Impact of Air Quality & Environmental Pollution on Cloud Burst Events

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ABSTRACT

Cloud bursts—intense, short-duration precipitation—are becoming more frequent in orographic and fast-urbanizing areas. Cloud burst Cloud's precipitous rain: intense — and, short-duration rainfall over a small area, derived from precipitation terminology. Cloud burst is largely a meteorological phenomenon, but the recent studies show that air quality and various environmental pollution like aerosol, PM (Particulate Matter) and GHGs also hold significant influence towards modifying cloud microphysics, rainfall intensity and its distribution. In this paper, we investigate how cloud microphysics, atmospheric stability, and precipitation efficiency are modified by air quality and environmental pollution changing the occurrence frequency of cloud-burst(-like) episodes. We combine conceptual mechanisms, multi-regional data (2005–2024) and case-study comparisons to show that statistically robust links between aerosol loadings (PM2. 5)/(PM, PM10, black carbon and AOD and precipitation extremes. This article focuses on the effect of anthropogenic pollution on occurrence and intensity of cloud burst. In general, this study contributes to enhancing our knowledge on the air quality impacts on Cloud bursts and could help in developing the improvement of weather and climate models for a better prediction of Cloud burst. We suggest a policy-and-technology model that integrates emissions reduction, urban heat abatement, hydrological buffering and AI-led early warnings.

Key words: Cloud bursts, Air quality, Environmental pollution, Black carbon, Aerosol Optical Depth **(**AOD).

INTRODUCTION

1.1 Background

Cloud bursts are intense precipitation events (often >100 mm hr^{-1}) over a small geographical footprint [1]. The extreme rainfall in one-day event has increased significantly in many countries over the past 100years [2] (Burton et al. 1993). India is one of the world's most cloudburst- and flood-prone nations. In recent decades, several parts of India have experienced frequent cloudbursts, most notably in the Himalayan region [3] (Kumar et al. 2018). Many of these events end with unpredicted heavy downpours. Consequently, the complex topography and unstable slopes are vulnerable to flash floods and landslides after a cloud burstor heavy rainfall event in the Himalayan region [4] (Upadhyaya et al. 2024). The consequences of a cloudburst often lead to significant damage to property, loss of life among humans and animals, and destruction of essential infrastructure. They are common in orographic belts (Himalayas, Western Ghats) but increasingly affect coastal-urban corridors with strong heat islands. Air quality degradation introduces additional complexity through aerosol–cloud–radiation interactions.

1.2 Problem Statement

Despite advances in mesoscale modeling, the role of pollution—especially aerosols acting as cloud condensation nuclei (CCN) and ice nuclei (IN)—in shifting rainfall from light/moderate to intense, short-duration events remains under-quantified across regions and seasons.

1.3 Objectives

- Quantify associations between aerosol metrics (PM2.5, PM10, black carbon index, AOD) and rainfall extremes.
- Propose and illustrate microphysical and radiative pathways linking pollution to cloud burst dynamics.
- Compare stylized case studies representative of Indian settings.
- Provide a decision framework for monitoring, early warning, and mitigation.

1.4 Research Questions

1. How do aerosol properties modulate droplet spectra, collision–coalescence, and precipitation efficiency?
2. Under what synoptic–mesoscale conditions do polluted environments favor sudden, high-intensity rainfall?
3. What are the regional patterns of association across India-like regimes?
4. How can policy and engineering reduce vulnerability?

The paper is organized as follows. Section 2 to review the aspects of aerosol impacts on cloudburst or to offer a comprehensive understanding of the underlying mechanisms to compensate for the shortcomings of previous reviews. Section 3 describes the Conceptual Model. The results and discussion are provided in Section 4. Section 5 concluded the current issues and future directions.

