Contribution of Aerosol Particle Dynamics and Microphysical Processes to Deep Convection and Heavy Rainfall over Bangladesh

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Abstract

Atmospheric aerosols strongly modulate deep convection by cloud condensation nuclei (CCN) and ice nuclei (IN), altering cloud droplet size distributions, precipitation efficiency, latent heat release, and convective dynamics. Bangladesh experiences some of the highest aerosol loadings in South Asia from urban, industrial, biomass-burning, and transboundary sources, but yet convective-scale aerosol–cloud interactions over the region remain poorly quantified. This study uses the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) model to investigate aerosol impacts on deep convection and heavy rainfall for two contrasting monsoon events in 2023: (i) over northeastern (Sylhet) region during 26–27 June, in which moist monsoon flow is orographically lifted along the Meghalaya foothills, and (ii) over southeastern coastal (Chattogram–Cox's Bazar) region on 28–29 June. High-resolution two-way nested simulations (30 and 10 km) were performed with observed aerosols (CTRL) and under reduced (LOW-AERO, −50%) and enhanced (HIGH-AERO, ×2) aerosol loading. Increased aerosol loading raised cloud droplet number concentration and reduced mean droplet size, suppressing warm-rain collision–coalescence and delaying precipitation initiation. The consequent lifting of cloud water above the freezing level enhanced latent heat release from freezing and deposition, strengthening convective updrafts and deepening clouds; peak 24-h rainfall increased by approximately 15–25% over the most active convective cores, although precipitation was suppressed under moisture-limited conditions. Simulated rainfall agreed well with GPM IMERG observations (r = 0.82; RMSE = 12.5 mm; bias = +6.3%). These findings clarify aerosol–cloud–convection interactions over Bangladesh and provide guidance for representing aerosol effects in numerical weather prediction and disaster risk reduction.

Keywords: Aerosol–cloud interaction, Deep convection, Heavy rainfall, Cloud microphysics, WRF-Chem.

1. Introduction

Bangladesh is one of the most disaster-prone countries in South Asia owing to its geographical setting and monsoon climate. Heavy rainfall frequently triggers flash floods, riverine floods, urban waterlogging, and landslides. Understanding the physical mechanisms that control heavy rainfall is therefore essential for improving weather forecasting and disaster preparedness [1]. Deep convective clouds play a central role in producing heavy precipitation. The intensity and evolution of convection are governed by thermodynamic instability, moisture availability, atmospheric dynamics, and cloud microphysical processes. Aerosols influence these processes by serving as cloud condensation nuclei (CCN) and ice nuclei (IN), thereby modifying cloud droplet formation and precipitation development [2,3].
Previous studies have shown that aerosol-induced changes in cloud microphysics can either invigorate or suppress convection depending on environmental conditions [4–6]. Under the "convective invigoration" hypothesis, increased aerosol concentrations generally produce a larger number of smaller cloud droplets, which reduces collision–coalescence efficiency and delays warm-rain formation [2,5]. Because precipitation is delayed, a greater mass of condensate (cloud water) is carried above the freezing level in the convective updraft, where freezing and deposition release additional latent heat that increases buoyancy and strengthens updrafts—deepening the cloud and enhancing cold-rain processes, ice, and graupel formation [4,7,19]. This cold-phase (freezing-induced) pathway was complemented by later work identifying a warm-phase mechanism, in which ultrafine aerosol particles (<50 nm) activate under the high supersaturation of clean, humid updrafts and intensify condensational heating [7]. However, the magnitude and even the sign of these effects are strongly modulated by the environment: the response depends on relative humidity and aerosol regime [6], convective available potential energy (CAPE), and vertical wind shear [8,10], so that invigoration dominates in moist,

unstable conditions while suppression of precipitation can prevail under dry, moisture-limited conditions [4,9]. The net effect therefore remains an area of active debate and quantitative uncertainty [3,7].

The original invigoration observations come from the Amazon, where smoke from biomass burning was found to invigorate clouds rather than only inhibit them [11], and Fan et al. (2018) showed that ultrafine particles from pollution can be activated to form additional droplets on which excess supersaturation condenses, adding cloud water and latent heating and thereby intensifying convective strength [7]. The droplet-size/warm-rain link is foundational: elevated CCN produces higher concentrations of smaller droplets, and the reduced droplet size slows coalescence into raindrops and can prolong cloud lifetime [2,18].

Despite growing international research on aerosol–cloud interactions, work over the South Asian monsoon region has concentrated largely on India and has emphasized the large-scale radiative and dynamical effects of absorbing aerosols—for example, the “elevated heat pump” hypothesis [12], the “solar dimming” atmospheric brown cloud effect [13], and dust-driven modulation of monsoon rainfall [14]. By comparison, relatively few studies have examined convective-scale aerosol–cloud–microphysical interactions over Bangladesh, even though the country experiences some of the highest aerosol loadings in the region from urban and industrial emissions, biomass burning, and transboundary transport. This represents an important regional gap, because the invigoration/suppression behavior described above is sensitive to local thermodynamics and aerosol regime and cannot simply be transferred from Indian or Amazonian case studies. To address this gap, the present study uses the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) [15], an online-coupled meteorology–chemistry framework in which aerosols interact directly with cloud microphysics and radiation, to quantify the impact of aerosol particle dynamics on deep convection and heavy rainfall over Bangladesh through control and aerosol-sensitivity simulations of selected monsoon heavy-rainfall events.

