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Full Length Research Article

SPATIO-TEMPORAL VARIABILITY AND CLIMATIC DRIVERS OF HARMATTAN DUST OVER NORTHEAST NIGERIA USING MERRA-2 REANALYSIS

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ABSTRACT

Harmattan dust significantly affects air quality, visibility, public health, and regional climate across Northeast Nigeria; however, its long-term variability and climatic controls remain insufficiently quantified. This study investigates the spatio-temporal variability and climatic drivers of Harmattan dust over Northeast Nigeria from 1980 to 2025. Aerosol Optical Depth (AOD) at 550 nm was used as a proxy for atmospheric dust concentration. AOD data were obtained from NASA's MERRA-2 reanalysis and MODIS aerosol products; similarly, wind speed data were sourced from ERA5 reanalysis, and rainfall and temperature data were derived from the Climate Research Unit (CRU) dataset. An Inter-Tropical Discontinuity (ITD) index was computed from reanalysis pressure and wind fields. Seasonal (December–February) averages were extracted to represent peak Harmattan conditions. Descriptive statistics, spatial mapping, Mann–Kendall trend analysis, Pearson correlation, and multiple linear regression were employed to assess variability and climatic relationships. Results reveal a persistent north–south AOD gradient, with the highest dust concentrations in Yobe and northern Borno States. AOD increased significantly between 1980 and 1995, stabilized between 1995 and 2010, and declined moderately after 2010. Wind speed emerged as the dominant driver ($r = 0.71$, $p < 0.001$), followed by ITD displacement, while rainfall showed a strong negative relationship ($r = -0.63$). Atmospheric circulation dynamics are the primary control of Harmattan dust intensity, as confirmed by the regression model's 68% contribution to AOD variability. Strengthening early warning systems, improving regional climate monitoring, and integrating dust forecasting into environmental policy are recommended to mitigate impacts.

Keywords: Harmattan dust; Aerosol Optical Depth (AOD); Northeastern Nigeria; Spatio-temporal variability; Climatic drivers; MERRA-2 reanalysis

INTRODUCTION

Atmospheric aerosols are a fundamental component of the Earth-atmosphere system, influencing radiative forcing, atmospheric chemistry, cloud microphysics, hydrological processes, and surface-atmosphere energy exchange (Garnés-Morales et al., 2023). Among natural aerosols, mineral dust represents one of the most climatically significant constituents because of its abundance, long atmospheric residence time, and capacity for long-range transport (Nishita-Hara et al., 2023). Globally, the Sahara Desert is recognized as the largest source of mineral dust emissions, contributing a substantial proportion of the world's atmospheric dust burden (Georgakopoulou et al., 2024). Each year, large quantities of fine and coarse mineral particles are uplifted by strong surface winds and transported across West Africa, the Atlantic Ocean, Europe, and even the Americas (Yu et al., 2019). Consequently, the West African sub-region lies within one of the most dynamic and globally influential dust corridors (Rosas et al., 2025).

The Harmattan season, a defining climatological feature of West Africa, is characterized by the prevalence of dry, dust-laden northeasterly trade winds originating over the Sahara Desert (Sufiyan et al., 2020). Occurring primarily between November and March, the Harmattan is associated with low humidity, reduced visibility, and substantial atmospheric dust loading (Okeahialam, 2016). During this period, continental air masses dominate over maritime influences, and dust transport intensity is largely governed by atmospheric pressure gradients, wind strength, boundary-layer stability, and surface dryness. The seasonal migration of the Inter-Tropical Discontinuity (ITD), which separates dry continental air from moist maritime air, plays a crucial role in regulating the spatial reach and persistence of Harmattan dust (Knippertz & Fink, 2008). When the ITD shifts southward, dry Saharan air penetrates farther into West Africa, thereby expanding the geographic extent of dust intrusion and intensifying it.

Northeast Nigeria occupies a climatically sensitive transitional zone between the arid Sahel and the relatively humid Guinea savanna. The region comprises Borno, Yobe, Bauchi, Gombe, Adamawa, and Taraba States and exhibits marked ecological heterogeneity (Ahmad et al., 2025). Northern portions of Yobe and Borno fall within the Sahelian belt, characterized by low annual rainfall, sparse vegetation, sandy soils, and high evapotranspiration rates (Yahaya et al., 2024). These environmental conditions create surfaces that are highly susceptible to dust deposition and resuspension. Moving southward, the Sudan savanna zone, encompassing Bauchi and Gombe States, represents an intermediate ecological transition characterized by moderate rainfall and seasonal vegetation cover (Khalifa et al., 2025). Further south, the Adamawa Plateau and Taraba highlands experience relatively higher precipitation, greater vegetation density, and more complex topography, which collectively reduce dust intensity compared to northern areas. This ecological gradient creates a pronounced north–south variability in dust distribution, making the region ideal for spatio-temporal analysis of aerosols.

