



Relationships of Rainfall and Satellite-derived Aerosol Optical Depth over the Western Part of Karnataka

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Abstract Atmospheric aerosols play a crucial role in regulating Earth's radiative balance and hydrological cycle by interacting with radiation and cloud microphysical processes. Understanding the long-term variability of aerosols and their relationship with precipitation is particularly important over monsoon-dominated regions such as the Western parts of Karnataka, India. This study investigates the climatological characteristics and trends of Aerosol Optical Depth (AOD) and rainfall over the region bounded by 12°–15° N latitude and 74°–78° E longitude for the period 2001–2024 using satellite-based observations. Monthly AOD data were obtained from the MODIS Terra Collection 6.1 Level-3 product, while rainfall estimates were used from the GPM IMERG Final Run dataset. The results reveal a distinct seasonal cycle in both AOD and rainfall. Rainfall exhibits a pronounced monsoonal peak during June–September, with maximum values observed in July, reflecting the dominance of the southwest monsoon over the region. AOD shows elevated values during the pre-monsoon months, associated with increased dust loading and anthropogenic emissions, followed by a reduction during the monsoon due to wet scavenging processes. However, relatively higher AOD values are also observed during peak monsoon months, which may be attributed to enhanced marine aerosol transport, hygroscopic growth under high humidity conditions, and transport of desert dust. Long-term trend analysis indicates interannual variability in AOD and rainfall, highlighting the influence of both regional emissions and large-scale climatic processes. This study provides a satellite-based assessment of aerosol and rainfall variability over the Western parts of Karnataka and contributes to a better understanding of aerosol–monsoon interactions in a climatically sensitive region. The findings are relevant for climate change with respect to build up rainfall has no role on rainfall of the study area. The results are useful for environmental management, and regional sustainability planning.

Index Terms - Aerosol Optical Depth (AOD), Rainfall Variability, MODIS, GPM IMERG, Western Karnataka.

1. Introduction

Atmospheric aerosols are an important component of the climate system, influencing Earth's energy balance directly by scattering and absorbing solar radiation and indirectly by modifying cloud properties and precipitation processes (IPCC, 2021). Aerosol–cloud–precipitation interactions remain one of the largest sources of uncertainty in climate predictions, particularly over tropical and monsoon-affected regions (Rosenfeld et al., 2008).

India experiences a strong seasonal cycle driven by the southwest monsoon, which accounts for nearly 70% of the annual rainfall (Gadgil, 2003). The Western Ghats, including the Western parts of Karnataka, play a critical role in orographic rainfall enhancement during the monsoon season. Aerosol loading over this region varies significantly due to natural sources such as sea salt and dust, as well as anthropogenic emissions from biomass burning and urban activities (Ramachandran et al., 2012).

Satellite observations have become indispensable for monitoring aerosols and precipitation over large spatial and temporal scales. The Moderate Resolution Imaging Spectroradiometer (MODIS) provides long-term global aerosol observations, widely used for climatological and trend studies (Platnick et al., 2017). Similarly, the Global Precipitation Measurement (GPM) mission offers high-resolution and reliable precipitation estimates, particularly through the IMERG Final Run product (Huffman et al., 2020). Despite several studies on aerosols and rainfall over India, region-specific long-term analyses focusing on the Western parts of Karnataka remain limited.

In this context, the present study aims to examine the climatology and long-term variability of aerosol optical depth and rainfall over the Western parts of Karnataka (12° – 15° N, 74° – 78° E) using long-term satellite observations from 2001 to 2024. By analysing monthly, seasonal, and annual variations, this study seeks to improve understanding of aerosol and rainfall behaviour in a climatically sensitive region and provide insights relevant to climate change and environmental sustainability.

2. Study Area

The study focuses on the western parts of Karnataka, India, located along the windward side of the Western Ghats Mountain range, bounded by 12° – 15° N latitude and 74° – 78° E longitude. This region includes coastal and adjoining hilly areas characterized by complex topography, dense vegetation, and strong land–atmosphere interactions. The Western Ghats act as a major orographic barrier, forcing moisture-laden south-westerly winds to ascend, resulting in heavy monsoonal rainfall during the southwest monsoon season.

