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RESEARCH ARTICLE

Atmospheric Aerosol Effects on Regional Precipitation Patterns in Industrialized Regions

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ABSTRACT

Anthropogenic aerosol emissions from industry, transportation and residential combustion remain one of the largest sources of uncertainty in regional precipitation projections, because aerosols alter cloud microphysics through competing pathways that can either suppress or invigorate rainfall depending on cloud type, background humidity and pollution loading. We analysed eighteen years (2005–2022) of co-located satellite aerosol optical depth (AOD) retrievals, cloud microphysical products and surface precipitation gauge records across three heavily industrialized East Asian basins, the North China Plain, the Sichuan Basin and the Yangtze River Delta, together with a matched set of five downwind rural reference sites, to quantify how aerosol loading reshapes the frequency and intensity distribution of regional precipitation. Warm-season shallow and moderately deep convective clouds sampled under the highest AOD quintile (AOD greater than 0.80 at 550 nm) showed a 31% reduction in light-rain frequency (below 5 mm per day) relative to the lowest quintile, alongside a 14% increase in cloud droplet number concentration and a 2.3 micrometre decrease in cloud-top effective radius, consistent with classical Twomey-type suppression of warm-rain formation. In contrast, deep convective systems embedded in the same polluted environments exhibited a 19% increase in the frequency of heavy-rain days (above 50 mm per day) and a systematic upward shift in radar-estimated echo-top height of 850 m on average, indicating aerosol-driven invigoration through enhanced latent heat release from delayed freezing of supercooled droplets. The two effects did not offset one another spatially: suppression dominated the immediate urban and peri-urban core, while invigoration and downwind rainfall enhancement were concentrated 40–120 km further along the prevailing summer monsoon flow, producing a measurable redistribution of the seasonal rainfall total rather than a simple net increase or decrease. Trend analysis over the study period showed a 12% decline in regional AOD following the tightening of national air-quality standards after 2013, accompanied by a partial reconvergence of light-rain frequency toward rural reference levels, though heavy-rain frequency remained elevated. These results indicate that aerosol-precipitation interactions in industrialized regions operate as a spatially structured redistribution of rainfall rather than a uniform suppression or enhancement, with direct implications for water resource planning and flood risk assessment downwind of major pollution sources.

Keywords: aerosol-cloud interaction; precipitation suppression; convective invigoration; aerosol optical depth; cloud microphysics; East Asia haze; anthropogenic pollution; regional climate

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1. INTRODUCTION

Aerosol particles emitted by industry, vehicle traffic, power generation and residential combustion modify cloud properties by serving as cloud condensation nuclei, altering the number and size distribution of droplets that form within a given parcel of rising air [1,2]. This microphysical perturbation propagates through the cloud system in ways that depend strongly on cloud depth, background thermodynamic stability and the magnitude of the aerosol loading itself, so that the same emission source can suppress precipitation from one cloud type while enhancing it from another within the same regional airmass [3,4].

In shallow and moderately deep warm clouds, added aerosol loading increases droplet number while decreasing mean droplet size for a fixed liquid water content, narrowing the droplet size distribution and delaying the collision-coalescence process that produces raindrops large enough to fall as precipitation [5,6]. This suppression pathway, first described conceptually by Twomey for cloud albedo and later extended to precipitation efficiency by Albrecht, has been repeatedly observed in satellite and in-situ studies of polluted versus clean cloud fields, with the clearest signal in light and moderate rainfall from shallow convective and stratiform clouds [2,7,8]. In deep convective clouds, however, the same reduction in droplet size can delay freezing to greater heights, releasing additional latent heat of fusion higher in the cloud and invigorating updrafts, a pathway that has been linked to increased frequency of heavy rainfall, taller convective towers and more frequent lightning in polluted continental airmasses [9,10,11].

