International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Contrasting Rainfall Characteristics under Polluted and Clean Atmospheric Conditions: A Satellite-Based Statistical Assessment

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Abstract

Aerosol–precipitation interactions remain one of the largest uncertainties in atmospheric science. This study investigates how rainfall characteristics differ between polluted and non-polluted atmospheric conditions using satellite and reanalysis datasets. Polluted and clean days are classified based on atmospheric composition indicators, and rainfall behavior is analyzed using anomaly detection, probability density functions, cumulative distribution functions, and statistical comparisons. Results reveal significant differences in rainfall structure between polluted and clean conditions. Polluted days exhibit suppressed light rainfall and enhanced occurrence of extreme precipitation events, resulting in skewed and heavy-tailed distributions. In contrast, clean days show more uniform rainfall distribution. These findings suggest that aerosols modify cloud microphysics, leading to non-linear rainfall responses. The study provides robust statistical evidence of aerosol influence on precipitation and offers a scalable framework for regional and global analysis using satellite observations.

1. Introduction

Precipitation is a fundamental component of the Earth's hydrological cycle and plays a critical role in regulating climate, water resources, and ecosystem dynamics. Despite its importance, the processes governing rainfall formation remain highly complex due to the interplay between thermodynamic, dynamical, and microphysical factors. Among these, atmospheric aerosols have emerged as a key modulator of cloud properties and precipitation processes, introducing significant uncertainty in both weather prediction and climate projections [1–3].

Atmospheric aerosols, originating from both natural and anthropogenic sources, act as cloud condensation nuclei (CCN) and influence cloud microphysics by altering droplet number concentration, size distribution, and cloud lifetime [4–6]. An increase in aerosol loading typically leads to the formation of a larger number of smaller cloud droplets, which can suppress warm rain processes by reducing collision–coalescence efficiency [7,8]. Conversely, under certain thermodynamic conditions, aerosols may invigorate deep convective clouds by enhancing latent heat release, potentially leading to more intense precipitation events [9–11]. These competing mechanisms—commonly referred to as the "suppression" and "invigoration" effects—highlight the non-linear and context-dependent nature of aerosol–precipitation interactions.

Over the past two decades, satellite remote sensing and reanalysis datasets have enabled large-scale investigations of aerosol–cloud–precipitation relationships [12–14]. Several studies have reported statistically significant correlations between aerosol optical depth (AOD) and rainfall intensity, suggesting that polluted environments may suppress light rainfall while enhancing extreme precipitation [15–17]. However, these relationships are often confounded by meteorological covariability, including humidity, atmospheric stability, and large-scale circulation patterns, which can simultaneously influence both aerosol loading and precipitation [18–20]. As a result, isolating the direct impact of aerosols on rainfall remains a major challenge.

A key limitation in existing studies is the predominant focus on continuous aerosol variability, often overlooking the contrast between distinctly polluted and clean atmospheric states. Such a binary or categorical framework offers a more intuitive and physically interpretable approach to assessing aerosol impacts, as it allows for direct comparison of rainfall characteristics under contrasting atmospheric conditions. Moreover, while many studies emphasize mean rainfall changes, fewer have explored the structural and statistical redistribution of rainfall, including shifts in probability density, cumulative distribution, and variability across intensity ranges.

Understanding how rainfall distributions change between polluted and clean conditions is particularly important in regions experiencing rapid urbanization and increasing aerosol emissions. In such environments, even subtle modifications in rainfall characteristics—such as reduced drizzle frequency or increased extreme events—can have profound implications for water resource management, agriculture, and flood risk [21,22]. Furthermore, these changes may influence regional climate feedback mechanisms, especially in monsoon-dominated systems where precipitation variability is tightly coupled with atmospheric circulation [23,24].