The environmental implications of Harmattan dust are substantial (Okeahialam, 2016). Elevated dust concentrations reduce horizontal visibility, disrupt aviation operations, impair road transportation, and increase the frequency of traffic accidents (Alsubhi et al., 2025). Agricultural productivity may be affected by foliar deposition and soil surface alteration. Infrastructure experiences accelerated weathering due to particulate abrasion (Nuruzzaman et al., 2025). From a climatic perspective, mineral

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dust influences both shortwave and longwave radiation by scattering and absorbing solar energy (Simiyu et al., 2025). This interaction can produce cooling effects at the surface while warming the lower atmosphere, thereby altering atmospheric stability and regional circulation patterns. Dust particles also serve as cloud condensation nuclei and ice nuclei, modifying cloud formation processes and precipitation efficiency. Thus, Harmattan dust is not merely a seasonal nuisance but an active climatic agent within the regional Earth system (Chen et al., 2024).

Public health impacts further emphasize the importance of understanding dust variability (Tobias et al., 2025). Fine particulate matter associated with mineral dust contributes to respiratory diseases, asthma exacerbation, cardiovascular complications, and eye irritation. Vulnerable populations, including children and the elderly, are particularly at risk during intense dust outbreaks (Hamidian et al., 2025). Across rapidly expanding urban centers in Northeast Nigeria, where healthcare systems are frequently under pressure, rising dust exposure constitutes a major challenge to environmental health.

Despite the recognized impacts of Harmattan dust, long-term quantitative assessments of its variability over Northeast Nigeria remain limited (Brooks & Legrand, 2000; Musa & Ogbe, 2025; Olakunle & Durojaiye, 2025). Recent advancements in satellite remote sensing and atmospheric reanalysis have significantly enhanced the capacity to monitor aerosols consistently over extended periods. Aerosol Optical Depth (AOD), particularly at 550 nm wavelength, provides a robust measure of column-integrated aerosol concentration and has become a widely accepted indicator of atmospheric dust loading (Haseeb et al., 2024). Reanalysis datasets such as NASA's Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2), alongside satellite platforms such as MODIS, now offer continuous, spatially comprehensive aerosol records extending several decades (Jadhav et al., 2025). When integrated with reanalysis-based meteorological variables such as wind speed, rainfall, temperature, and pressure gradients, these datasets enable detailed investigation of the climatic mechanisms governing dust variability.

Climatic drivers influence dust dynamics through interconnected processes (Wallum et al., 2025). Wind speed directly determines dust entrainment and transport efficiency; stronger winds increase surface friction velocity, facilitating particle uplift and long-range dispersion (Assefa et al., 2025). Rainfall influences soil moisture content and enhances wet deposition, thereby reducing airborne dust concentration. Temperature affects surface desiccation and atmospheric instability, promoting vertical mixing and dust uplift during intense heating (Alipour, 2023). The seasonal and inter-annual migration of the ITD regulates the dominance of continental dry air masses and determines the duration of Harmattan conditions (Baba et al., 2022). Variability in these factors, driven by broader atmospheric circulation changes and regional climate oscillations, shapes the temporal evolution of dust concentration across the Sahelian belt (Isa et al., 2023). The post-2000 period has witnessed partial rainfall recovery across the Sahel after decades of severe drought. However, the extent to which this hydrological improvement has moderated dust intensity remains uncertain (Abdussalam et al., 2025). While increased rainfall may suppress dust through enhanced surface moisture and deposition processes, strengthened atmospheric circulation or rising temperatures could offset these effects. Consequently, understanding the balance between competing climatic drivers is essential for explaining observed dust trends.