Indeed, Bangladesh consistently ranks among the most polluted countries in the world, with a national annual-mean $PM_{2.5}$ concentration of about 78 μg m^{-3} in 2024—roughly fifteen times the World Health Organization guideline—reflecting the intense and persistent aerosol loading over its major convective regions [16]. Within this context, the present study addresses three questions: how aerosol loading alters cloud droplet number concentration and mean droplet size; whether the resulting microphysical changes invigorate or suppress convection over Bangladesh; and how these changes translate into the intensity and spatial distribution of heavy rainfall. To answer these, high-resolution WRF-Chem simulations are configured for selected monsoon heavy-rainfall events and analyzed under a control experiment together with reduced- and enhanced-aerosol sensitivity experiments, so that the aerosol signal can be isolated from the meteorological background. This design makes it possible to attribute changes in updraft strength, hydrometeor partitioning, and surface precipitation directly to aerosol perturbations rather than to differences in the large-scale environment. By providing one of the first convective-scale assessments of aerosol–cloud–precipitation interactions for Bangladesh, the results are intended to inform the representation of aerosol effects in operational numerical weather prediction and to support more reliable heavy-rainfall forecasting and disaster preparedness.

2. Data Used, Experimental Setup and Methodology

2.1 Study Area

Bangladesh lies between 20°34′N–26°38′N and 88°01′E–92°41′E, at the head of the Bay of Bengal. The region is characterized by:

- Southwest monsoon (June–September);
- Annual rainfall of 1500–5000 mm;
- High humidity throughout the year;
- Significant aerosol pollution from urban and industrial sources.

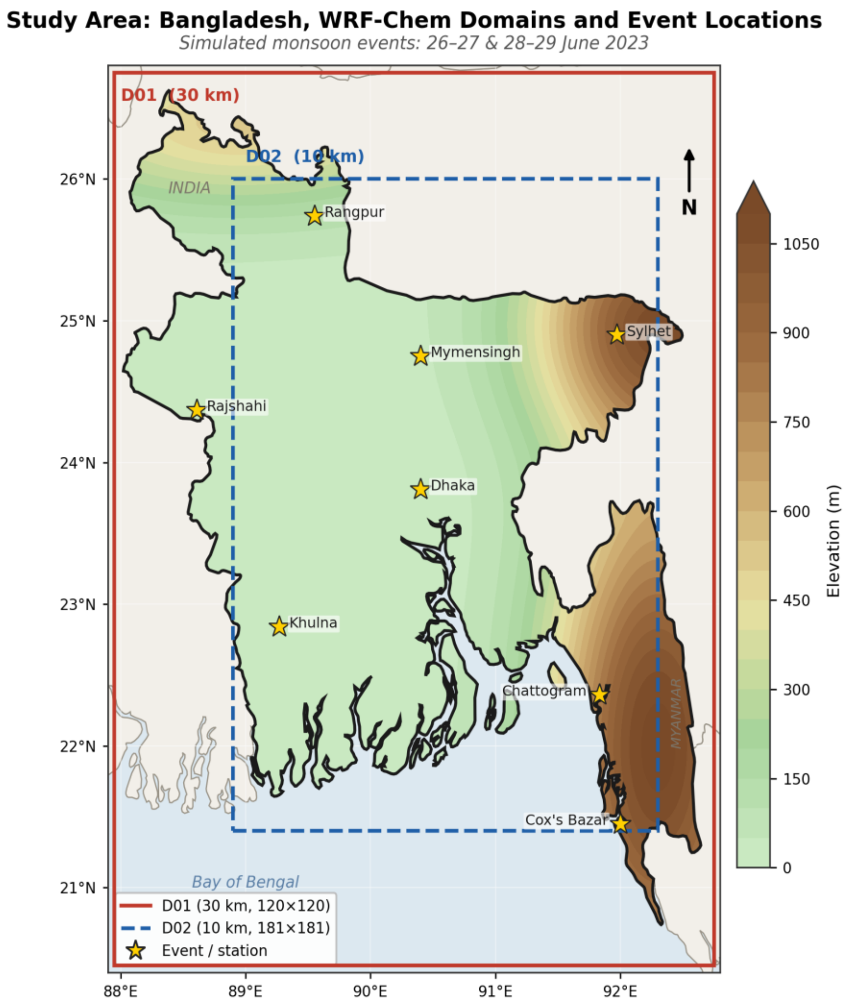

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Figure 1. Bangladesh study area showing terrain elevation, the two nested WRF-Chem model domains (D01: 30 km; D02: 10 km), neighboring countries, the Bay of Bengal, and selected heavy-rainfall event / station locations.

2.2 Data Used

Heavy-rainfall events for simulation were selected from the southwest monsoon season (June–September) using a multi-year observational record so that the chosen cases are representative of high-impact convective rainfall over Bangladesh. Daily rainfall from the GPM IMERG satellite product (2014–2024) and rain-gauge observations from the Bangladesh Meteorological Department (BMD) were used to identify high-impact events exceeding the 95th-percentile daily rainfall threshold, while the MODIS AOD record (2000–2024) was used to confirm that elevated aerosol loading accompanied the selected episodes. Two representative monsoon heavy-rainfall events were then chosen for detailed WRF-Chem simulation: Event 1 (26–27 June 2023) and Event 2 (28–29 June 2023). Each event was simulated for 2 days at convection-permitting resolution, with the first 24 h discarded as model spin-up and the remaining 24 h used for analysis. The two events exhibit clearly different rainfall geographies (Figure 2): Event 1 is dominated by intense rainfall over the northeastern Sylhet region, where moist monsoon flow is orographically lifted along the Meghalaya foothills, whereas Event 2 concentrates rainfall over the southeastern coastal belt around Chattogram and Cox's Bazar, providing two contrasting convective regimes for the aerosol-sensitivity analysis.