Climatically, the region experiences a tropical monsoon climate with four distinct seasons: winter (December–February), pre-monsoon (March–May), southwest monsoon (June–September), and post-monsoon (October–November). Annual rainfall is predominantly concentrated during the monsoon months, with July often recording the highest precipitation. Due to its proximity to the Arabian Sea, the region is also influenced by marine aerosols, long-range transported dust, and anthropogenic emissions from coastal and inland sources. These factors make the western parts of Karnataka a climatically sensitive region for studying aerosol variability and its association with rainfall.

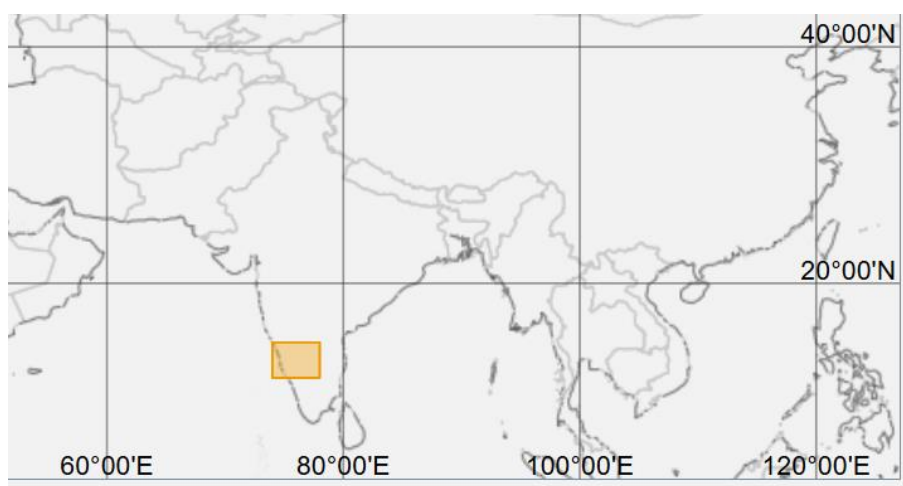


Figure 1. Study area showing the Western parts of Karnataka State (12° – 15° N, 74° – 78° E).

3. Methodology

The monthly mean Aerosol Optical Depth at 550 nm was obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra Level-3 Collection 6.1 dataset (MOD08_M3). MODIS AOD products have been extensively validated and are widely used for aerosol climatology studies (Platnick et al., 2017). Monthly AOD data were extracted for the study region using the NASA GES DISC, which provides a wide range of Earth observation datasets. Area-averaged values were generated for the period January 2001 to December 2024, ensuring uniform spatial and temporal sampling across the study domain.

Rainfall data were obtained from the Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) Final Run product (Version 07). The IMERG Final Run dataset integrates satellite observations with gauge-based precipitation measurements and is recommended for climatological and hydrological studies (Huffman et al., 2020). Monthly rainfall estimates were extracted for the same spatial domain (12° – 15° N, 74° – 78° E) and time period as the AOD data to ensure consistency.

The rainfall data were originally provided in inches per month and subsequently converted to millimeters. Area-averaged monthly rainfall values were computed to examine seasonal and interannual variability and to facilitate comparison with aerosol climatology. The AOD dataset corresponds to MODIS Terra monthly Level-3 observations at 550 nm, while rainfall estimates were

obtained from the GPM IMERG Final Run product. Both datasets were harmonized to a common temporal resolution (monthly) to ensure comparability.

To examine the seasonal behaviour of aerosols and rainfall, monthly climatologies were constructed by averaging each calendar month over the entire study period (2001–2024). This approach highlights recurring seasonal patterns and reduces the influence of short-term variability. Seasonal means were further computed based on standard meteorological seasons: winter (December–February), pre-monsoon (March–May), southwest monsoon (June–September), and post-monsoon (October–November).

Long-term variability in aerosol loading was assessed using annual mean values derived from monthly observations and for rainfall, it was assessed using annual total rainfall derived by summing monthly rainfall values for each year. Linear regression analysis was applied to the annual time series to estimate trends over the study period. The goodness of fit was evaluated using the coefficient of determination (r), which provides a measure of how well the regression model explains interannual variability. Trend lines were visually examined to identify increasing or decreasing tendencies in AOD and rainfall. To explore the relationship between aerosol loading and precipitation, monthly climatological AOD and rainfall were analysed together using a combined graphical approach. This enabled the identification of seasonal co-variability and contrasting patterns between aerosol abundance and rainfall intensity. Particular attention was given to monsoon and pre-monsoon periods, during which aerosol–meteorology interactions are expected to be most pronounced.