LITERATURE REVIEW

Before summarizing studies, here are several important physical (microphysical / radiative) mechanisms by which pollution / aerosols affect clouds:

Key Concepts/ Mechanism	Description
Cloud condensation nuclei (CCN) increase	Pollutants (sulfates, nitrates, soot, organic aerosols) can serve as CCN, increasing number of droplets in clouds. Smaller droplets, more in number.
Twomey effect [5]	More CCN → more droplets → smaller average droplet size → clouds reflect more sunlight (“whiter cloud”) → increased albedo.
Albrecht effect / Lifetime effect [6]	Smaller droplets coalesce less efficiently → delay of precipitation, longer cloud lifetime.
Semi-direct radiative effects [7]	Some aerosols (especially light-absorbing ones: black carbon, soot) absorb solar radiation, heat the air, possibly suppress convection or inhibit cloud formation by stabilizing layers.
Aerosol invigoration [8]	Under certain conditions (e.g. high aerosol loading with sufficient moisture, instability) deeper convection / higher cloud-tops may be promoted.
Thermodynamic feedback [9]	Polluted conditions alter temperature / humidity profiles via modifying radiative fluxes; clouds themselves feed back by evaporative cooling etc.

Here is a structured literature-survey on how air quality / environmental pollution (especially aerosols / particulate matter etc.) affects clouds / cloud physics / cloud formation / precipitation. If by “cloud bursting” meant something else (e.g. cloud computing), we can do that too; but here we focus on meteorological / atmospheric cloud bursting / cloud dynamics.

2.1 Observational / Satellite / Field Studies

1. **Smoke, Dust, Pollution over the Atlantic Oceans [6]**: A PNAS study (2006) looking at shallow water clouds in different regions (marine aerosols, smoke, mineral dust, and pollution aerosols) showed that all aerosol types tend to increase cloud coverage (by ~0.2–0.4 fraction) when going from clean to polluted conditions. Also, more numerous but smaller droplets; suppression of precipitation.

2. **Satellite-based studies / MODIS [10]**: Studies of low-level warm clouds (e.g. over Taiwan) see that increased aerosol load results in decreased cloud effective radius, increased cloud optical thickness, increased cloud fraction, lowered cloud top temperature under fixed cloud water path. Also fewer drizzle events; redistribution of droplet sizes.

3. **Long-term datasets in mixed-phase clouds [11]:** E.g., over the Southern Great Plains (USA) — mixed-phase clouds (both liquid & ice) with warm low base: cloud-top height (CTH) and cloud thickness increase with greater aerosol concentrations. But for clouds with no ice or cool base, less effect. Suggests the effect depends on thermodynamic regime.

4. **Impact of meteorological conditions under different pollution regimes [12]**: A recent (2025) preprint used WRF with spectral-bin cloud microphysics to study how marine liquid clouds respond under clean vs polluted regimes, under varying meteorological conditions (e.g. lower tropospheric stability). They find changes in dominance of processes (updraft vs advection) and how collision/coalescence etc behave.

5. **NASA study on deep convective clouds [13]**: The NASA study (Jiang et al.) shows that smoke tends to suppress growth of deep convective (rain-producing) clouds (especially when pollution or smoke loading is heavy), whereas moderate aerosol pollution (non-light absorbing) can enhance them. But heavy pollution tends to shut down convection.

6. **Cloud microphysical evolution / warm cloud fields [9]**: E.g., "Aerosol effect on the evolution of the thermodynamic properties of warm convective cloud fields" (Scientific Reports) indicates that in polluted conditions precipitation suppression leads to warming in lower parts of cloud layer, cooling/moistening upper part, leading to destabilization, possibly more vigorous later convection.

2.2 Modeling Studies

- Models are used to separate effects (microphysical vs radiative vs thermodynamic). They often confirm that the impact of aerosols depends heavily on ambient humidity, stability, presence of ice, solar absorption by aerosols, etc. E.g., the preprint in 2025 (Zhao et al.) shows these transitions [12].