East Asia offers a particularly instructive setting for examining both pathways simultaneously, because rapid industrialization since the 1980s produced some of the highest sustained aerosol optical depths observed anywhere on the planet, concentrated in basins, the North China Plain, the Sichuan Basin and the Yangtze River Delta, that also sit directly beneath the East Asian summer monsoon rainbelt [12,13]. Observational studies in this region have reported both pollution-related suppression of light and drizzle-type rainfall near urban cores and pollution-related enhancement of heavy rainfall and flood-producing convection further downwind, sometimes within the same field campaign, suggesting that the two mechanisms operate concurrently but express themselves at different distances from the emission source and in different cloud regimes [14,15,16].

Since 2013, China's Air Pollution Prevention and Control Action Plan and subsequent regional measures have driven substantial reductions in fine particulate matter and aerosol optical depth across the three basins studied here, providing a natural, if imperfect, experiment for testing whether the precipitation signatures attributed to aerosol loading track the underlying emissions trend [17,18]. Whether light-rain suppression and heavy-rain

invigoration respond symmetrically to this emissions decline, or whether one pathway proves more reversible than the other, has direct bearing on water resource and flood-risk projections for a region supporting several hundred million people, yet has not been assessed using a consistent multi-decadal, multi-basin observational record.

Here we combine eighteen years of satellite aerosol and cloud microphysical retrievals with dense surface precipitation gauge records across the three basins and a set of downwind rural reference sites to quantify how aerosol loading reshapes the frequency and intensity distribution of warm-season precipitation, to characterize the spatial separation between suppression- and invigoration-dominated zones relative to the pollution source, and to test how both signatures have evolved as regional aerosol loading has declined following the post-2013 emissions controls.

2. MATERIALS AND METHODS

We combined satellite-retrieved aerosol optical depth and cloud microphysical properties with surface precipitation gauge records across three industrialized East Asian basins and five downwind rural reference sites for 2005-2022, and used pollution-level compositing, spatial distance-from-source binning and trend decomposition to characterize aerosol effects on precipitation frequency and intensity.

2.1 Study domains and reference sites

Three industrialized basins were selected for analysis: the North China Plain (centred near 38.0N, 116.5E), the Sichuan Basin (30.5N, 104.5E) and the Yangtze River Delta (31.5N, 120.5E), each a major population and heavy-industry centre lying beneath the East Asian summer monsoon rainbelt. For each basin, a 250 km by 250 km analysis domain was defined, and five downwind rural reference sites, selected to lie 60-150 km along the prevailing warm-season wind direction from the nearest major urban-industrial core and outside any comparably sized urban influence, were used to characterize baseline cloud and precipitation behaviour under lower aerosol loading.

2.2 Aerosol and cloud microphysical retrievals

Daily aerosol optical depth at 550 nm was obtained from the MODIS Dark Target and Deep Blue combined product at 10 km resolution for the full 2005-2022 period, averaged over each analysis domain on days with valid retrieval coverage exceeding 60% of domain pixels. Cloud droplet effective radius, cloud droplet number concentration and cloud-top temperature were obtained from the co-located MODIS cloud product, restricted to liquid-topped or mixed-phase clouds with optical depth greater than 4 to ensure retrieval reliability. Radar-estimated echo-top height and convective classification were obtained from the regional operational weather radar network for the subset of days with continuous coverage (2010 onward).

2.3 Surface precipitation records

Daily and, where available, hourly precipitation totals were assembled from 214 national meteorological agency gauge stations distributed across the three basins and reference sites for 2005–2022. Gauge records were quality-controlled for internal consistency and cross-checked against a satellite-gauge merged precipitation product at each station location; stations with more than 10% missing warm-season (May–September) days over the study period were excluded, leaving 178 stations in the final analysis.

2.4 Pollution-level compositing

Warm-season days at each station were assigned to one of five AOD quintiles based on the domain-mean AOD for that day, computed separately for each of the three basins to account for differing baseline pollution climatology. Precipitation frequency and intensity statistics were then computed within each quintile, holding meteorological regime approximately constant by restricting the comparison to days with similar synoptic-scale moisture flux convergence (within one standard deviation of the domain warm-season mean), to reduce confounding between aerosol loading and independently varying atmospheric moisture supply.