4. Results and Discussion

4.1 Interannual variation of Rainfall

The interannual variability of annual total rainfall over the western parts of Karnataka during the period 2001–2024 is shown in Figure 2. The region exhibits substantial year-to-year variability in rainfall, with annual totals ranging from approximately 1200 mm to over 2000 mm, reflecting fluctuations in the strength and spatial distribution of the southwest monsoon.

Several years, such as 2007, 2010, 2020, and 2024, recorded relatively higher rainfall amounts, indicating stronger monsoon activity and enhanced moisture transport towards the windward slopes of the Western Ghats. In contrast, comparatively lower rainfall was observed during years such as 2002, 2012, and 2016, which may be associated with weaker monsoon circulation or unfavourable large-scale atmospheric conditions.

Despite pronounced interannual fluctuations, the rainfall time series does not exhibit a clear monotonic increasing or decreasing trend over the study period. This suggests that rainfall variability over the region is predominantly governed by natural climate variability, particularly variations in monsoon dynamics, rather than long-term linear change. Similar interannual variability in monsoon rainfall has been widely reported over peninsular India, emphasizing the sensitivity of regional precipitation to large-scale atmospheric circulation patterns.

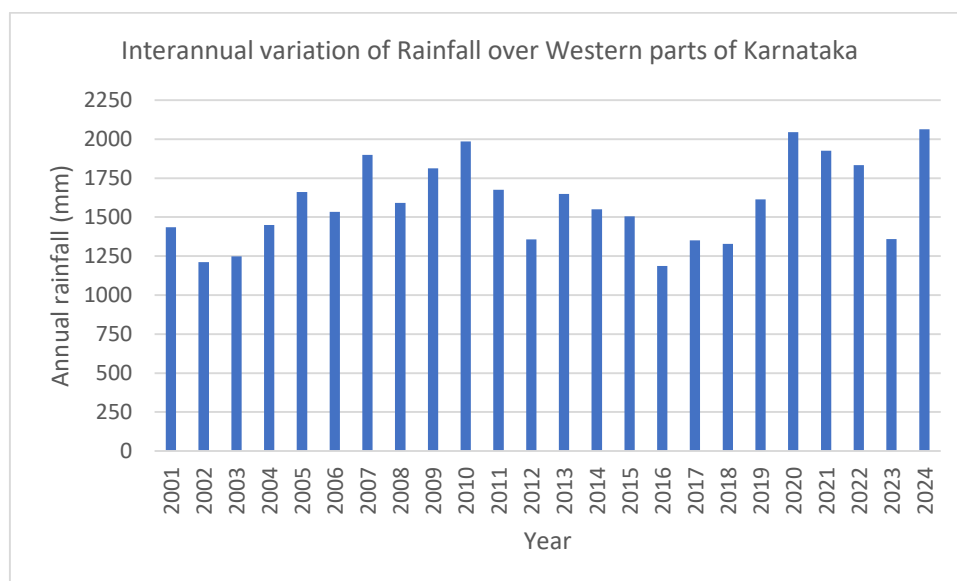


Figure 2. Interannual variability of annual rainfall over the Western parts of Karnataka State during 2001-2024.

4.2 Monthly Rainfall Climatology

The monthly rainfall climatology over the western parts of Karnataka for the period 2001–2024 reveals a pronounced seasonal cycle dominated by the southwest monsoon (Figure 3). Rainfall during the winter months (December–February) remains minimal, with mean monthly values generally below 20 mm, indicating dry atmospheric conditions and weak convective activity.

A gradual increase in rainfall is observed during the pre-monsoon months (March–May), reflecting the buildup of moisture and increasing atmospheric instability prior to the onset of the monsoon. Rainfall increases sharply from June, marking the arrival of the southwest monsoon, and reaches a maximum during July, with mean monthly rainfall exceeding 350 mm. Elevated rainfall continues through August and September, highlighting the sustained influence of monsoonal circulation and orographic lifting along the Western Ghats.

During the post-monsoon period (October–November), rainfall decreases progressively as the southwest monsoon withdraws from the region. The strong concentration of rainfall during the monsoon months underscores the critical role of large-scale monsoon dynamics and regional topography in controlling precipitation over the western parts of Karnataka. This seasonal rainfall pattern provides an essential background for understanding aerosol variability and aerosol–rainfall interactions over the study region.