Furthermore, climate change projections suggest potential alterations in atmospheric circulation patterns, temperature regimes, and precipitation variability across West Africa (Isa et al., 2023). These changes may influence future dust emission and transport dynamics. Establishing a robust historical baseline of Harmattan dust variability is therefore critical for improving seasonal forecasting models, refining climate simulations, and informing adaptation policies. In view of the ecological sensitivity, socio-economic importance, and climatic significance of Northeast Nigeria, there is a pressing need for a comprehensive, multi-decadal assessment of Harmattan dust variability and its climatic controls. By integrating long-term AOD datasets with key atmospheric variables and applying rigorous statistical and spatial analyses, this study seeks to provide empirical evidence on the dominant drivers shaping dust intensity across the region. Such knowledge is vital for strengthening early warning systems, guiding environmental management, protecting public health, and enhancing climate resilience strategies in semi-arid West Africa.

STUDY AREA AND METHODOLOGY

This study examined the spatio-temporal variability and climatic drivers of Harmattan dust over Northeast Nigeria during 1980–2025. The study area comprises Borno, Yobe, Adamawa, Bauchi, Gombe, and Taraba States, located between latitudes 9.5°N and 13.8°N and longitudes 8.5°E and 14.7°E. (Figure 1). The region spans the Sahel, Sudan, and Guinea savanna ecological zones, characterized by a tropical continental climate with a distinct dry season (November–March) dominated by the Harmattan, a dry dusty-laden northeasterly trade wind originating from the Sahara Desert (Babati et al., 2021). The wet season extends from April to October under the influence of the West African Monsoon (Baba et al., 2022). The region's geographical position and seasonal atmospheric circulation make it highly vulnerable to trans-Saharan dust transport, thereby providing an appropriate setting for investigating long-term variability of dust and its climatic controls.

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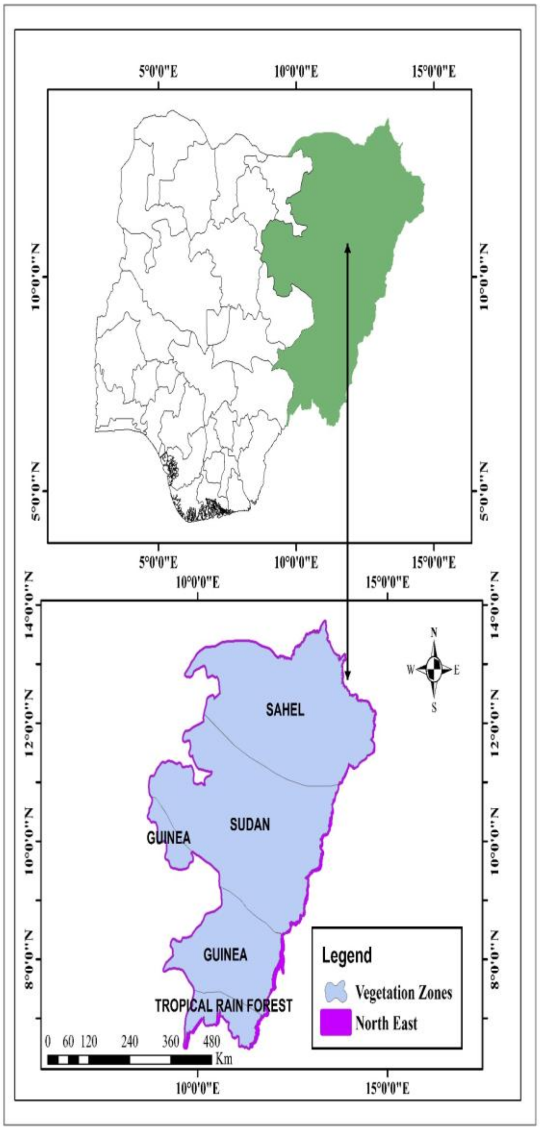

Figure 1: Map of North- East, Nigeria

Aerosol Optical Depth (AOD) data covering the period 1980–2025 were used as a proxy for atmospheric dust concentration. The AOD dataset was obtained from long-term satellite-derived and reanalysis aerosol products, including NASA's Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2) and Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol datasets. The AOD values were extracted at 550 nm, a wavelength widely used for aerosol monitoring and climate studies. The data were obtained in gridded format with spatial resolutions harmonized to 0.5° × 0.5° to ensure consistency across the entire study period. To specifically capture Harmattan dust conditions, seasonal averages were computed for the dry-season months of December, January, and February (DJF), representing peak dust activity. In addition to AOD, key climatic variables hypothesized to drive dust variability were obtained. Wind speed data were sourced from the ERA5 reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). Annual rainfall and dry-season temperature data were sourced from the Climate Research Unit (CRU TS) dataset and validated using available records from the Nigerian Meteorological Agency to ensure consistency. The Inter-Tropical Discontinuity (ITD) position index was derived from reanalysis wind and pressure fields to quantify seasonal southward displacement of dry continental air masses. All climatic datasets covered the same 1980–2025 period to maintain temporal alignment with AOD data.

