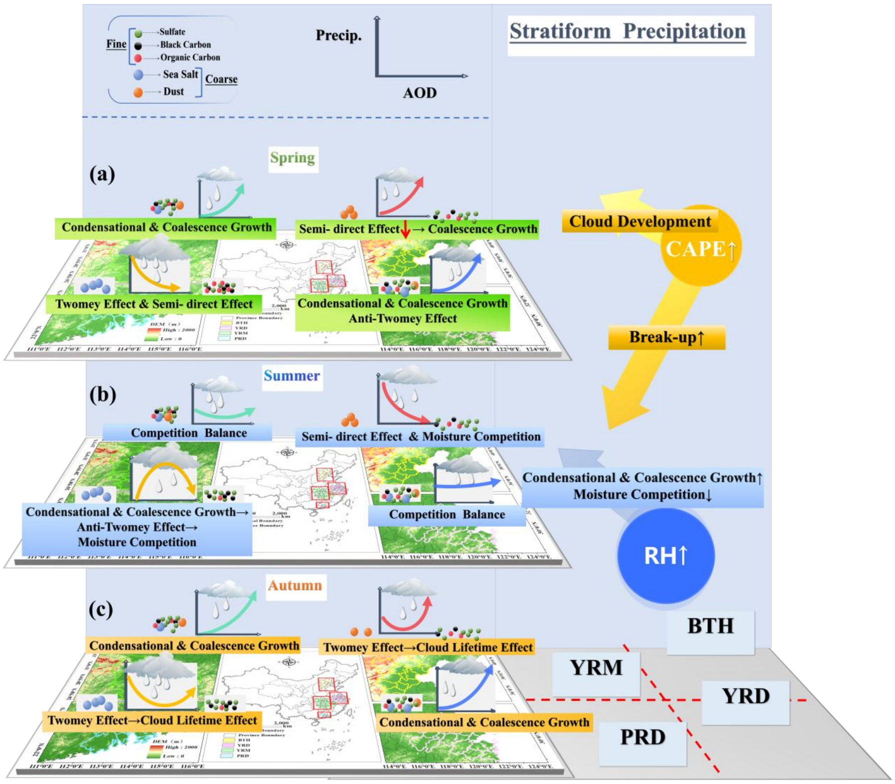

Fig. 10. Theoretical framework of aerosol impact on stratiform precipitation in the BTH, YRD, YRM, and PRD. The form of this expression is similar to that shown in Fig. 9.

6 Conclusion

This study systematically examined the impact of aerosols on precipitation parameters, vertical structures, and microphysical processes in convective and stratiform precipitation across China's four major urban clusters (the BTH, YRD, YRM, and PRD) — during spring, summer, and autumn, utilizing the DPR-MERRA-2-ERA5 dataset. It further explores aerosol sensitivity to RH and CAPE, revealing regional heterogeneity, seasonal dependency, and the underlying

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microphysical processes of aerosol effects. The research indicates that physical processes, including condensational growth, coalescence growth, semi-direct effects, and moisture competition effects from aerosol-sourced CCN, trigger the Twomey effect, Anti-Twomey effect, and cloud lifetime effect, resulting in varied precipitation alterations. Additionally, an increase in aerosol loading diminishes the regional disparities in precipitation characteristics, with a more pronounced effect during the spring and summer. The precipitation parameters exhibit greater regional variability than seasonal variability, and convective precipitation experiences more significant seasonal and regional changes compared to stratiform precipitation. Based on the findings in Section 3-5, the physical mechanisms by which aerosols at varying concentrations influence convective precipitation (Fig. 9) and stratiform precipitation (Fig. 10) are illustrated, with the following specific conclusions:

For convective precipitation (Fig. 9): Precipitation in the BTH region is influenced by seasonal variations in dust aerosols. During spring (Fig. 9a) and summer (Fig. 9b), dust aerosols exert significant impacts, whereas their contributions declines in autumn (Fig. 9c), resulting in distinct precipitation characteristics. Specifically, as the total aerosol concentration increases, the proportion of dust aerosols rapidly decrease. This reduction weakens the semi-direct effect of dust while enhancing the particle coalescence processes, thereby diminishing precipitation suppression. However, insufficient moisture supply and frequent dust events in spring collectively reduce the overall precipitation below the levels observed in the other three regions. In autumn, when the DUA constitutes a minor fraction, rising aerosol