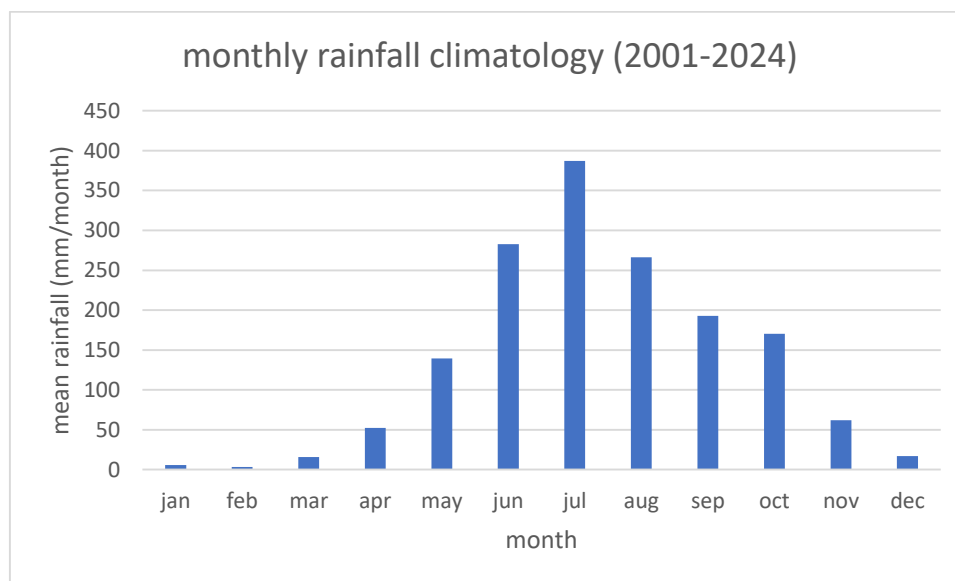


Figure 3. Monthly rainfall climatology over the western parts of Karnataka State during 2001–2024

4.3 Long-Term Trend in Aerosol Optical Depth

The interannual variability and long-term trend of annual mean aerosol optical depth (AOD at 550 nm) over the western parts of Karnataka during the period 2001–2024 are illustrated in Figure 4. The AOD time series exhibits noticeable year-to-year fluctuations, indicating substantial variability in aerosol loading over the region.

A linear regression applied to the annual mean AOD values suggests a weak increasing tendency over the study period. The fitted trend line indicates a gradual rise in AOD, while the coefficient of determination ($R^2 \approx 0.5$) reflects a moderate level of agreement between the observed values and the linear trend. This suggests that although a long-term increase in aerosol loading is present, interannual variability driven by meteorological conditions and episodic emission events also plays a significant role.

The observed increase in AOD may be attributed to a combination of factors, including growing anthropogenic emissions, regional urbanization, and changes in land-use practices over southern India. However, the absence of a strong monotonic trend highlights the influence of natural variability, particularly monsoon strength and atmospheric circulation patterns, in modulating aerosol concentrations over the study region.

These results are consistent with previous studies reporting weak to moderate increases in aerosol loading over parts of peninsular India during the satellite era. The long-term AOD trend provides an important context for interpreting seasonal aerosol behaviour and its interaction with regional rainfall patterns.