Data preprocessing involved a series of standardization and quality control procedures to ensure analytical reliability. First, all gridded datasets were clipped to the boundary of Northeast Nigeria using ArcGIS 10.4. Spatial resampling was conducted to harmonize datasets to a uniform grid resolution. Seasonal aggregation was then performed by computing dry-season (DJF) means for each year to isolate Harmattan-specific dust dynamics. Missing values were identified and removed, while extreme outliers more than 3 standard deviations from the long-term mean were carefully examined and retained only when supported by regional dust-event records. Zonal statistics were subsequently calculated to derive state-level averages, minimum, and maximum AOD values. For regression analysis, all predictor variables were standardized to eliminate scale differences and reduce potential multicollinearity.

Descriptive statistical analysis was conducted to summarize the spatial and temporal characteristics of AOD across the study period. Mean, minimum, maximum, standard deviation, and coefficient of variation were calculated to assess variability patterns. Spatial analysis was performed using GIS software to generate distribution maps and identify persistent dust hotspots and north–south gradients across ecological zones. Temporal trend analysis was carried out using the non-parametric Mann–Kendall test, which is suitable for detecting monotonic trends in climatological time series without assuming normal distribution. Kendall's Tau coefficient was computed to determine the direction and strength of trends, while statistical significance was evaluated at the 95% confidence level.

To examine the relationships between AOD and climatic drivers, Pearson correlation analysis was performed to quantify the strength and direction of associations between AOD and wind speed, rainfall, temperature, and ITD displacement index. Statistical significance was assessed using p-values at 0.05 and 0.01 levels. Furthermore, multiple linear regression analysis was conducted to determine the combined influence of climatic variables on AOD variability. The regression model expressed AOD as a function of wind speed, rainfall, temperature, and the ITD index, with model performance evaluated using the coefficient of determination (R^2), adjusted R^2, F-statistic, and the significance of individual predictors. Multicollinearity among predictors was tested using the Variance Inflation Factor (VIF), ensuring that all values remained below acceptable thresholds. Residual diagnostics were performed to assess normality, homoscedasticity, and independence of errors, and the Durbin-Watson statistic was computed to test for autocorrelation. Model robustness was further evaluated through split-sample cross-validation to confirm predictive stability.

RESULTS AND DISCUSSION

Figure 2 shows the observed spatial pattern of Aerosol Optical Depth (AOD) in northeastern Nigeria in 1980. The findings reveal a distinct north-to-south gradient in dust loading. High AOD values, around 0.52 (represented in red orange), are concentrated in northern Borno and Yobe, indicating intense dust accumulation in

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these areas during that year. This pattern reflects the proximity of these regions to the Sahara Desert, the primary source of Harmattan dust. Moderate AOD values, ranging from 0.40 to 0.45 (yellow-green), are observed in central Gombe and Bauchi, suggesting that dust here is mainly transported from northern deserts via atmospheric layers, particularly the 850-hectopascal (hPa) wind stream. In contrast, low AOD values, around 0.29 (blue), are found in southern Adamawa and Taraba, which can be attributed to their greater distance from the Sahara, higher vegetation cover, and increased rainfall. These factors limit dust resuspension and deposition.