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concentrations initially suppress precipitation through the Twomey effect, while simultaneously promoting cloud development, subsequently enhancing precipitation through increased CCN availability. The YRD exhibits a persistent precipitation increase with increasing aerosol concentrations owing to the ample moisture supply. While sharing similar seasonal trends with the BTH, its underlying mechanisms differ significantly: abundant water vapor enables continuous precipitation growth during spring (Fig. 9a) and summer (Fig. 9b), primarily attributable to enhanced droplet condensation and coalescence processes. The PRD exhibits the most pronounced seasonal variability, attributable to shifts in the composition of hygroscopic aerosols (SSA). During spring (Fig. 9a), precipitation in the PRD is significantly higher than in other regions under low aerosol loading due to SSAs. As aerosol concentrations increase, diminishing SSA proportion weakens this enhancement until rising hygroscopic organic carbon subsequently reinforces precipitation. In summer (Fig. 9b), sufficient moisture initially promotes droplet growth through condensation-coalescence under low aerosol levels. However, the subsequent aerosol accumulation intensifies moisture competition and suppresses precipitation. Monsoon-influenced sea-salt overabundance (Xiao et al., 2025) further amplifies this competition effect, resulting in overall lower precipitation rates compared to other regions.

For stratiform precipitation (Fig. 10): Overall, stratiform and convective precipitation share fundamental similarities yet exhibit distinct microphysical processes due to differing cloud formation conditions. With a lower moisture supply

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than convective systems, stratiform precipitation in the BTH region is suppressed during summer (Fig. 10b) through aerosol semi-direct effects and moisture competition. Similarly, in the PRD, spring precipitation is reduced by organic carbon aerosols (Fig. 10a), which act as both hygroscopic and light-absorbing particles (Zhuang et al., 2025). This occurs when an insufficient moisture supply enhances the radiation-absorbing effect, dominating the precipitation reduction mechanism.

Furthermore, variations in RH and CAPE modulate aerosol-precipitation interactions, as shown in Figs. 9–10. Specifically, elevated RH indicates enhanced moisture availability, which facilitates rapid droplet growth through condensation and coalescence under suitable aerosol loading. Regarding dynamic influences, increased CAPE provides favorable conditions for cloud development while simultaneously enhancing droplet break-up through intensified turbulence, hindering cloud droplet growth, and suppressing precipitation, particularly in summer and the PRD region.

Overall, aerosol impacts on precipitation result from complex couplings among regional aerosol composition, moisture transport patterns, atmospheric stability, and precipitation types, generating both linear and nonlinear responses. These complex dynamics establish essential theoretical underpinnings for formulating atmospheric cleanup techniques in significant metropolitan centers, enhancing early warning systems for extreme precipitation occurrences, and refining regional climate models.

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7 Discussion

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 structures and microphysical processes across multiple regions and seasons in China. This extended scope has led to the following new 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. Nevertheless, it is important to acknowledge that considerable uncertainties persist in satellite data processing and retrieval algorithms, especially under complex atmospheric and surface conditions. Additionally, spatiotemporal resolution and format discrepancies across multisource data introduce unavoidable uncertainties. This study primarily focuses on the vertical structural characteristics of precipitation, whereas the analysis of aerosol data lacks comprehensive three-dimensional matching. Currently, vertical profiling of aerosols relies primarily on aircraft sounding (Zhou et al., 2023) and simulated radar signals (Fajardo-Zambrano et al., 2022), which remain spatially limited. Satellite remote sensing is hindered by inadequate resolution and deficiency in three-dimensional information (Li et al., 2022). However, the successful

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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). Future collaborative observations from the GPM and EarthCARE will produce enhanced datasets on clouds, precipitation, and aerosols, thus facilitating more robust in-depth studies within this research framework. Subsequent research should integrate supplementary meteorological variables and machine-learning methodologies to more effectively delineate aerosol effects and examine their responsiveness to meteorological influences. Notably, as Zhao et al.(2025) revealed distinct aerosol-cloud interaction patterns over land versus ocean in the YRD, the absence of cloud parameter products in this study may inherently limit the depth of the aerosol-precipitation mechanism analysis. This methodological constraint thus necessitates the future integration of high-resolution cloud parameter datasets to refine research findings, enabling a comprehensive exploration of aerosol-cloud-precipitation coupling mechanisms, specifically encompassing dry and wet aerosol removal processes and precipitation feedback loops.

Data availability

The V07A GPM 2ADPR products used in this paper are openly available at the NASA Goddard Space Flight Center's Precipitation Processing System (PPS) team (https://storm.pps.eosdis.nasa.gov/ storm/).

Author contributions

H P & Z L: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation. X H: Writing – original draft, Validation,

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Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. W A: Writing – review & editing, Project administration. S H & J Q: Writing – review & editing, Investigation. X Z: Writing – review & editing, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Zhen Li and Heyuan Peng contributed equally to this work and should be considered as co-first authors. The authors thank the anonymous reviewers for their constructive comments and suggestions, which have greatly improved the quality of this paper.

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