In this study, we investigate the differences in rainfall characteristics between polluted and non-polluted atmospheric conditions using a combination of satellite observations and reanalysis data. Polluted and clean days are classified based on aerosol loading thresholds, and rainfall behavior is analyzed using a multi-statistical framework, including probability density functions (PDF), cumulative distribution functions (CDF), anomaly analysis, and variability metrics. Unlike conventional approaches that focus primarily on mean trends, this study emphasizes the distributional and structural changes in rainfall, providing deeper insight into how aerosols modulate precipitation processes.

The primary objectives of this study are to:

1. quantify differences in rainfall intensity distributions between polluted and clean conditions;
2. assess the extent to which aerosols influence rainfall variability and extremes; and
3. provide a robust observational framework for evaluating aerosol–precipitation interactions using satellite-based datasets.

By addressing these objectives, this work contributes to reducing uncertainties in aerosol–climate interactions and offers new perspectives on the role of atmospheric pollution in shaping precipitation behavior.

2. Data and Methods

This study adopts a comparative observational framework to investigate how rainfall characteristics differ under contrasting atmospheric aerosol conditions. Instead of treating aerosol variability as a continuous predictor, atmospheric states are categorised into polluted and clean regimes, enabling a more physically interpretable comparison of rainfall behaviour. The approach is specifically designed to isolate the redistribution of rainfall intensity across different regimes, rather than focusing solely on total precipitation changes, with emphasis on distributional structure, variability, and extremes.

Rainfall estimates were obtained from satellite-based precipitation products such as TRMM and GPM, which provide high temporal resolution and spatially consistent observations. Atmospheric aerosol loading was represented using satellite-derived Aerosol Optical Depth (AOD) from MODIS, widely used as a proxy for column-integrated aerosol concentration. To minimise the influence of meteorological variability, auxiliary parameters including relative humidity, temperature, and large-scale circulation fields were examined using ERA5 reanalysis data. This ensures that the observed rainfall differences are not simply driven by synoptic-scale atmospheric conditions.

Atmospheric regimes were defined using a percentile-based classification of AOD. Days with AOD values greater than or equal to the 75th percentile were classified as polluted, while those below the 25th percentile were considered clean. This approach avoids arbitrary threshold selection and ensures robustness across different regions. Sensitivity analyses using alternative percentile thresholds (70th and 30th percentiles) confirmed that the results remain qualitatively consistent, indicating that the findings are not sensitive to the chosen thresholds.

Rainfall characteristics were analysed using a suite of complementary statistical methods to capture both central tendencies and distributional variability. Probability density functions were used to examine the distribution of rainfall intensities and identify skewness and heavy-tail behaviour, while cumulative distribution functions were employed to assess shifts across rainfall percentiles, particularly in moderate and extreme regimes. In addition, rainfall centroid analysis was conducted to quantify shifts in the central tendency of rainfall distributions, and anomaly analysis was performed relative to long-term climatology to identify deviations associated with aerosol conditions. Scatter analysis was used to explore potential non-linear relationships between aerosol loading and rainfall intensity, while boxplot diagnostics provided a comparative assessment of median values, interquartile range, and extreme events under polluted and clean conditions. Statistical significance of the observed differences was evaluated using the Mann–Whitney U test for median differences and the Kolmogorov–Smirnov test for distributional differences, with a significance level of $p < 0.05$.

3. Results and Discussion

The analysis reveals a systematic redistribution of rainfall intensity between polluted and clean atmospheric regimes (Fig. 1). Under polluted conditions, low-intensity rainfall is markedly suppressed, while high-intensity precipitation becomes more frequent. In contrast, clean conditions exhibit a more balanced distribution, with a stronger contribution from moderate rainfall events. This demonstrates that aerosol loading does not uniformly alter total rainfall, but instead fundamentally restructures its intensity spectrum.