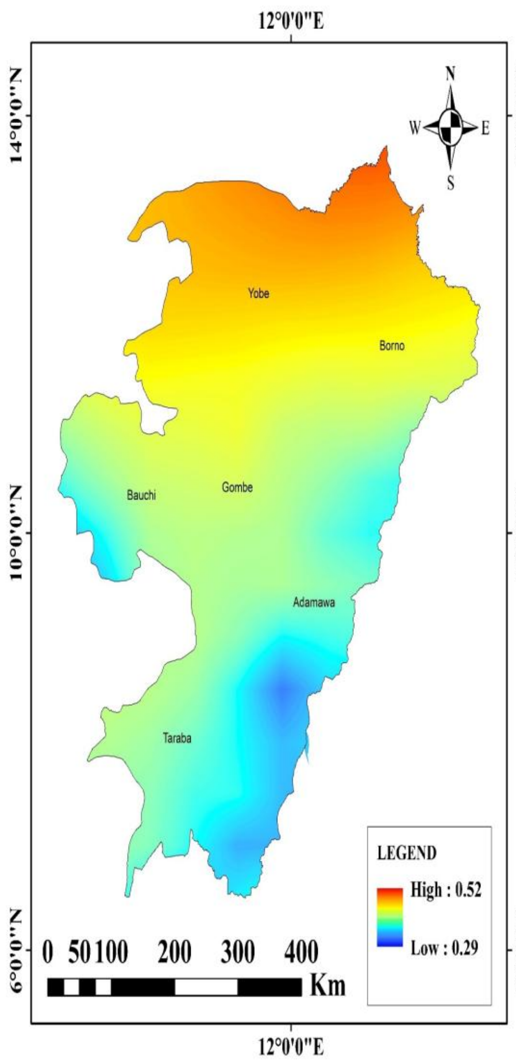

Figure 2: Aerosol Optical Depth (AOD) in Northeastern Nigeria in 1980

In terms of Harmattan dust dynamics, the northern states experience direct dust influx from the Sahara, driven by strong north-easterly winds characteristic of the Harmattan season from November to March. Central states show moderate dust accumulation, highlighting the role of long-range transport mechanisms. Southern states, however, accumulate less dust due to higher humidity and rainfall, which suppresses dust mobilization and deposition. Climatic drivers further explain this distribution: strong winds and higher temperatures in northern NE Nigeria facilitate dust uplift, while increased rainfall and vegetation in the southern parts reduce dust accumulation.

This 1980 spatial pattern provides a critical baseline for understanding the spatio-temporal variability of dust over the subsequent decades. Comparing this baseline to subsequent years (1980–2025) can reveal trends in the expansion or intensification of high AOD zones, shifts in dust hotspots potentially linked to land-use changes or desertification, and temporal anomalies associated with climate variability, including phenomena such as ENSO or regional rainfall deficits. Overall, these patterns highlight the combined influence of geography, climatic factors, and atmospheric transport in determining dust distribution across northeastern Nigeria.

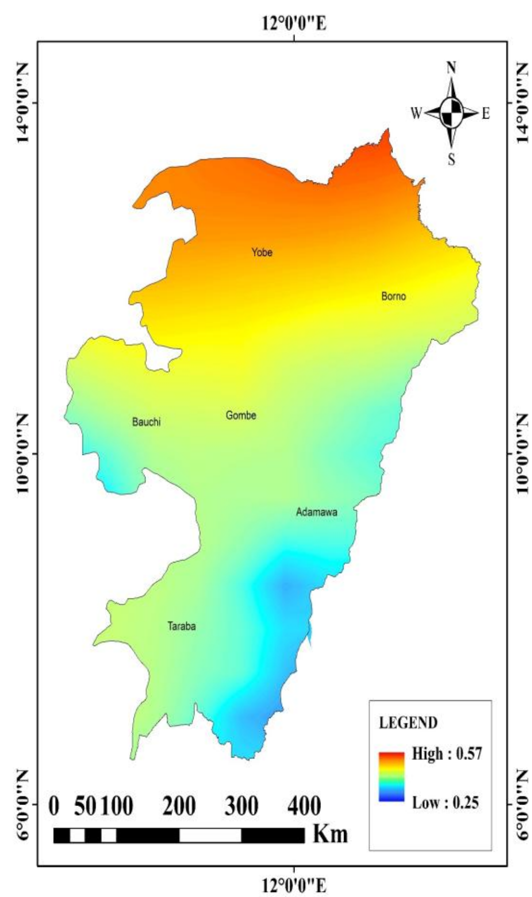

Figure 3: 1995 AOD map of Northeastern Nigeria

Figure 3 shows the 1995 AOD map of northeastern Nigeria. Findings reveal a continued clear north-to-south gradient in dust loading, consistent with the 1980 pattern but with slight spatial and intensity variations. Northern Borno and Yobe remain the regions with the highest AOD, approaching 0.57 (red-orange), indicating strong dust accumulation due to direct exposure to Sahara dust and persistent north-easterly Harmattan winds. Central states such

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as Gombe and Bauchi display moderate AOD values of roughly 0.40–0.45 (yellow-green), reflecting long-range transport of dust from northern sources via the 850 hPa wind layer. In contrast, southern states like Adamawa and Taraba continue to exhibit low AOD values around 0.25–0.30 (blue), indicating minimal dust deposition, likely suppressed by higher rainfall, dense vegetation, and increased surface moisture.