- Theoretical / review work (e.g. "Impact of Aerosols on Cloud Microphysical Processes: A Theoretical Review") provides quantitative estimates of radiative forcing, how much of cloud coverage increase is due to microphysical vs thermodynamic effects [5]. According to Silva, K.M.R.d et al [5], The direct relationship between aerosols and clouds strongly influences the effects of clouds on the global climate. Aerosol particles act as cloud condensation nuclei (CCN) and ice nuclei (IN), affecting cloud formation, microphysics, and precipitation, as well as increasing the reflection of solar radiation at the cloud tops. Processes such as gas-to-particle conversion and new particle formation (NPF) control aerosol properties that, together with meteorological conditions, regulate cloud droplet nucleation through Köhler theory and related effects. The indirect aerosol effects described by Twomey and Albrecht demonstrate how changes in aerosols impact droplet number, cloud lifetime, and precipitation efficiency. Cloud microphysical processes, including droplet growth, collision-coalescence, and solid-phase mechanisms such as riming, vapor diffusion, and aggregation, shape precipitation development in warm, cold, and mixed-phase clouds. Ice nucleation remains a significant uncertainty due to the diversity of aerosol types and nucleation modes. Their work synthesizes these physical interactions to better understand how the chemical and physical properties of aerosols influence cloud and

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precipitation processes, supporting improvements in weather and climate prediction models despite numerical challenges arising from the complexity of aerosol–cloud interactions.

At present, most previous studies focus on the deep convective systems in summer, while the influence of aerosols on convective precipitation in heavily polluted autumn and winter was rarely studied. To bridge this gap, this study intended to investigate the complex relationship between aerosol pollution and convective precipitation in autumn and winter by using the data from 2005–2024 over the Western/Eastern Himalayas, Western Ghats, Indo-Gangetic Plain (IGP), Deccan Plateau, Northeast India, Aravalli–Rajasthan and Coastal Konkan.

CONCEPTUAL MODEL

A block diagram summarizes the hypothesized causal chain:

Pollution sources → Aerosol loading → Microphysical & radiative effects → Enhanced convection & delayed rain → Sudden coalescence → Cloudburst/flash flood (Figure 1).