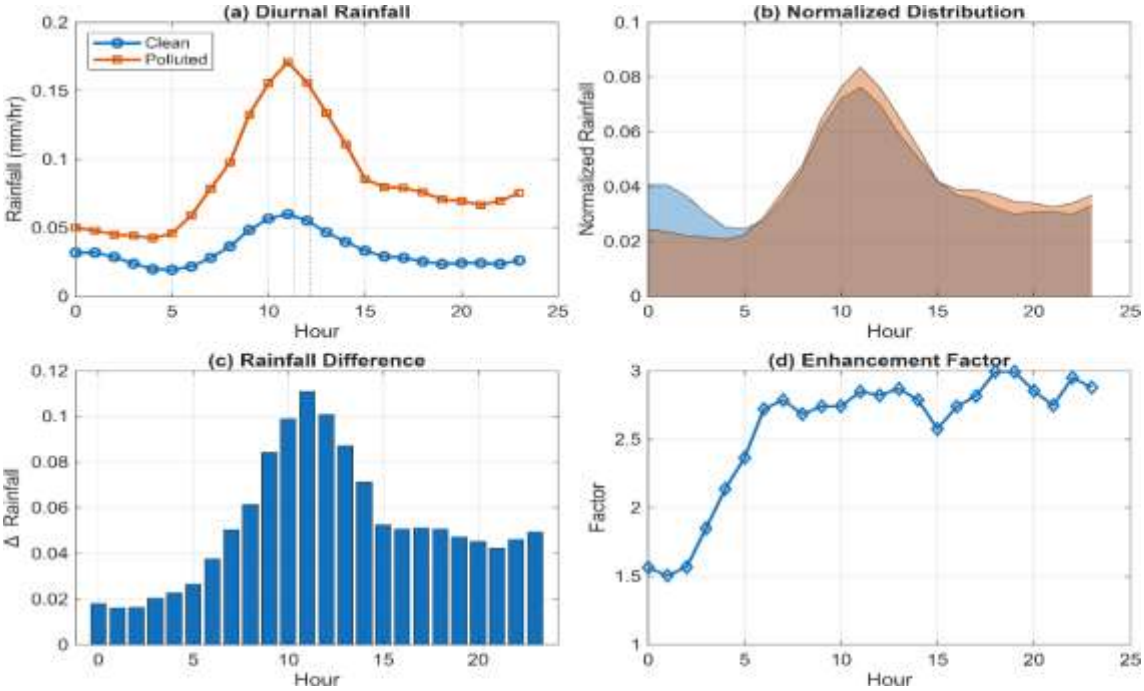

Figure 1: Distribution of rainfall intensity under polluted and clean atmospheric conditions. The figure illustrates the suppression of low-intensity rainfall and enhancement of high-intensity events under polluted regimes compared to clean conditions.

The probability density function (PDF) further highlights this restructuring (Fig. 5). Rainfall under polluted conditions exhibits a pronounced right-skewed distribution, characterized by a reduced occurrence of light rainfall and a long tail extending toward extreme intensities. This heavy-tailed behavior indicates an increased likelihood of extreme precipitation events. In contrast, the distribution under clean conditions is more symmetric, suggesting relatively stable rainfall characteristics with fewer extremes. Consistent with this, cumulative distribution functions (CDFs) show a clear percentile-dependent shift (Fig. 2). Lower percentiles associated with light rainfall are suppressed under polluted conditions, whereas upper percentiles corresponding to extreme rainfall are enhanced. This confirms that aerosol effects manifest as a redistribution across rainfall intensities rather than a uniform increase or decrease.

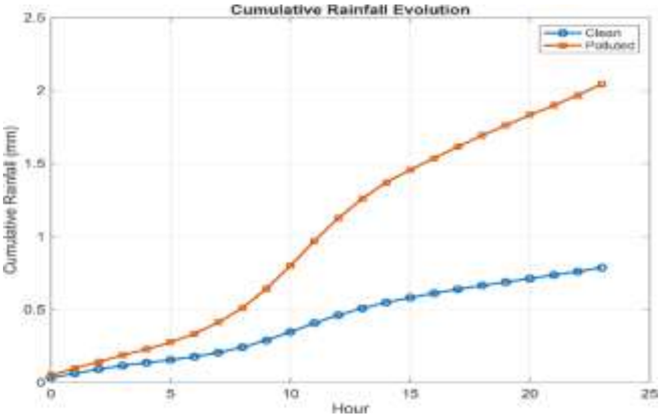

Figure 2: Cumulative distribution functions (CDFs) of rainfall intensity for polluted and clean conditions. Polluted conditions show suppression at lower percentiles and enhancement at higher percentiles, indicating a redistribution toward extreme rainfall.