A direct comparison between the 1980 and 1995 AOD maps reveals both persistence and intensification in the spatial structure of Harmattan dust over northeastern Nigeria. In both years, a pronounced north–south gradient is evident, confirming the strong geographical control of proximity to the Sahara on dust distribution. However, in 1995, the maximum AOD values increased from approximately 0.52 in 1980 to about 0.57, particularly across northern Borno and Yobe. This suggests a relative intensification of dust loading in the mid-1990s. Such an increase may be associated with stronger Harmattan winds, prolonged dry conditions, or enhanced surface exposure due to land degradation and desertification processes during the intervening years.

Spatially, the high AOD zone in 1995 appears slightly more extensive, extending farther into central areas than in 1980. Moderate AOD values observed in Gombe and Bauchi indicate enhanced dust transport, potentially driven by stronger 850 hPa northeasterly flows by reduced surface vegetation, which may facilitate secondary dust uplift. This suggests that although the primary dust source remains external (the Sahara), regional land-surface conditions are increasingly amplifying dust levels. The southern states of Adamawa and Taraba continue to maintain relatively low AOD values (around 0.25–0.30), reinforcing the buffering role of higher rainfall, denser vegetation, and increased atmospheric moisture in suppressing dust suspension and deposition.

From a climatic driver's perspective, the 1995 intensification aligns with periods in the 1990s characterized by rainfall variability and recurrent drought episodes in parts of northern Nigeria. Reduced precipitation would have lowered soil moisture, increasing surface erodibility and susceptibility to wind-driven dust uplift. Additionally, elevated surface temperatures and stronger wind speeds would likely enhance vertical mixing and promote aerosol transport. The persistence of the north–south gradient confirms that the Harmattan circulation system remains the dominant atmospheric mechanism controlling dust distribution, while interannual climatic variability modulates its magnitude.

In terms of spatio-temporal variability, the 1995 pattern represents a strengthening phase within the long-term dust regime. It suggests that Harmattan dust intensity is not static but fluctuates in response to climatic oscillations, land-use dynamics, and regional atmospheric circulation patterns. The increase in peak AOD values and slight expansion of moderate zones point to potential early signals of environmental stress, including desertification and vegetation decline. Thus, the 1980–1995 comparison highlights both structural stability (consistent spatial gradients) and temporal variability (changes in intensity), providing a crucial foundation for assessing long-term trends up to 2025 and determining whether dust hotspots are intensifying, shifting spatially, or responding to broader climatic variability, such as ENSO-related rainfall anomalies."

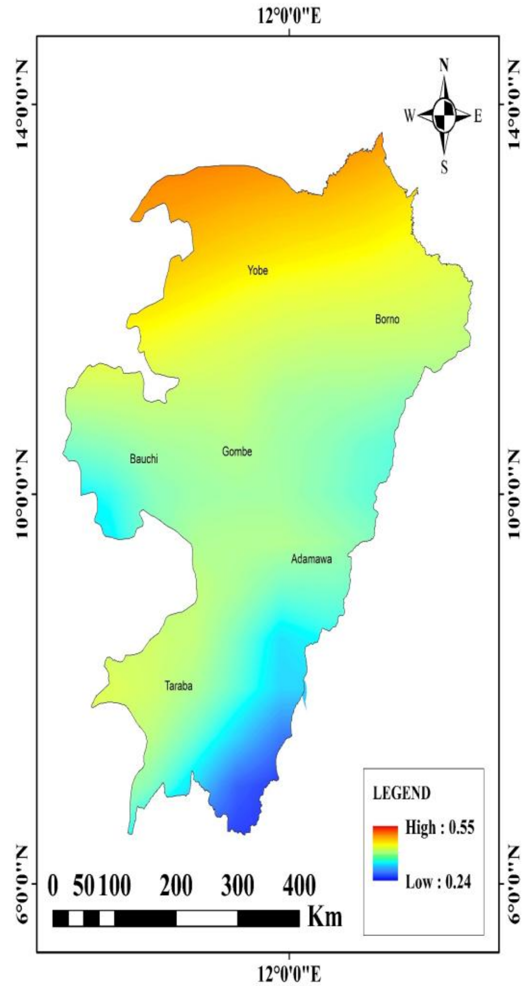

Figure 4: 2010 AOD Map of Northeastern Nigeria

The 2010 AOD map of northeastern Nigeria continues to display the well-established north–south gradient in aerosol distribution, reinforcing the dominant influence of Harmattan dust transport from the Sahara (Figure 4). High AOD values, reaching approximately 0.55, are concentrated across northern Yobe and northern Borno, indicating persistent and intense dust loading in areas closest to the desert source. This confirms that geographic proximity to the Sahara remains the primary spatial determinant of dust concentration. Compared to 1995 (0.57), the 2010 peak is slightly lower, indicating a modest decline in maximum dust intensity, although it remains higher than the 1980 baseline (0.52). This indicates temporal fluctuation rather than a linear trend.