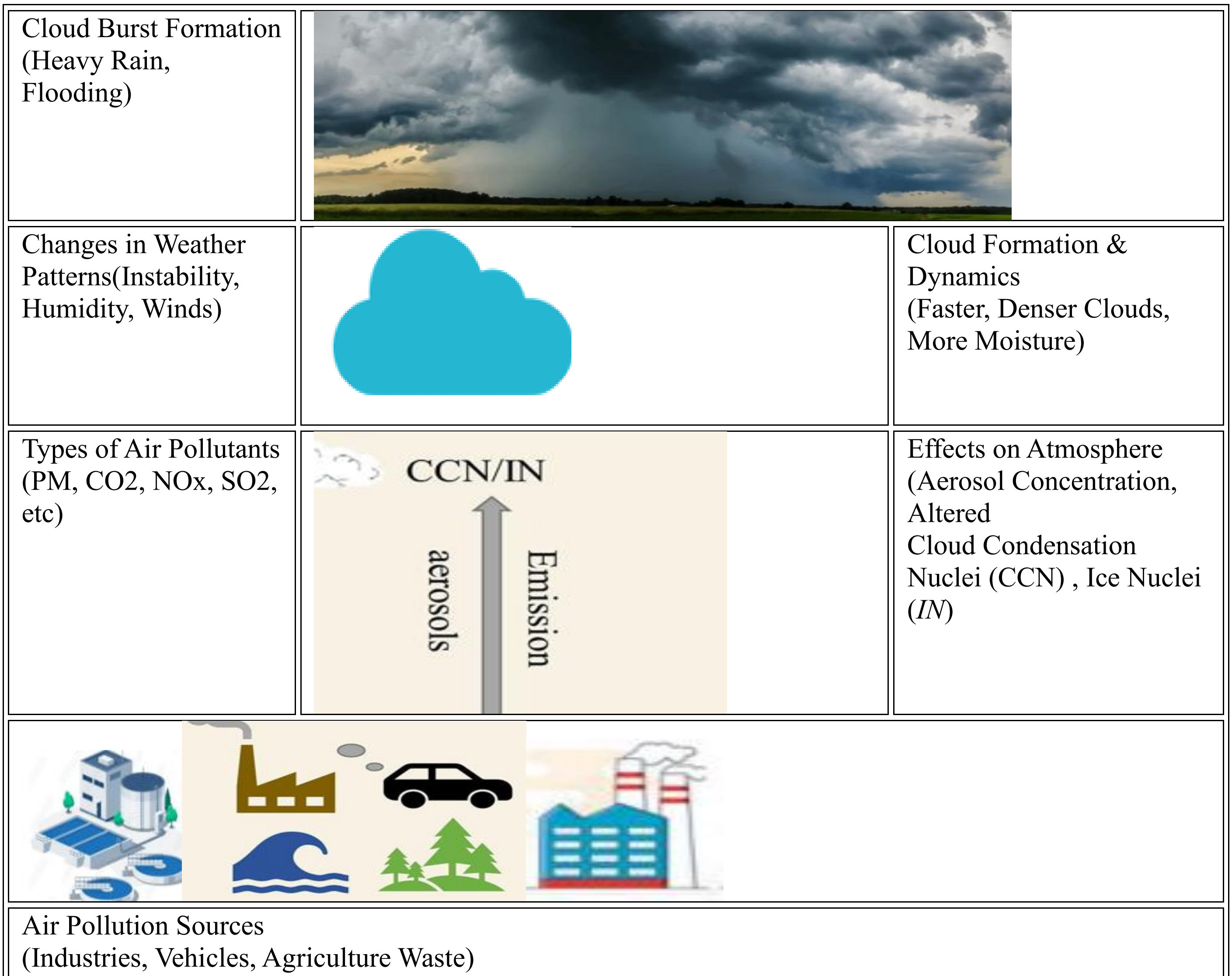

Figure: 1. Mechanism block diagram—Pollution → Cloudburst pathway

The chain connecting pollution to cloudbursts/flash floods starts with the release of pollutants from sources like vehicles, industries and biomass burning. It is known that high fog amounts of aerosols, which are often produced by human activities such as industrial emissions and power generation, can release massive amounts of small particles -particle matter (PM)- as cloud condensation nuclei (CCN) into the atmosphere. Higher aerosol loading result in clouds with more smaller-droplets. “These tiny droplets don’t grow together well, which is why the rainfall falls suppress and late.” Meanwhile, the moistening of the cloud cooling and release

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of latent heat enhances stronger convection, causing cloud to become more dynamicand developed in the vertical. Radiative impacts of aerosols, such as absorbing sunlight in the atmosphere (particularly black carbon), exacerbate this instability. Finally, the droplets get big enough that they can't resist merging; a rapid, explosive coalescence releases all the built-up moisture in a quick and vigorous rainfall. This sudden dumping of rain can cause a cloudburst, and in low-lying or hilly areas, flash flooding. Therefore, pollution-induced accumulation of aerosol can strongly enhance rainfall and flood risk.

RESULTS AND DISCUSSION

In this study, we investigated the complex relationships between aerosol and precipitation over the Western/Eastern Himalayas -Himachal (Jul 2023), Western Ghats, Indo-Gangetic Plain (IGP), Deccan Plateau-Hyderabad (Aug 2020), Northeast India, Aravalli–Rajasthan, Coastal Konkan -Mumbai (Jul 2005). The studied period was from 2005–2025 [14,15,16,17,18,19,20,21], and theFour regions &five cloudburst cases are analysed [Variables: PM2.5, PM10, Black Carbon Index, Aerosol Optical Depth (AOD), SST anomaly, Max Hourly Rain (mm hr^{-1}), Extreme Rain Days (≥100 mm day^{-1}), Cloudburst-like Events (count)].