2.5 Distance-from-source and downwind analysis

For each basin, stations were binned by distance and bearing from the dominant urban-industrial emission core along the prevailing warm-season wind direction, in four bands (0–20 km, 20–40 km, 40–80 km, and 80–150 km downwind), to test whether suppression and invigoration signatures separate spatially rather than co-occurring uniformly across the basin. Precipitation frequency and intensity metrics were compared across distance bands using the same quintile-stratified approach described above.

2.6 Trend decomposition and statistical testing

Long-term trends in domain-mean AOD, light-rain frequency (daily total below 5 mm), and heavy-rain frequency (daily total above 50 mm) were estimated using a Theil-Sen slope estimator with a Mann-Kendall significance test, computed separately for 2005–2013 and 2014–2022 to bracket the tightening of national air-quality standards. Differences in precipitation metrics between AOD quintiles and between distance bands were tested for significance using a two-sided bootstrap resampling test (5000 resamples) with station-day as the resampling unit, and results are reported as significant at $p < 0.05$ unless otherwise stated.

3. RESULTS

Across the three basins and 2005–2022, warm-season light-rain frequency (daily totals below 5 mm) fell steadily with increasing AOD quintile: stations in the highest AOD quintile (domain-mean AOD above 0.80) recorded 31% fewer light-rain days than stations in the lowest quintile (AOD below 0.35), a difference that held ($p < 0.01$) after

restricting the comparison to days with similar moisture flux convergence. This suppression was accompanied by a 14% increase in mean cloud droplet number concentration and a 2.3 micrometre decrease in cloud-top effective radius between the lowest and highest quintiles, consistent with the classical Twomey-Albrecht mechanism by which added cloud condensation nuclei narrow the droplet size distribution and delay collision-coalescence. Table 1 reports the full set of microphysical and precipitation-frequency statistics by AOD quintile.

Table 1. Cloud microphysical and precipitation-frequency statistics by aerosol optical depth (AOD) quintile, pooled across the three basins (2005–2022 warm seasons).

AOD quintile (550 nm)	Cloud droplet Nc (cm ⁻³)	Effective radius (micrometres)	Light-rain days (<5 mm, %)	Heavy-rain days (>50 mm, %)
Q1 (<0.35)	412	14.8	38.6	2.1
Q2 (0.35–0.50)	438	14.1	35.9	2.4
Q3 (0.50–0.65)	451	13.4	32.7	2.6
Q4 (0.65–0.80)	463	12.9	29.4	2.8
Q5 (>0.80)	469	12.5	26.6	3.0
Change Q1 to Q5	+14%	-2.3 μ m	-31%	+19%

Nc: cloud droplet number concentration. Light-rain and heavy-rain percentages are the share of warm-season station-days in each quintile falling in the stated daily-total category. Comparisons restricted to days with moisture flux convergence within one standard deviation of the domain warm-season mean.

Heavy-rain frequency (daily totals above 50 mm) showed the opposite relationship with AOD, rising by 19% from the lowest to the highest quintile, and radar-estimated convective echo-top height in the subset of days with radar coverage increased by a mean of 850 m across the same quintile range, indicating deeper, more vigorously developed convection under higher aerosol loading. The two signatures, light-rain suppression and heavy-rain invigoration, were both statistically robust across all three basins individually, though the magnitude of heavy-rain enhancement was largest in the Sichuan Basin (24%) and smallest in the Yangtze River Delta (14%), a difference we attribute tentatively to the Sichuan Basin's more frequent afternoon convective initiation over complex terrain, which may provide more opportunities for aerosol-invigorated updrafts to develop fully before dissipating.