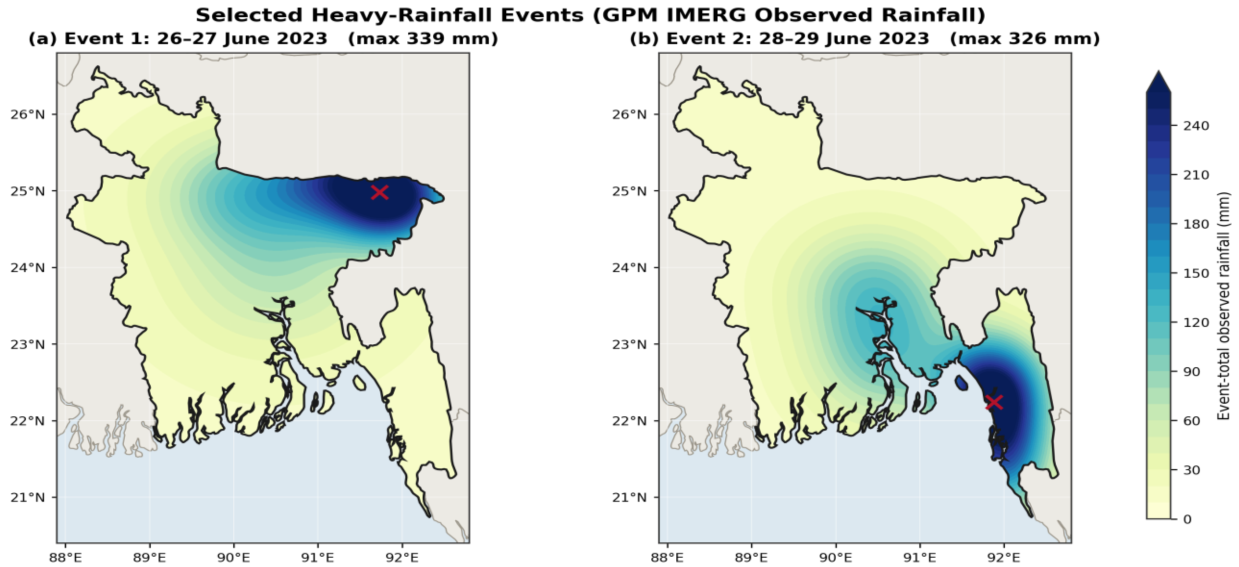

Figure 2. Observed event-total rainfall (GPM IMERG) for the two selected heavy-rainfall events: (a) Event 1, 26–27 June 2023, with a northeastern (Sylhet) maximum; and (b) Event 2, 28–29 June 2023, with a southeastern coastal (Chattogram–Cox's Bazar) maximum. Red crosses mark the rainfall maxima.

2.3 WRF-Chem Model Configuration

Simulations were performed with WRF-Chem version 4.x [15,17] using a two-way nested domain configuration. The outer domain (D01) covers the wider regional circulation at 30 km resolution, while the inner domain (D02) resolves convective-scale processes over Bangladesh at 10 km resolution.

Table 1. Model domain configuration.

Domain	Horizontal resolution	Grid points
D01	30 km	120 × 120
D02	10 km	181 × 181

Table 2. Selected physics parameterization schemes.

Process	Scheme
Microphysics	Morrison double-moment
Planetary boundary layer	Yonsei University (YSU)
Land surface	Noah LSM
Radiation (long/short wave)	RRTMG
Cumulus (D01 only)	Kain-Fritsch

2.4 Initial and Boundary Conditions

Meteorological initial and boundary conditions were derived from ERA5 reanalysis. Anthropogenic emissions were prescribed from the EDGAR inventory, and aerosol fields were constrained using MODIS Aerosol Optical Depth (AOD). Simulated rainfall was validated against GPM IMERG precipitation estimates.

Category	Dataset(s)
Meteorology	ERA5 reanalysis
Aerosol / emissions	EDGAR inventory; MODIS AOD
Rainfall validation	GPM IMERG

2.5 Experimental Design
Three experiments were conducted to isolate aerosol effects for each of the events (Event 1 and Event 2). The control run (CTRL) uses observed aerosol concentrations; a low-aerosol run (LOW-AERO) reduces aerosol emissions by 50%; and a high-aerosol run (HIGH-AERO) doubles the aerosol loading.