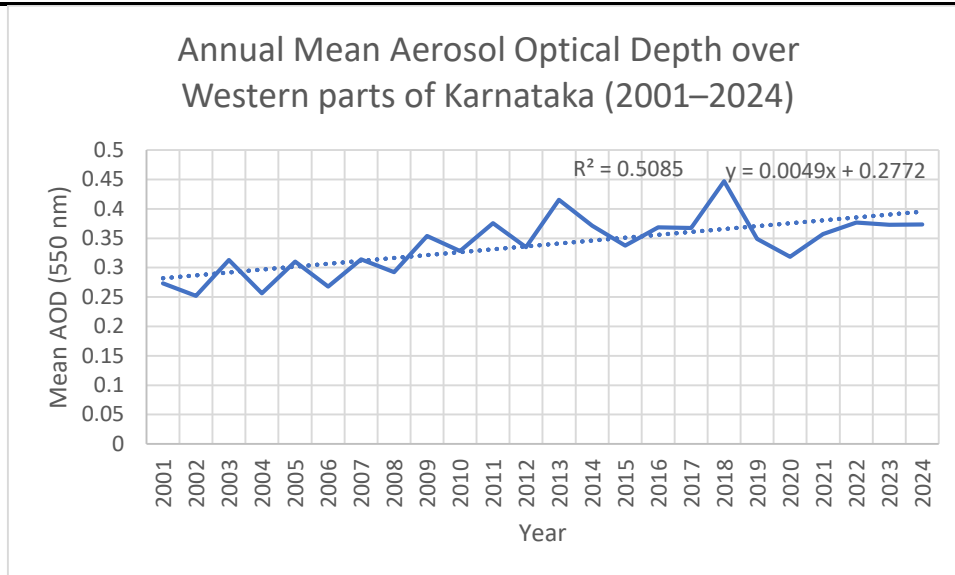


Figure 4. Annual mean aerosol optical depth (AOD) at 550 nm over the western parts of Karnataka State during 2001-2024.

4.4 Monthly Climatology of Aerosol Optical Depth

The monthly climatology of aerosol optical depth (AOD at 550 nm) over the western parts of Karnataka for the period 2001–2024 exhibits distinct seasonal variability (Figure 5). Lower AOD values are observed during the winter months (December–February), indicating relatively clean atmospheric conditions associated with reduced emission sources and stable meteorological conditions.

AOD shows a gradual increase during the pre-monsoon months (March–May), with peak values occurring during April and May. This enhancement may be attributed to increased dust transport, biomass burning activities, and intensified anthropogenic emissions under dry and convectively active conditions. Elevated boundary-layer heights and enhanced atmospheric mixing during the pre-monsoon season can further contribute to increased aerosol loading.

During the southwest monsoon months (June–September), AOD values exhibit mixed behaviour. While rainfall-driven wet scavenging is expected to reduce aerosol concentrations, relatively elevated AOD values are observed during certain monsoon months, particularly July. This behaviour can be explained by the combined influence of marine aerosol transport from the Arabian Sea, hygroscopic growth of aerosols under high humidity conditions, and uncertainties in satellite aerosol retrievals in cloudy environments.

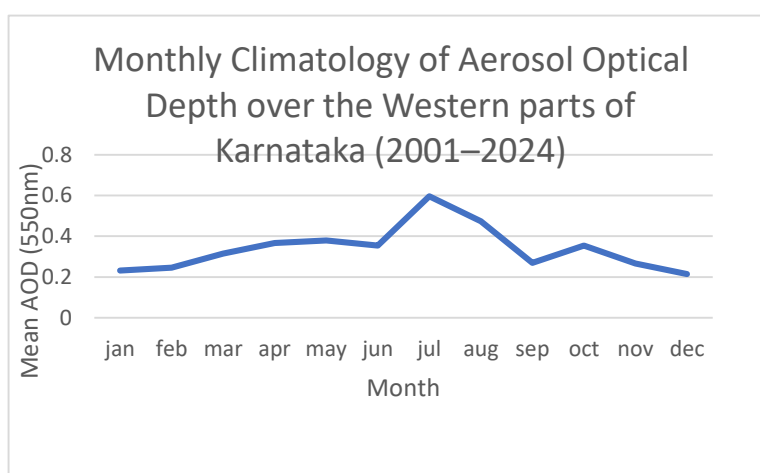


Figure 5. Monthly climatology of Aerosol optical depth (AOD) at 550 nm over the Western parts of Karnataka State (2001-2024).

Following the monsoon season, AOD values decrease during the post-monsoon months (October–November), reflecting reduced aerosol emissions and improved atmospheric cleansing by prior rainfall. The observed monthly AOD climatology highlights the complex interplay between aerosol sources, meteorology, and removal processes over the western parts of Karnataka.

4.5 Seasonal Mean Aerosol Optical Depth

The seasonal mean aerosol optical depth (AOD at 550 nm) over the western parts of Karnataka during 2001–2024 is shown in Figure 6. Clear seasonal contrasts are observed, reflecting the influence of both emission sources and meteorological conditions on aerosol loading.

The lowest seasonal mean AOD values occur during the winter season (DJF), corresponding to relatively stable atmospheric conditions, reduced long-range transport, and minimal regional emission activity. This period is characterised by cleaner atmospheric conditions over the study region.

AOD values increase during the pre-monsoon season (MAM), consistent with enhanced dust transport, biomass burning, and anthropogenic emissions under dry conditions. Increased atmospheric mixing and boundary-layer height during this season further contribute to elevated aerosol concentrations.