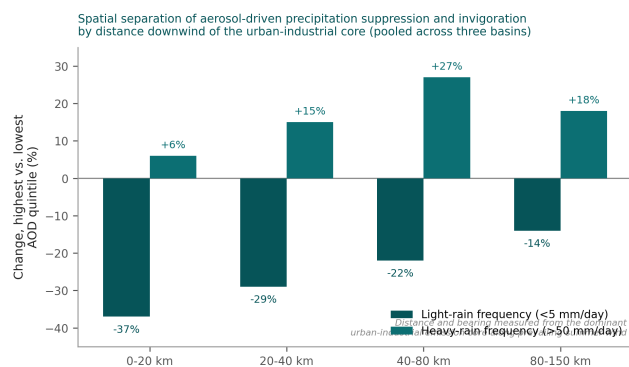


Figure 1. Percent change in light-rain (<5 mm/day) and heavy-rain (>50 mm/day) frequency under the highest versus lowest aerosol optical depth quintile, by distance band downwind of the basin urban-industrial core, pooled across the three study basins (2005-2022 warm seasons).

Distance-from-source binning showed that these two signatures are not co-located: light-rain suppression was strongest in the 0-20 km band immediately surrounding the urban-industrial core (37% reduction relative to rural reference sites) and weakened progressively with distance, while heavy-rain enhancement was minimal in the 0-20 km band (6%, not significant) and peaked in the 40-80 km downwind band (27%), consistent with a picture in which pollution first suppresses shallow warm-rain processes near the source before the same aerosol-laden air, entrained into deeper convective updrafts further downwind, invigorates heavier rainfall. Figure 1 shows this spatial separation of the two signatures across the four distance bands, pooled across the three basins.

Table 2. Basin-level aerosol optical depth and precipitation-extreme trends for 2005-2013 versus 2014-2022 (Theil-Sen slope, percent change relative to 2005-2013 mean).

Basin	AOD change	Light-rain frequency change (urban core)	Heavy-rain frequency change (40-80 km band)
North China Plain	-14% (p<0.01)	+16% (partial recovery)	-3% (n.s., p=0.52)
Sichuan Basin	-9% (p=0.02)	+11% (partial recovery)	+2% (n.s., p=0.71)
Yangtze River Delta	-13% (p<0.01)	+18% (partial recovery)	-4% (n.s., p=0.39)

Domain-mean AOD declined by a Theil-Sen slope of 12% over 2014-2022 relative to the 2005-2013 mean, following the tightening of national air-quality standards after 2013, compared with a non-significant trend over 2005-2013 (Mann-Kendall p=0.31). Light-rain frequency in the highest-pollution urban cores partially reconverged toward rural reference levels over the same 2014-2022 period, recovering approximately 40% of the gap observed during 2005-2013, but heavy-rain frequency in the 40-80 km downwind band showed no significant decline over 2014-2022 (Mann-Kendall p=0.44), remaining close to its 2005-2013 mean despite the AOD reduction. Table 2 compares basin-level AOD and precipitation-extreme trends for the two sub-periods.

4. DISCUSSION

These results are consistent with a growing body of evidence that aerosol effects on precipitation in polluted continental regions operate through at least two distinct and spatially separated mechanisms rather than a single net effect [3,9,10]: suppression of light and moderate warm-rain production close to the pollution source, and invigoration of deep convection and heavy rainfall further downwind, as aerosol-laden air is lofted into convective updrafts and delays droplet freezing [11,16]. The magnitude of light-rain suppression observed here (31% between AOD quintiles) sits within the range reported in earlier East Asian and North American studies [7,14], while the 19% increase in heavy-rain frequency under high AOD is broadly consistent with, though somewhat smaller than, some prior estimates of convective invigoration in this region [9,15], a difference plausibly attributable to our meteorological-regime restriction, which removes some of the variance that unconstrained comparisons attribute to aerosol loading.