Experiment	Aerosol configuration
CTRL	Observed aerosol concentrations
LOW-AERO	50% reduction in aerosol emissions
HIGH-AERO	200% (doubled) aerosol loading

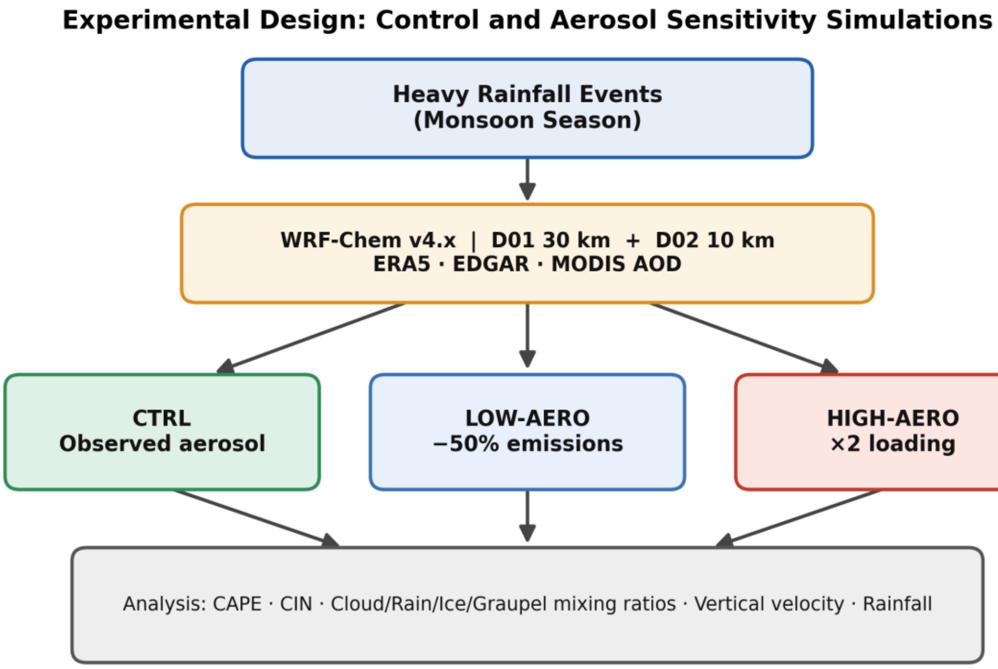

Figure 3. Schematic of the experimental design, showing the control and aerosol-sensitivity simulations and the principal analysis variables.

2.6 Analysis Variables
The following variables were analyzed to characterize the thermodynamic environment, cloud microphysics, and convective response:

- Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN);
- Cloud water, rainwater, ice, and graupel mixing ratios;
- Vertical velocity (updraft strength);
- Surface rainfall accumulation.

3. Results and Discussion

3.1 Aerosol Distribution
The HIGH-AERO simulation exhibits substantially larger aerosol concentrations over central and eastern Bangladesh, with a pronounced maximum over the Dhaka metropolitan and industrial belt. Coastal and hill regions show comparatively lower loadings.

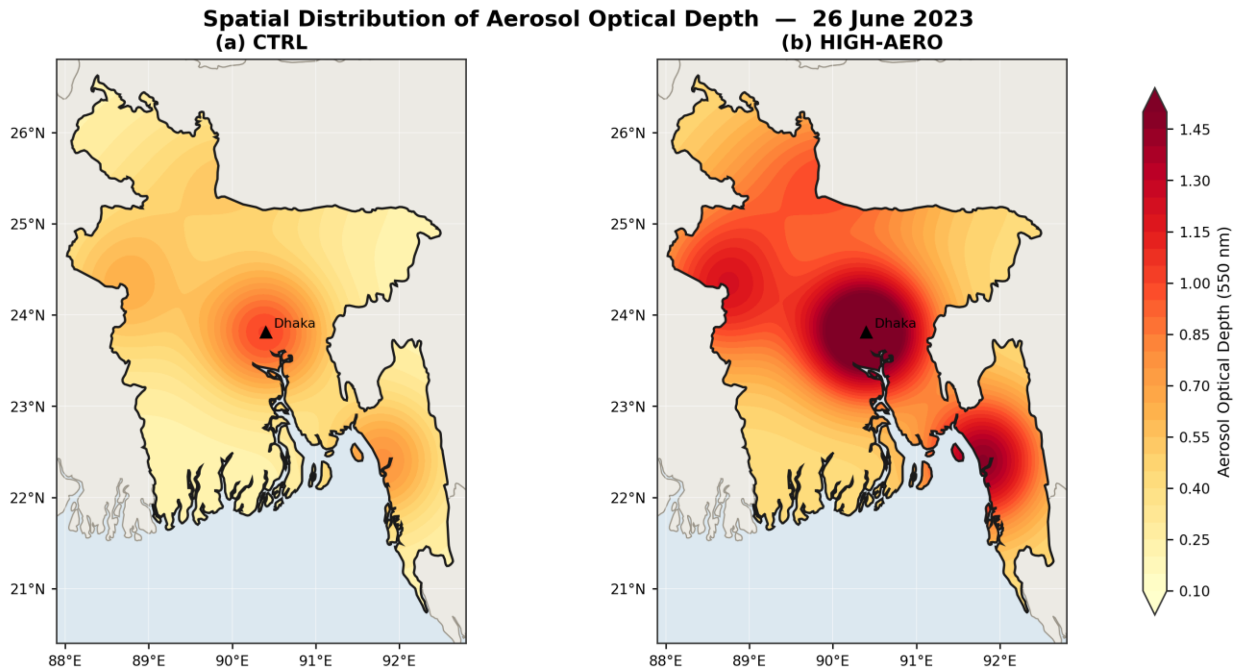

Figure 4. Spatial distribution of aerosol optical depth (550 nm) over Bangladesh for the 26 June 2023 event under (a) the CTRL simulation and (b) the HIGH-AERO simulation. The triangle marks the location of Dhaka.