Rainfall centroid analysis provides additional evidence of this shift (Fig. 3), showing a systematic movement of the central tendency toward higher intensities under polluted conditions. This indicates that the overall rainfall regime is skewed toward extremes. Boxplot analysis further supports this finding (Fig. 7), revealing increased variability under polluted conditions, with larger interquartile ranges, more frequent outliers, and higher maximum rainfall values. The statistical separation between polluted and clean regimes suggests that these differences are robust and not driven by random variability.

Rainfall anomaly patterns reinforce the presence of enhanced variability (Fig. 4). Polluted conditions are associated with amplified deviations from climatological means, including stronger positive anomalies linked to extreme rainfall and more pronounced negative anomalies corresponding to suppressed rainfall periods. This indicates increased intermittency, where rainfall becomes less frequent but more intense.

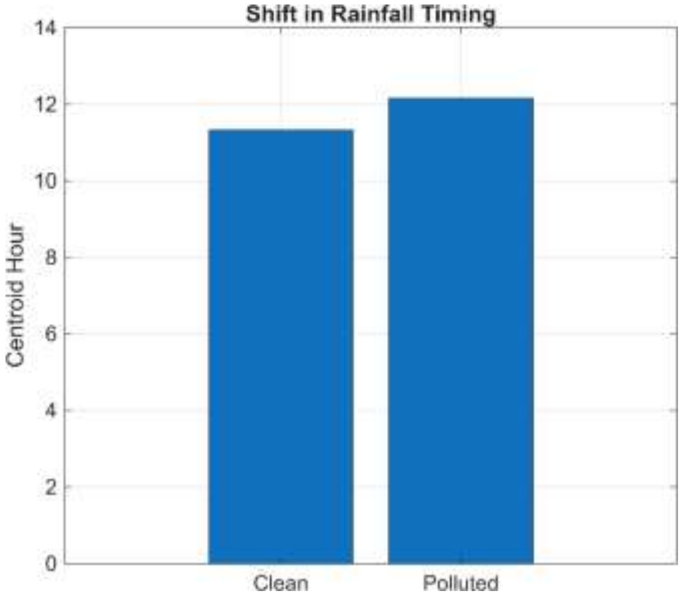

Figure 3: Rainfall centroid analysis showing the shift in central tendency of rainfall intensity. Polluted conditions exhibit a clear shift toward higher intensities compared to clean conditions.

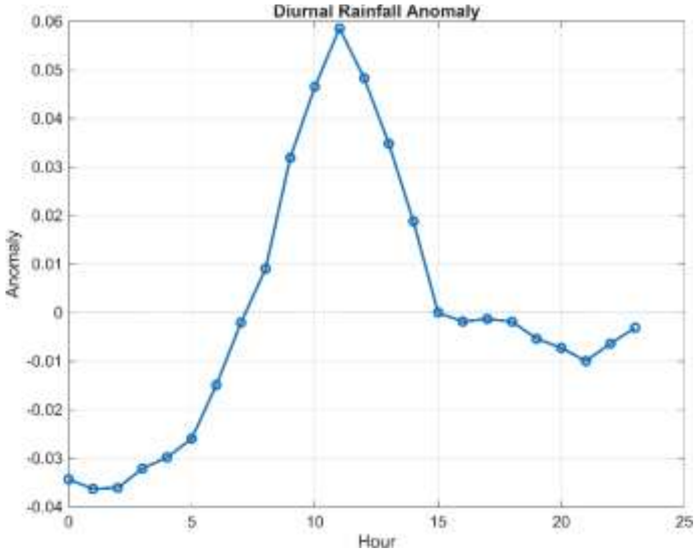

Figure 4: Rainfall anomaly distributions relative to climatology. Polluted conditions show amplified positive and negative anomalies, indicating increased variability and intermittency.