The southwest monsoon season (JJAS) exhibits the highest seasonal mean AOD values. Although monsoonal rainfall is expected to reduce aerosol loading through wet scavenging, elevated AOD during this season suggests the influence of marine aerosols transported from the Arabian Sea and hygroscopic growth of aerosols under high relative humidity conditions. Additionally, persistent cloud cover during the monsoon may introduce uncertainties in satellite-based aerosol retrievals, contributing to apparent increases in AOD.

During the post-monsoon season (ON), AOD values decrease relative to monsoon levels, reflecting reduced aerosol sources and effective atmospheric cleansing by preceding monsoon rainfall. The seasonal variation of AOD highlights the dominant role of regional meteorology in regulating aerosol optical properties over the western parts of Karnataka.

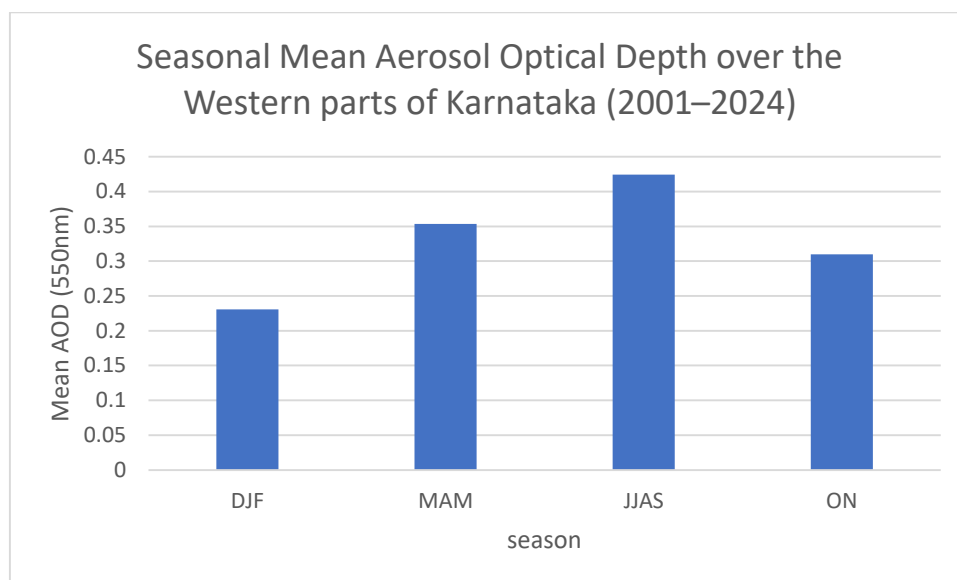


Figure 6. Seasonal mean aerosol optical depth (AOD) at 550 nm over the Western parts of Karnataka State (2001-2024).

4.6 Relationship Between AOD and Rainfall

The relationship between aerosol optical depth (AOD) and rainfall over the western parts of Karnataka was examined using monthly climatological values of both parameters (Figure 7) and with respect time (Figure 8). The comparison reveals a clear seasonal contrast between aerosol loading and precipitation, highlighting the complex interactions between aerosols and monsoon-driven meteorology.

Rainfall exhibits a sharp increase during the southwest monsoon months (June–September), with peak precipitation occurring in July, whereas AOD shows relatively elevated values during the pre-monsoon and early monsoon periods. During the peak monsoon season, enhanced rainfall is generally associated with a reduction in aerosol concentrations, indicating the role of wet scavenging, whereby precipitation efficiently removes aerosols from the atmosphere.

However, the coexistence of relatively high AOD and intense rainfall during certain monsoon months suggests that aerosol–rainfall interactions over this region are not governed by a simple inverse relationship. Factors such as marine aerosol transport from the Arabian Sea, hygroscopic growth of aerosols under high relative humidity, and limitations of satellite aerosol retrievals in cloudy conditions may contribute to elevated AOD during periods of high rainfall.

The results emphasize that regional meteorology plays a dominant role in controlling both aerosol loading and precipitation over the western parts of Karnataka. Rather than implying direct causality, the observed patterns highlight the importance of large-scale circulation, orographic effects, and atmospheric moisture in shaping aerosol–rainfall variability. These findings underline the need for cautious interpretation of satellite-derived aerosol products in monsoon-dominated regions and demonstrate the value of long-term climatological analyses for understanding aerosol–precipitation interactions.