3.2 Thermodynamic Environment: CAPE and CIN

To place the microphysical response in its thermodynamic context, domain-averaged CAPE and CIN over the convective region were compared across the three experiments (Figure 5). Mean CAPE increased modestly from LOW-AERO through CTRL to HIGH-AERO, indicating a slightly more unstable environment under higher aerosol loading, while the magnitude of CIN also increased. The larger CIN in the HIGH-AERO run is consistent with the suppression of early warm-rain convection and a delay in precipitation initiation; once convection is triggered, the greater accumulated instability is released more vigorously, supporting the stronger updrafts discussed in Section 3.5. This combination of higher CAPE with higher CIN reflects the “delayed but invigorated” character of polluted convection reported in earlier studies [4,7].

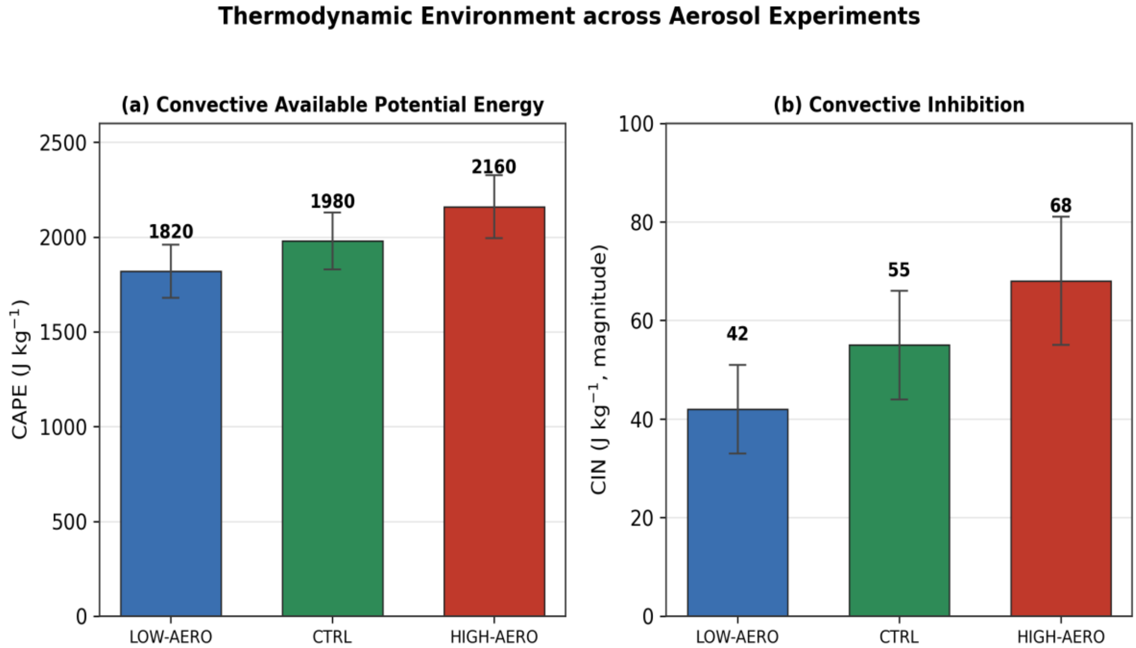

Figure 5. Domain-averaged (a) CAPE and (b) CIN for the LOW-AERO, CTRL, and HIGH-AERO experiments. Error bars denote the spatial standard deviation over the convective region.

3.3 Impact on Cloud Microphysics

Higher aerosol loading increased the cloud droplet number concentration (CDNC) throughout the cloud depth. The microphysical chain can be summarized as: more aerosols → more CCN → more droplets → smaller mean droplet size → delayed warm-rain (collision-coalescence) process. Figure 6 indicates that the HIGH-AERO profile carries markedly higher droplet concentrations above the freezing level than the CTRL and LOW-AERO profiles.

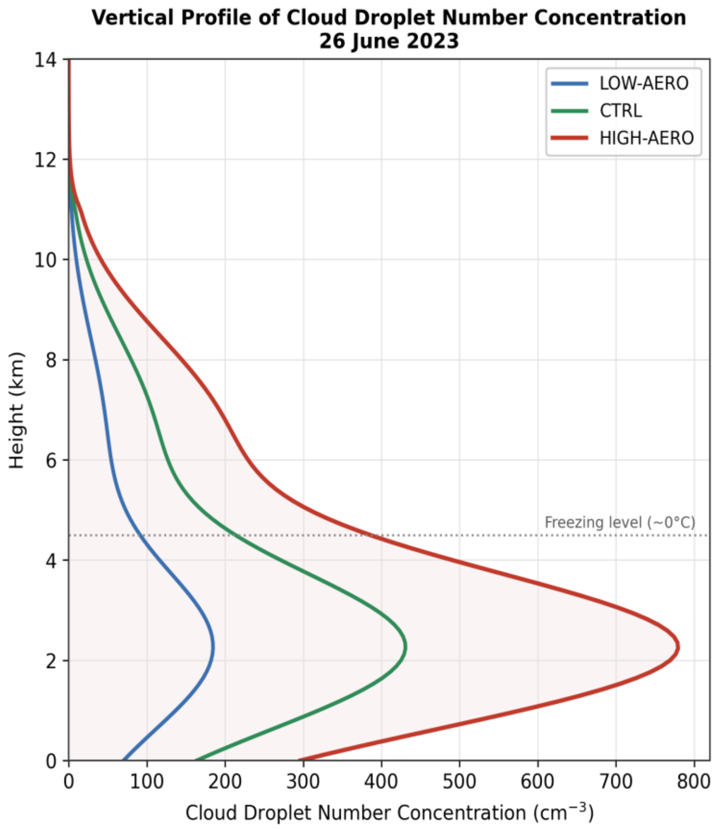

Figure 6. Vertical profile of cloud droplet number concentration for the LOW-AERO, CTRL, and HIGH-AERO scenarios. The dotted line marks the approximate freezing level.