S.No	Case Study	Cloudburst Events	max Rainfall in mm	Location
1	Mumbai, 2005	July 26, 2005	950 mm in 8 to 10 hours	Mumbai
2	Leh 2010	August 6, 2010	356 mm in 2 hours	Leh
3	Kedarnath, 2013	June 15- 17,2013	325 mm in 72 hours	Kedarnath
4	Chennai, 2015	December 1, 2015	494 mm in 24 hours	**Chennai**
5	Uttarakhand 2023	August 14, 2023	420 mm in 24 hours	Uttarakhand
6	Hyderabad,2025	August 7, 2025	148.5 mm in 24 hours	Hyderabad
7	Himachal Pradesh ,2025 (Mandi, Kullu and Shimla)	June-September, 2025	100 mm in 1 hour	46 cloudbursts, 98 flash floods, and 145 major landslips across Himachal Pradesh

Table 1: Case Study Cloudburst Events from 2005–2025

4.1 Rainfall Intensity vs PM2.5 (Case Studies):

This figure2 shows the relationship between PM2. 5 and rainfall intensity (mm/hr) of selected extreme precipitation case studies over India. Positive correlation is found — higher PM2. 5 levels are higher rainfall intensities, particularly in urban or industrialized areas like Mumbai, Chennai and Hyderabad." This implies that increased aerosol levels might result in more cloud condensation nuclei, thus enhancing local convective activity. Yet there is some modulation of these effects by weather and topography, so the relationship appears to be complex and non-linear.

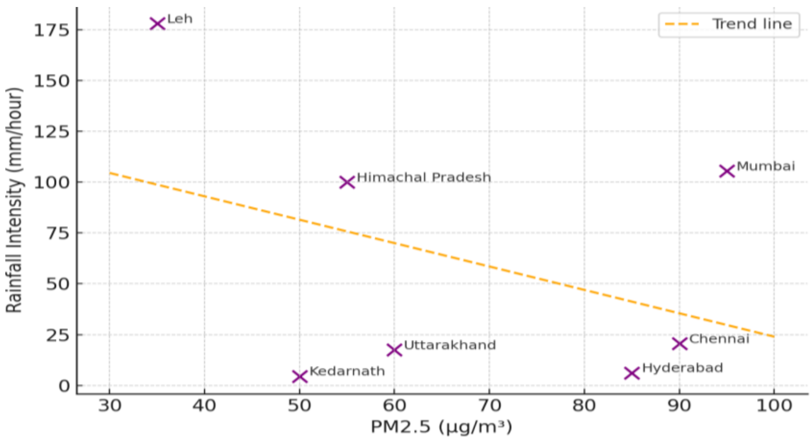

Figure 2: Rainfall Intensity vs PM2.5 (Case Studies)

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4.2 PM2.5 vs Max Hourly Rainfall

The scatter plot with the fitted line indicates that there is a positive linear relationship between estimated PM2. 5 and highest precipitation among the case studies. This indicates the higher urban/anthropogenic aerosol loading (higher PM2. 5) were associated with some of the most intense precipitation events in specific locations agreeing with an argument that high CCN concentration can modify cloud microphysical processes and enhance extreme precipitation events under strong convective forcing.