Further, the relationship among annual trend of rainfall and AOD and with the rainfall and AOD themselves are shown in Figure 8. Although there is good positive correlation of AOD and to lesser extent rainfall with respect to years, the relationship between AOD and rainfall is low, implying that the building up of mineral aerosol in the atmosphere is not a regulating factor of rainfall. The aerosol Optical Depth (AOD), indicates the build-up of atmospheric aerosols, for instance, such as dust, forest smoke, and atmospheric pollution, shows a clear increasing trend over the study period (Figure 8). In contrast, rainfall tends to be weakly long-term increasing trend increasing with respect to years. Although AOD and rainfall tend to increase over time, their direct relationship seems to be weak, implying that build-up of aerosols do not strongly control rainfall variability. The weak correlation of rainfall with AOD suggests that rainfall is seems to be influenced by meteorological/climatic factors, for eg., atmospheric circulation, atmospheric temperature, moisture source rather than aerosol concentrations alone.

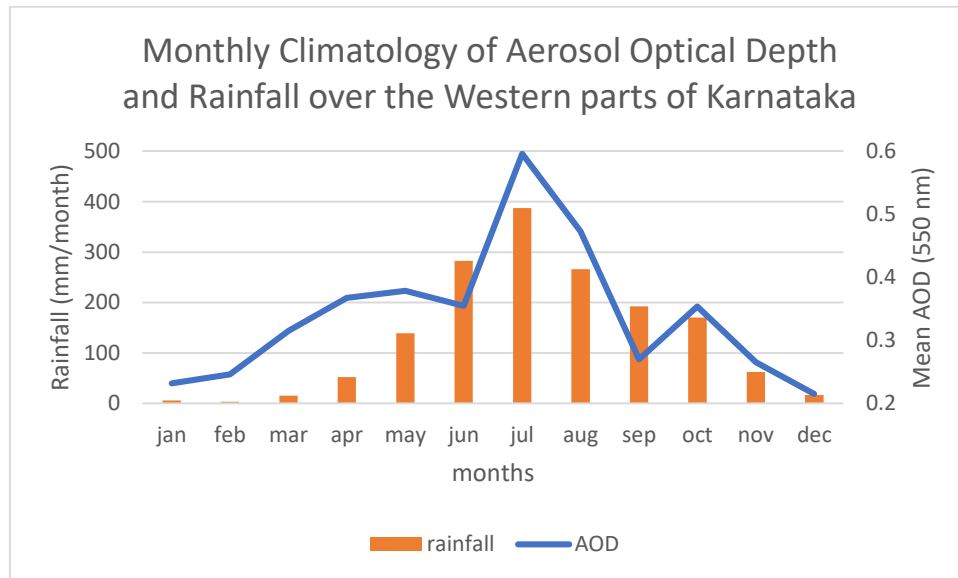


Figure 7. Monthly climatology of Aerosol Optical Depth (AOD) at 550 nm and Rainfall over the Western parts of Karnataka State.