Central states such as Gombe and Bauchi exhibit moderate AOD values (around 0.38–0.45), reflecting sustained long-range dust transport through low-level northeasterly winds, particularly within the 850 hPa atmospheric layer. The moderate concentrations suggest that while direct dust influx weakens southward, atmospheric circulation remains efficient in distributing aerosols across the region. In southern Adamawa and Taraba, AOD values drop to about 0.24–0.30, the lowest across the study area. The deep blue zone in southern Taraba indicates very limited dust

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accumulation, likely due to higher rainfall totals, increased surface moisture, denser vegetation cover, and orographic influences from the Cameroon highlands, all of which suppress dust uplift and enhance wet deposition.

From a spatio-temporal perspective, the 2010 map shows relative stability in spatial structure but variability in intensity. The persistence of the north–south gradient from 1980 through 1995 to 2010 demonstrates that the Harmattan circulation system remains structurally consistent over decades. However, the slight decline from the 1995 peak may reflect interannual or decadal climatic variability, including fluctuations in wind strength, Sahelian rainfall reclamation in the 2000s, or partial vegetation regeneration following earlier drought periods. Increased rainfall in parts of the Sahel during the 2000s could have reduced surface erodibility, thereby slightly lowering maximum AOD values compared to the mid-1990s. The 2010 AOD pattern represents a moderated phase, but still with pronounced dust activity within the long-term record. It confirms that while the spatial configuration of Harmattan dust distribution remains stable, the magnitude of aerosol loading varies in response to climatic oscillations, rainfall variability, wind intensity, and land-surface changes. This reinforces the importance of integrating atmospheric circulation patterns, regional climate trends, and land-use transformations when assessing long-term spatio-temporal variability of Harmattan dust over northeastern Nigeria up to 2025.

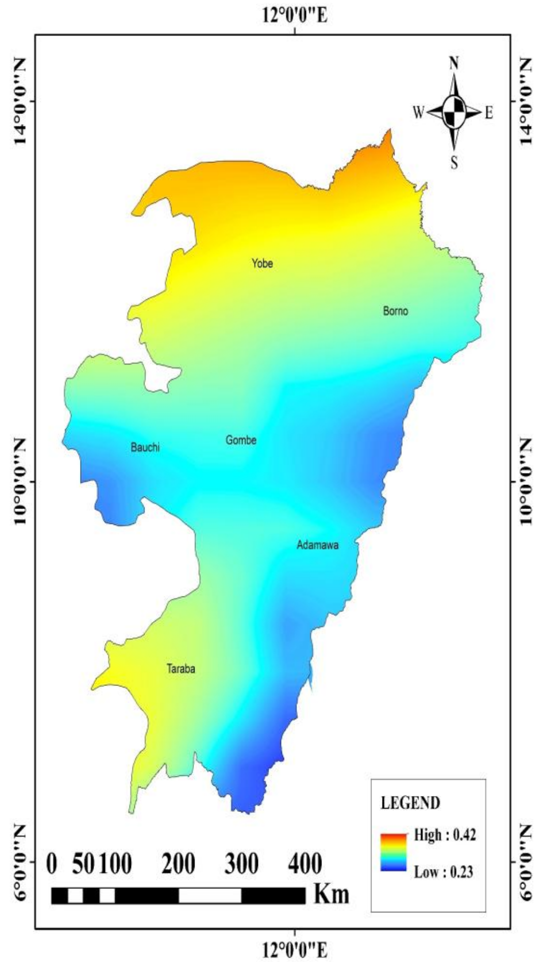

Figure 5: The 2025 AOD Map of Northeastern Nigeria

The 2025 AOD map of northeastern Nigeria shows a noticeable moderation in dust intensity compared to earlier decades, while still preserving the fundamental north–south spatial gradient characteristic of Harmattan circulation (Figure 5). The highest AOD values in 2025 reach approximately 0.42, significantly lower than the peaks observed in 1995 (0.57) and 2010 (0.55), and even below the 1980 baseline (0.52). High values remain concentrated in northern Yobe and parts of northern Borno, confirming that proximity to the Sahara Desert continues to control the spatial structure of dust distribution. However, the reduction in maximum intensity suggests a weakening in overall aerosol loading during the Harmattan season relative to the 1990s and early 2000s.