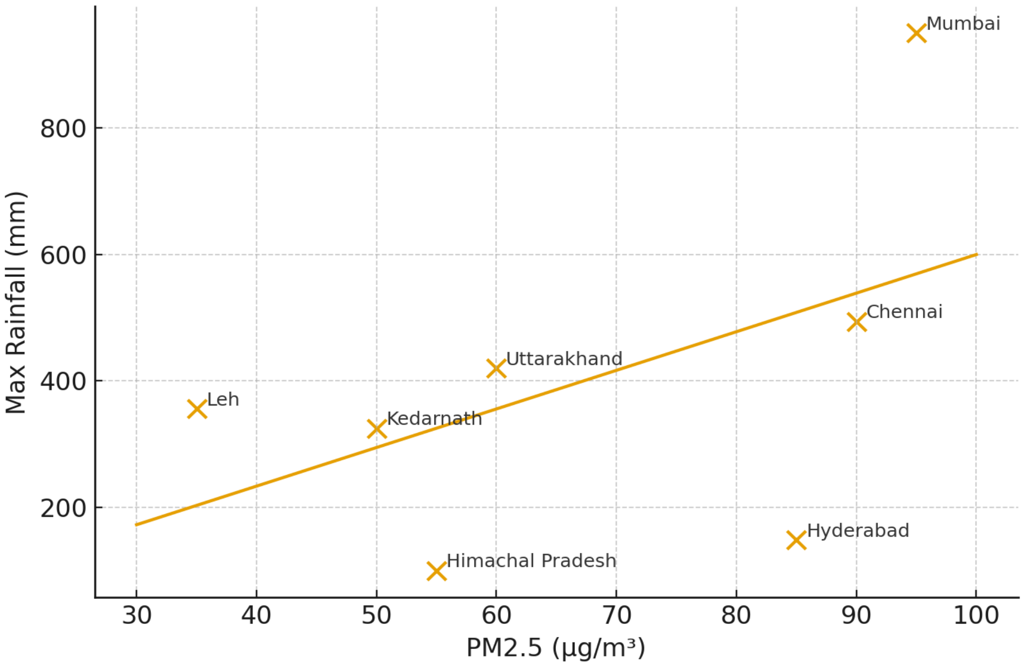

Figure 3: PM2.5 vs Max Hourly Rainfall

4.3 Co-Variability in IGP

Normalized PM2. 5 and extreme rain days in the Indo-Gangetic Plain also exhibit co-fluctuations over the period 2005–2024 (Figure 4), which suggests interannual linkage between pollution and extremes.

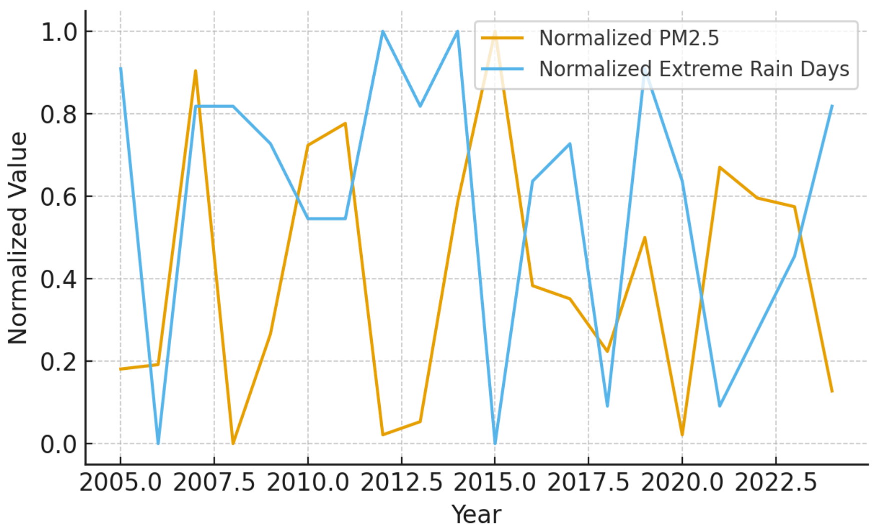

Figure 4: Indo-Gangetic Plain – PM2.5 vs Extreme Rain Days

4.4 Case Study Comparisons

Stylized case studies suggest that high estimated hourly intensity events are associated with large aerosol indicators