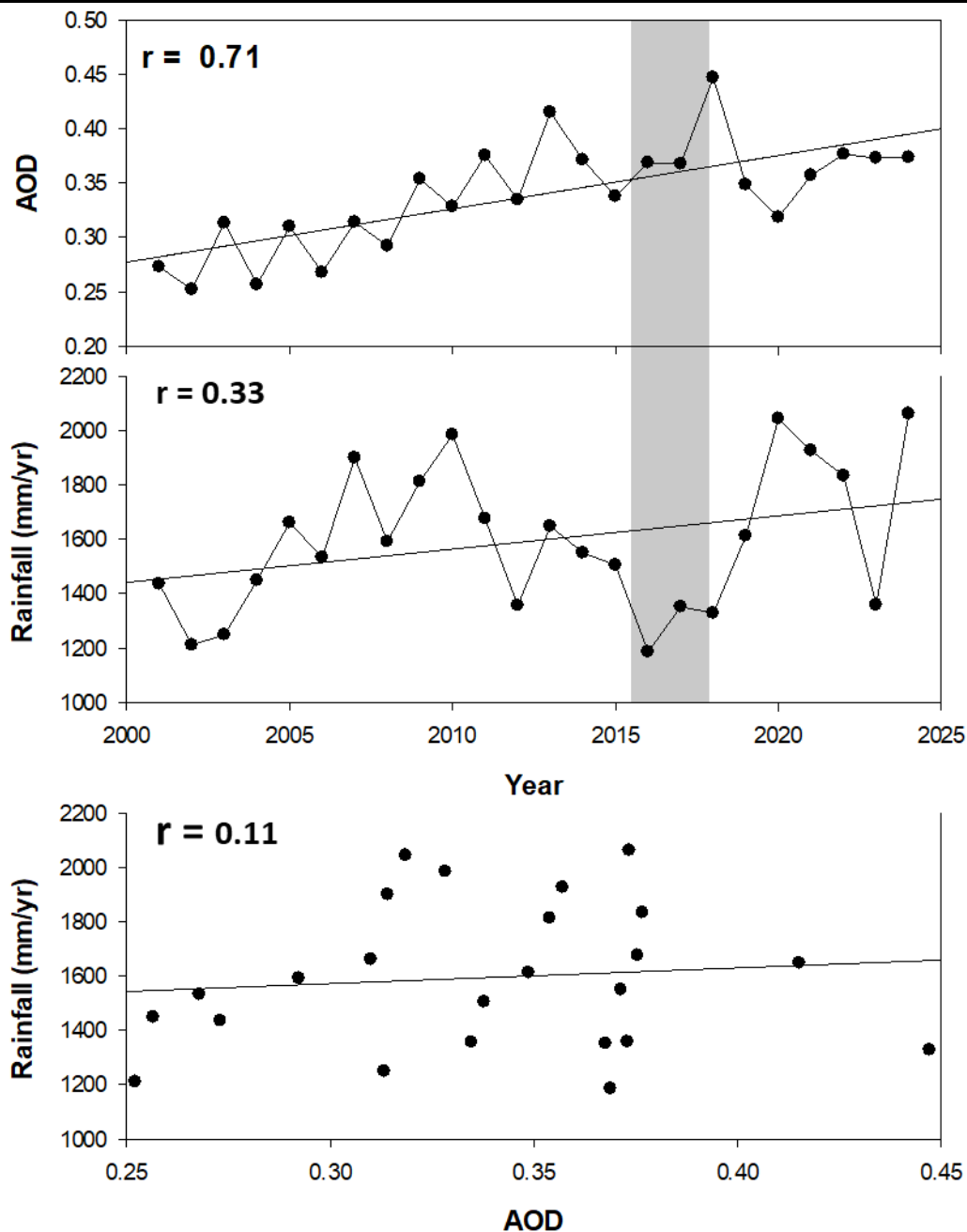


Figure.8. Relationship among AOD and rainfall in recent years.

5. Conclusions

This study presents a comprehensive satellite-based analysis of aerosol optical depth (AOD) and rainfall variability over the western parts of Karnataka (12–15°N, 74–78°E) for the period 2001–2024. Using long-term MODIS Terra aerosol observations and GPM IMERG rainfall data, the study examines interannual variability, monthly and seasonal climatology, and the relationship between aerosols and precipitation in a monsoon-dominated and topographically complex region.

The results reveal pronounced interannual variability in annual rainfall, primarily driven by fluctuations in southwest monsoon strength, with no clear long-term increasing or decreasing trend over the study period. Monthly rainfall climatology highlights the dominance of the southwest monsoon, with peak precipitation occurring during July, emphasizing the role of large-scale circulation and orographic lifting along the Western Ghats. In contrast, aerosol optical depth exhibits distinct seasonal variability, with lower values during winter, enhanced loading during the pre-monsoon season, and relatively elevated values during the monsoon months. Trend analysis of annual mean AOD indicates a weak increasing tendency over the study region, accompanied by considerable year-to-year variability. This suggests that aerosol loading over the western parts of Karnataka is influenced by a combination of anthropogenic emissions, natural sources, and meteorological factors. The combined analysis of AOD and rainfall climatology indicates that increased monsoon rainfall generally contributes to aerosol removal through wet scavenging, although elevated AOD during certain monsoon months highlights the influence of marine aerosols, hygroscopic growth, and satellite retrieval uncertainties under cloudy conditions. Overall, the study underscores the complexity of aerosol–rainfall interactions over monsoon-affected regions and demonstrates the value of long-term satellite observations for regional climate analysis. The findings provide a useful baseline for future studies focusing on aerosol composition, aerosol–cloud interactions, and climate change impacts over the Western

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Ghats region. Such insights are essential for supporting climate adaptation strategies, air quality management, and environmental sustainability planning.

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