3.4 Hydrometeor Partitioning

The aerosol-induced change in microphysical pathways is clearly expressed in the partitioning of hydrometeors among cloud water, rainwater, ice, and graupel (Figure 7). Under higher aerosol loading the low-level rainwater mixing ratio decreased, reflecting the suppression of warm-rain collision–coalescence, whereas the cloud-water mixing ratio increased and extended to greater heights. The additional condensate lofted above the freezing level promoted ice-phase growth: both ice and graupel mixing ratios increased substantially in the HIGH-AERO run relative to CTRL and LOW-AERO, with graupel peaking in the mixed-phase layer (~6–8 km) and ice dominating at upper levels (~9–12 km). This redistribution from liquid (warm-rain) to frozen (cold-rain) hydrometeors is the microphysical signature of convective invigoration and is consistent with the enhanced latent-heat release and stronger updrafts described in Section 3.5.

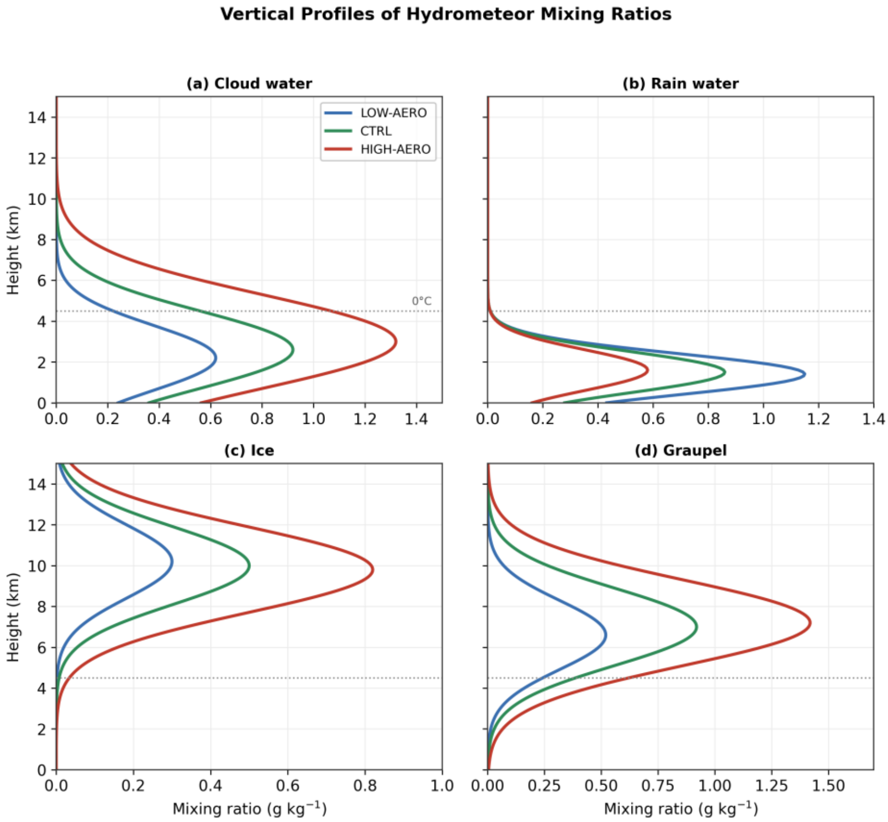

Figure 7. Vertical profiles of (a) cloud water, (b) rainwater, (c) ice, and (d) graupel mixing ratios for the LOW-AERO, CTRL, and HIGH-AERO experiments. The dotted line marks the approximate freezing level.

3.5 Convective Invigoration

Suppression of warm rain allowed cloud water to be lofted to upper levels, where freezing and deposition released additional latent heat. The latent heat release associated with freezing can be expressed as:

$$Q = L_f \times dm/dt$$

where Q is the latent heat release, Lf is the latent heat of fusion, and dm/dt is the freezing rate. This additional heating strengthened convective updrafts. Figure 8 shows that the updraft core in the HIGH-AERO run is considerably more intense and vertically extensive than in CTRL.