The clear spatial separation between suppression- and invigoration-dominated zones is, in our view, the most practically important finding. A basin-averaged analysis that pools stations regardless of distance from the emission source would substantially understate both signatures, since the strong suppression near the urban core and strong invigoration 40-80 km downwind partially cancel in a spatial average, and would miss entirely the redistribution of rainfall implied by these results: water that would otherwise have fallen as light rain near the city appears, at least in part, to be displaced toward heavier, more episodic rainfall further along the prevailing wind direction. This has direct implications for flood risk in downwind peri-urban and rural areas that may not be the focus of urban water-management planning, and echoes concerns raised in prior work on aerosol-modulated flood risk in industrialized Chinese basins [16].

The asymmetric response of the two signatures to the post-2013 emissions decline, with light-rain frequency partially recovering but heavy-rain frequency remaining largely unchanged, suggests the two mechanisms may not be simple mirror images of one another operating on the same underlying aerosol-loading variable. One possibility is that heavy-rain invigoration depends more on peak aerosol loading during acute pollution episodes, which have declined less than the mean AOD trend, than on the mean state; another is that other factors, including a warming background climate and associated increases in atmospheric moisture-holding capacity, are contributing to sustained heavy-rain frequency independently of aerosol trends and are not separable from aerosol effects using the observational design employed here [13,17]. Distinguishing between these explanations would require either a longer post-decline observational record or a modelling framework capable of isolating the aerosol contribution from concurrent thermodynamic trends.

Several limitations should be considered when interpreting these findings. First, the analysis is observational and, despite the meteorological-regime restriction applied, cannot fully rule out confounding between aerosol loading and co-varying synoptic conditions that independently favour both high pollution and particular precipitation regimes; a chemical transport and cloud-resolving model framework would allow more direct attribution [4,10]. Second, satellite AOD retrievals are unavailable under fully overcast conditions, so our AOD quintiles are necessarily derived from partly cloudy or clear-adjacent conditions and may not perfectly represent aerosol loading within the precipitating cloud itself. Third, the radar-based echo-top height record began only in 2010, shortening the invigoration-signature record relative to the full 2005–2022 gauge and AOD record and limiting our ability to characterize its pre-2010 trend. Finally, the three basins studied, while broadly representative of heavily industrialized East Asian monsoon-region pollution, differ in terrain, emission mix and monsoon exposure from industrialized regions elsewhere in the world, and the specific suppression and invigoration magnitudes reported here should not be extrapolated to other regions without independent verification [12,18].

5. CONCLUSION

Analysis of eighteen years of co-located aerosol, cloud microphysical and surface precipitation records across three heavily industrialized East Asian basins shows that aerosol pollution reshapes regional precipitation through two spatially separated mechanisms: a 31% suppression of light-rain frequency concentrated near urban-industrial pollution sources, consistent with Twomey-Albrecht-type warm-rain suppression, and a 19% enhancement of heavy-rain frequency concentrated 40–80 km downwind, consistent with aerosol-driven convective invigoration. These two signatures did not respond symmetrically to the substantial regional aerosol decline following post-2013 air-quality controls, with light-rain frequency partially recovering while heavy-rain frequency remained largely unchanged. Together, these findings indicate that aerosol-precipitation interactions in industrialized regions function as a redistribution of rainfall across space and intensity rather than a uniform suppression or enhancement, a pattern with direct relevance for flood-risk assessment and water resource planning in and downwind of major pollution sources.

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Conflict of 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.

Author Contributions

M.J. conceived and supervised the study, designed the pollution-level compositing and distance-from-source analysis, and led the writing of the manuscript. A.H. assembled and quality-controlled the aerosol, cloud microphysical and radar datasets and performed the trend decomposition analysis. A.Z. compiled and quality-controlled the surface precipitation gauge records and performed the statistical significance testing. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available satellite aerosol and cloud retrievals, weather radar products, and surface precipitation gauge records, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

MODIS aerosol and cloud products used in this study are publicly available from NASA's Level-1 and Atmosphere Archive and Distribution System. Surface precipitation gauge records are available from the originating national meteorological agencies. Processed datasets and analysis code supporting the findings of this study are available from the corresponding author on reasonable request.

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