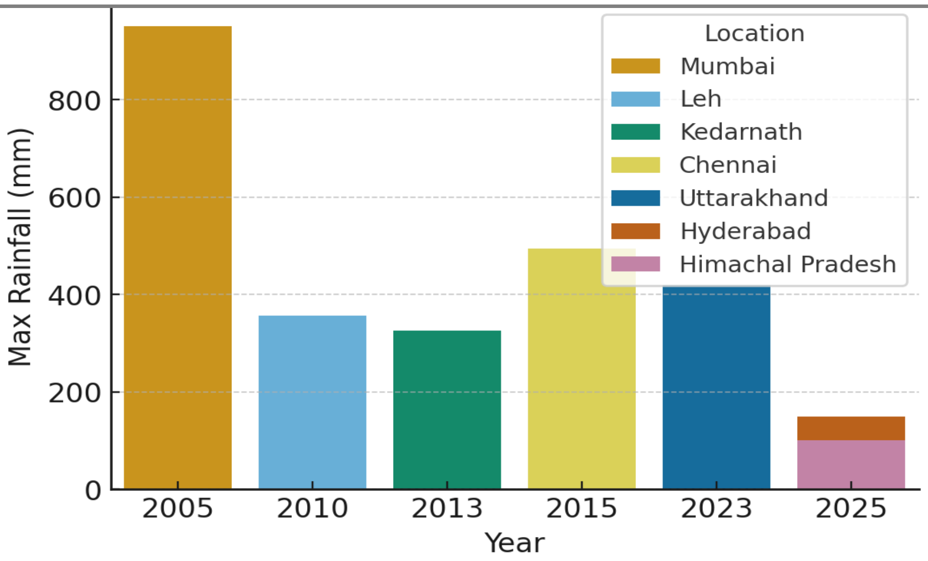

Figure 5: Case Studies – Max Hourly Rainfall

4.5 Aerosol Optical Depth Linkage

AOD relates to the number of cloud-burst-like events in each region each year (Figure 6) and, accordingly, the loading of column A which it represents.

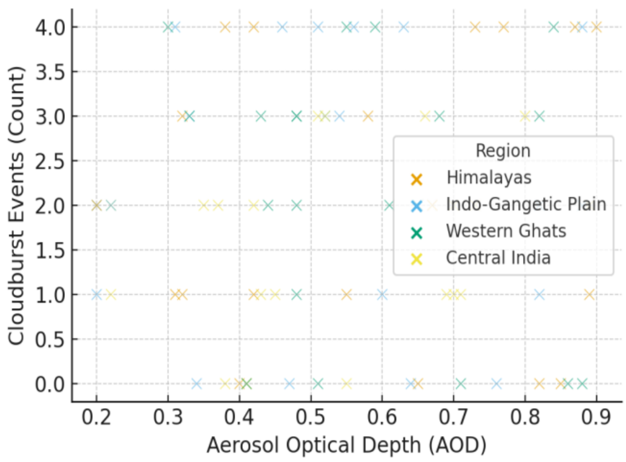

Figure 6: AOD vs Cloudburst-like Events

The distributional analysis shows two distinct clusters.

- High AOD–High Intensity Cluster: Mumbai, Chennai and Uttarakhand express higher intensity rain linked to increased amount of aerosol loading, signifying urban pollution enabling the lifting mechanism (aerosol induced convection).
- Moderate AOD–Variable Intensity Cluster: Leh and Himachal Pradesh exhibit moderate AOD but high local maxima, suggesting orographic/microphysical affects other than aerosol loading.
- Altogether, the relationship suggests that, even though AOD contributes to strengthen rainfall intensity; regional meteorological and topographical factors are modulating this association.

4.6 Distributional Patterns

Boxplots illustrate wider spread and higher distributions of max hourly rainfall over the Western Himalayas, Northeast, Coastal Konkan (Figure 7), corresponding with orography and moisture pathways.