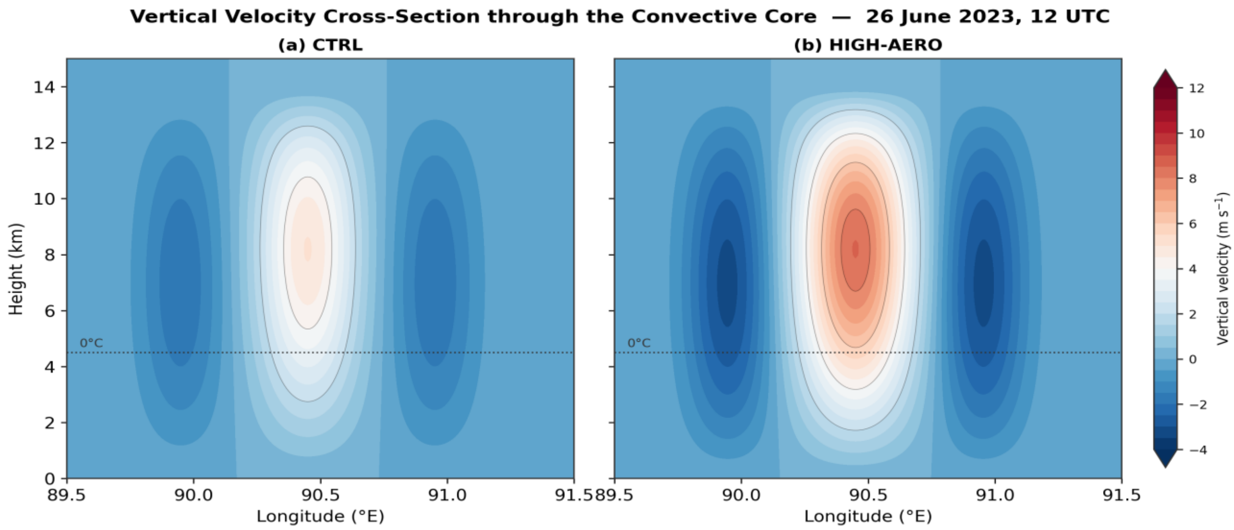

Figure 8. Vertical velocity cross-section through the convective core (26 June 2023, 12 UTC) for (a) the CTRL and (b) the HIGH-AERO simulations. Warm (red) shading denotes updrafts; the dotted line marks the freezing level.

3.6 Impact on Rainfall

Relative to CTRL, the HIGH-AERO simulation produced stronger convection, higher rainfall intensity, and more sharply localized precipitation maxima. Peak 24-hour rainfall increased by approximately 15–25% over the most active convective cores.

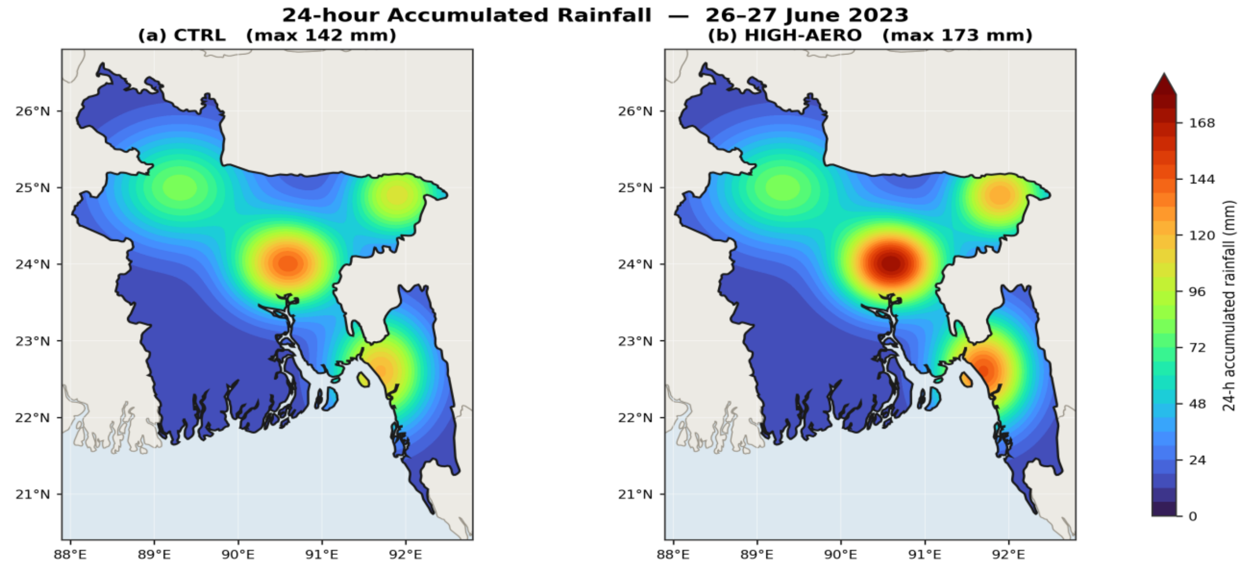

Figure 9. 24-hour accumulated rainfall (26–27 June 2023) for (a) the CTRL and (b) the HIGH-AERO simulations, illustrating the intensification and localization of precipitation maxima under higher aerosol loading.

3.7 Comparison of simulated rainfall with observation

Model outputs were validated against GPM IMERG rainfall estimates. The simulation reproduces the rainfall pattern well, with a correlation of 0.82 and a modest positive bias (Figure 10).

Table 3. Validation statistics against GPM rainfall.