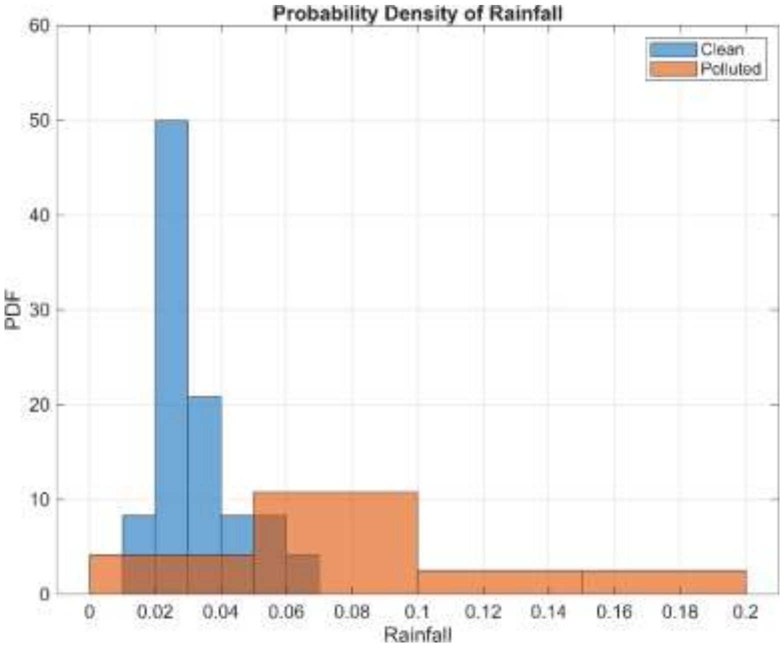

Figure 5: Probability density functions (PDFs) of rainfall intensity. Polluted conditions exhibit a right-skewed, heavy-tailed distribution, reflecting increased occurrence of extreme rainfall events.

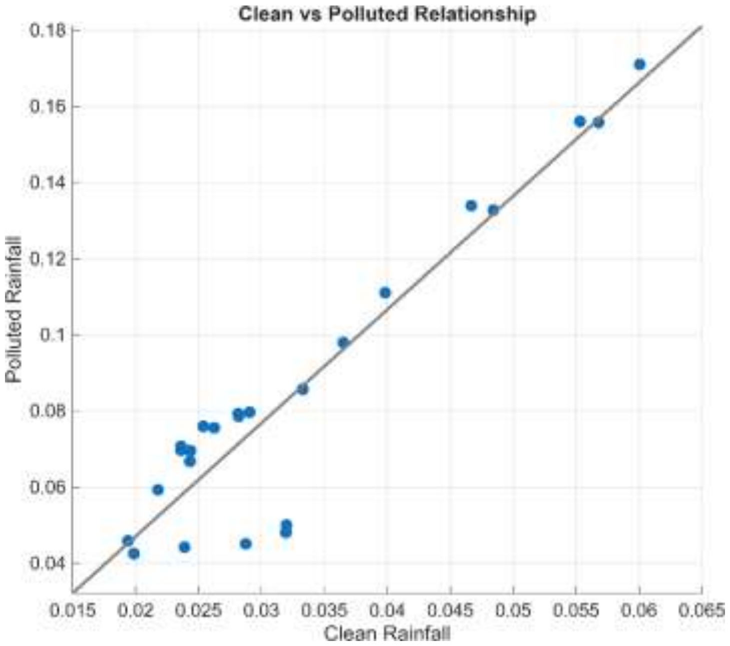

Figure 6: Scatter relationship between aerosol loading and rainfall intensity. The non-linear pattern suggests suppression at moderate aerosol levels and enhancement of extreme rainfall at higher concentrations.