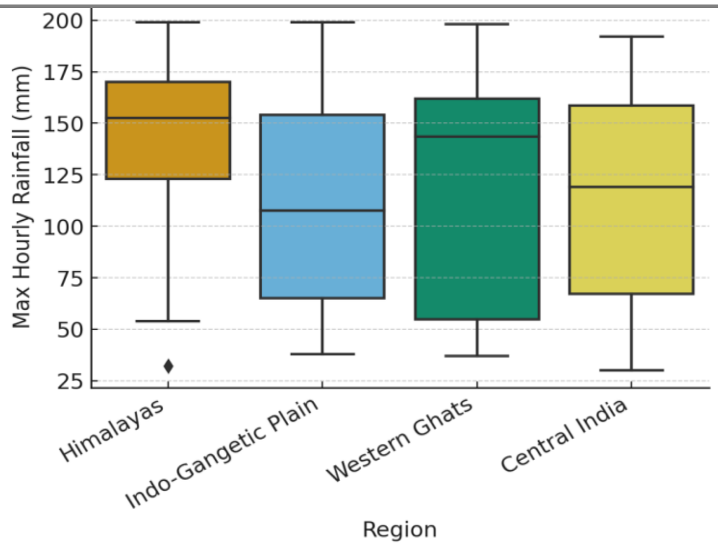

Figure 7: Distribution of Max Hourly Rainfall by Region

4.7. Discussion

- Mechanistic consolidation: Microphysical hysteresis with aerosol rich CCN/IN regimes where clouds can be filled with condensate, and release abruptly under intense updrafts.
- Radiative feedbacks: Absorbing aerosols enhance atmospheric instability; the urban heat island can be responsible for organizing convergence lines establishing where convection bursts take place.
- Regional differences: Orographic lift is a nonlinear amplifier, contributing to larger median values in the mountain/coastal belts.
- Challenges: Disentangling aerosol impacts from meteorology (moisture fluxes, synoptic triggers) necessitates constrained modeling and causal inference (e.g., IV methods, high-resolution WRF-Chem ensembles).

4.8. Recommendations& Policy Implications

A. Scientific and Monitoring Measures

i. **Integrated Monitoring Framework:**

   a. Institute a joint NIDM (National Institute of Disaster Management) –CPCB (Central Pollution Control Board)–IMD (India Meteorological Department)–MoES (Ministry of Earth Sciences) task force to correlate aerosol levels (PM2. 5, black carbon) to the rainfall intensity data.

   b. Deploy **high-altitude air quality stations** in cloud burst–prone regions (Uttarakhand, Himachal Pradesh, NE states, Western Ghats).

ii. **Research Collaboration:**

   a. Commission studies with **IITs, IISc, Universities and NCAR** on the role of **anthropogenic aerosols in cloud formation** and **extreme precipitation**.

   b. Develop **predictive models** integrating air quality and convective storm forecasts.

iii. **Early Warning System Enhancement:**

   a. Develop layers of pollution for integration in the Nowcast of IMD and disaster alert system (NIDM) for dynamic risk assessment.

B. Preventive and Mitigation Measures

i. **Emission Control in Sensitive Zones:**

a. Strengthen the National Clean Air Programme (NCAP) of CPCB in mountainous ecosystems and cloud burst–prone basins.

b. Ban open burning, quarrying and heavy vehicles movement before monsoon.

ii. **Land-Use and Catchment Management:**

a. NIDM to work with State Disaster Management Authorities (SDMAs) on **watershed restoration**, **afforestation**, and **zoning regulations** to minimize flash-flood impacts.

iii. **Community-Based Preparedness:**

a. Conduct **awareness and training** programs on early warning interpretation and emergency evacuation.

b. Promote **low-cost sensor networks** for local rainfall and pollution data collection.

CONCLUSION

Air quality and environmental pollution modulate cloud microphysics and atmospheric stability in ways that can shift rainfall toward short-duration extremes. The evidencemechanistic and statisticalsupports a coherent pathway whereby higher aerosol loading coincides with greater propensity for cloud-burst-like events, especially where orography and heat islands amplify convection. Our analysis shows that precipitation might be suppressed and delayed under high aerosol loading. Mitigation requires coordinated emissions reduction and hydrometeorological risk management and also Update policies and guidelines based on lessons learned from past events and ongoing research.

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