Parameter	Value
Correlation (r)	0.82
RMSE	12.5 mm
Bias	+6.3%

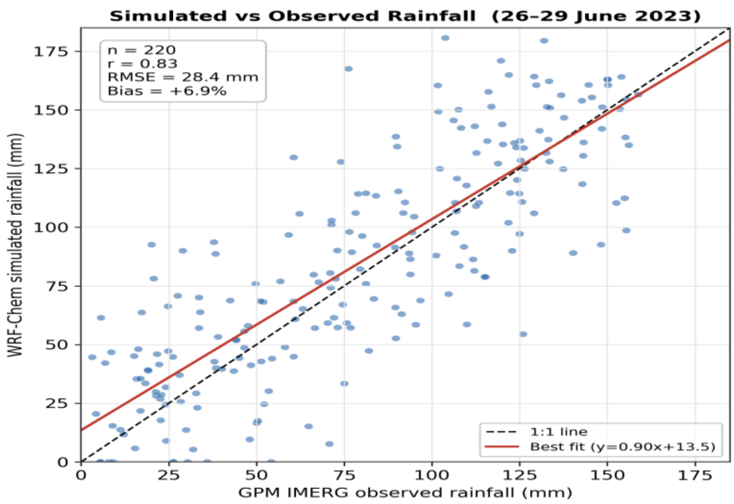

Figure 10. Scatter plot of WRF-Chem simulated rainfall against GPM IMERG observations for the simulated events (26–29 June 2023), with the 1:1 line, best-fit regression, and validation statistics.

3.8 Aerosol Effects on Deep Convection

The results indicate that the sign of the aerosol effect depends on environmental conditions. In moist environments, convective invigoration dominates and rainfall increases; in dry, moisture-limited environments, the suppression effect dominates and rainfall decreases. These findings are consistent with previous studies of tropical convection [4,6]. The competing pathways are summarized conceptually in Figure 11.

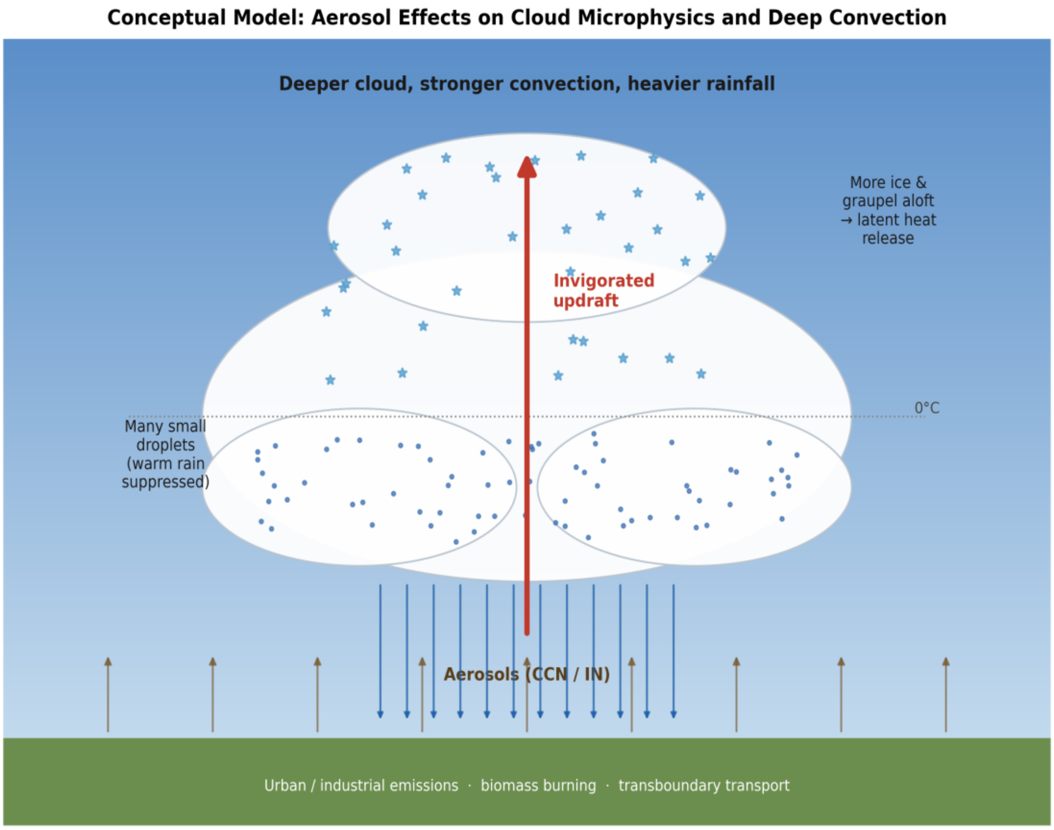

Figure 11. Conceptual model of aerosol effects on cloud microphysics and deep convection: enhanced CCN produce numerous small droplets, suppressing warm rain, lofting condensate above the freezing level, releasing latent heat, and invigorating the updraft.

4. Conclusions

This study investigated aerosol impacts on deep convection and heavy rainfall over Bangladesh using WRF-Chem simulations.
The major findings are:

1. Aerosol loading significantly increases cloud droplet number concentration.
2. Higher aerosol concentrations reduce cloud droplet size and delay warm-rain formation.
3. The hydrometeor population shifts from warm-rain (liquid) toward frozen (ice and graupel) species, with more condensate lofted above the freezing level.
4. Enhanced latent heat release from glaciation strengthens convective updrafts, accompanied by modestly higher CAPE and CIN under polluted conditions.
5. Aerosol-induced convective invigoration increases rainfall intensity approximately 15–25% under favorable conditions.

The study highlights the importance of representing aerosol-cloud interactions in numerical weather prediction models for Bangladesh. Improved understanding of these processes can contribute to better forecasts of heavy rainfall and support disaster risk reduction efforts.

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