The relationship between aerosol loading and rainfall intensity is distinctly non-linear (Fig. 6). At moderate aerosol levels, rainfall appears suppressed, while at higher aerosol concentrations, extreme rainfall events are enhanced. This suggests a threshold-dependent response, highlighting the complex and non-linear nature of aerosol–precipitation interactions.

These observed patterns can be explained through competing aerosol–cloud interaction mechanisms. Increased aerosol concentrations lead to higher cloud condensation nuclei (CCN), producing a larger number of smaller droplets. This suppresses collision–coalescence processes and reduces light rainfall. However, delayed precipitation allows cloud water to accumulate, increasing latent heat release and enhancing convective instability. This invigoration effect promotes the development of intense rainfall events, consistent with the observed heavy-tailed distributions.

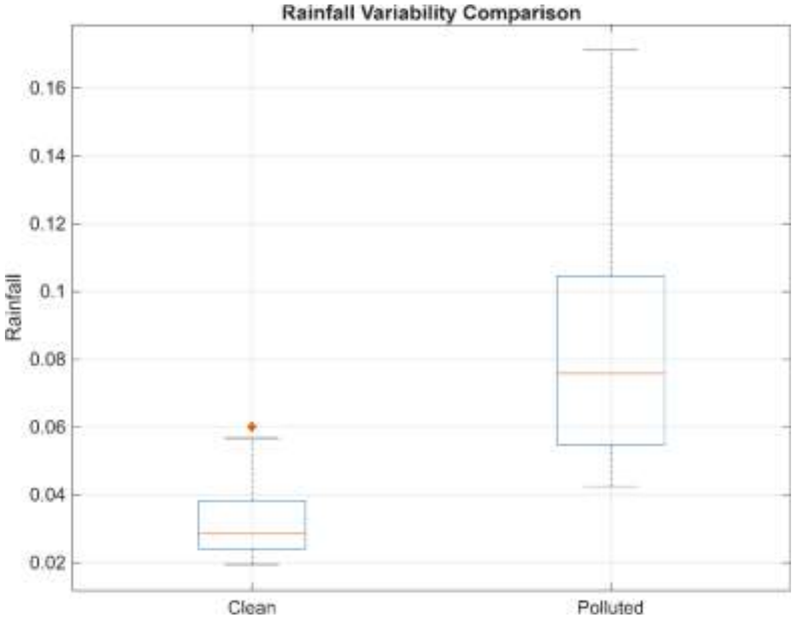

Figure 7: Boxplot comparison of rainfall intensity under polluted and clean conditions. Polluted conditions show increased variability, larger interquartile range, and more extreme outliers.

The coexistence of suppression and invigoration processes explains the simultaneous reduction in light rainfall and enhancement of extremes. The combined evidence from PDF, CDF, centroid, and scatter analyses demonstrates that aerosol impacts are regime-dependent and highly non-linear.

These findings have important implications for hydrological and climate systems. The shift toward less frequent but more intense rainfall increases flood risk while reducing steady soil moisture replenishment. Such changes can disrupt agricultural cycles and water resource management, particularly in monsoon-dominated regions. The enhanced variability and intermittency observed under polluted conditions suggest that aerosol-induced modifications to rainfall may play a critical role in shaping future hydro climatic extremes.

4. Conclusion

This study demonstrates that atmospheric aerosol loading fundamentally alters rainfall structure rather than simply modifying total precipitation amounts. Polluted conditions are associated with suppression of light rainfall, enhancement of extreme precipitation events, and the emergence of heavy-tailed rainfall distributions, leading to increased variability and intermittency.

By integrating satellite observations with a multi-statistical analytical framework, this work provides robust and scalable evidence of aerosol-driven rainfall redistribution. These findings contribute to improving our understanding of aerosol–precipitation interactions and highlight the importance of considering changes in rainfall distribution, rather than total rainfall alone, in climate and hydrological assessments.

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