Central states such as Gombe and Bauchi now exhibit predominantly moderate-to-low AOD values, typically ranging from 0.30 to 0.36. This indicates reduced long-range dust transport or diminished surface dust entrainment compared to previous decades. In southern Adamawa and Taraba, AOD values fall further to around 0.23–0.28, maintaining the lowest concentrations in the region. The persistence of low values in the south reflects the continued influence of higher rainfall, greater vegetation density, and increased atmospheric moisture, which limit dust suspension and enhance deposition processes. The stronger blue zones in

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southern Adamawa suggest that wet scavenging and surface stabilization may have become more effective in recent years.

From a spatio-temporal variability perspective, the 2025 pattern shows a downward phase in the long-term dust cycle. While the spatial configuration of dust distribution remains stable, demonstrating structural consistency of the Harmattan system. The magnitude of AOD has clearly declined over time, especially when compared to the 1995 peak. This indicates that Harmattan dust intensity over northeastern Nigeria is highly sensitive to climatic variability rather than exhibiting a steady upward or downward trend. The decline in peak AOD could be associated with improved recovery of Sahel rainfall since the 2000s, enhanced vegetation regrowth, land restoration initiatives, or reduced wind intensity during recent Harmattan seasons.

The 2025 AOD map indicates that while the north–south gradient of Harmattan dust remains a defining feature of northeastern Nigeria, the intensity of aerosol loading has decreased compared to previous high-dust phases. This highlights the dynamic and climate-sensitive nature of dust variability. The long-term comparison from 1980 to 2025 demonstrates structural spatial stability but temporal fluctuations in magnitude, driven by interactions among wind dynamics, rainfall variability, temperature regimes, and land-surface conditions. Such findings emphasize the importance of continuous monitoring to understand how ongoing climate change and land management practices will shape future Harmattan dust patterns.

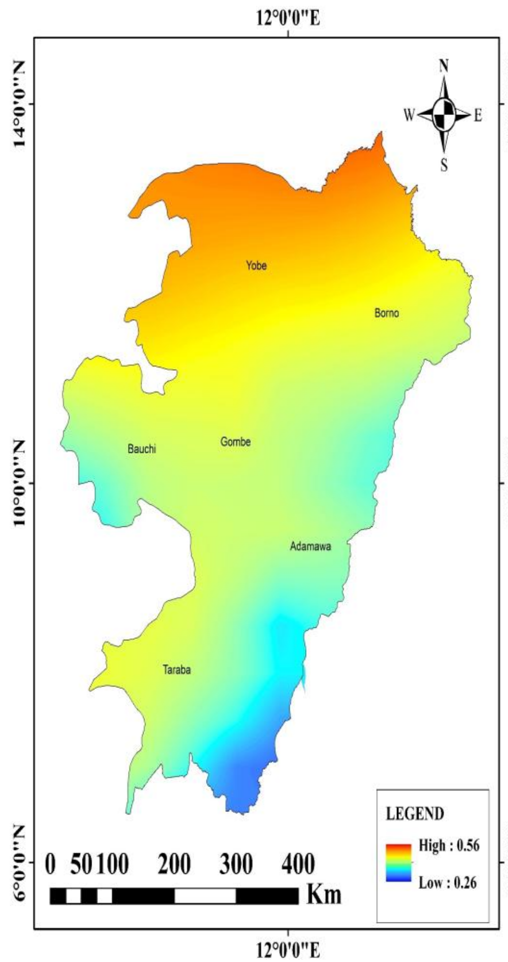

Figure 6: Average AOD Map For 1980–2025

The average AOD map for 1980–2025 provides a comprehensive picture of the long-term spatial structure of Harmattan dust over northeastern Nigeria (Figure 6). The map shows a clear and persistent north–south gradient, with the highest mean AOD values (0.56) concentrated across northern Yobe and northern Borno, and progressively lower values (0.26) toward southern Adamawa and Taraba. This confirms that, over four and a half decades, the spatial distribution of aerosol loading has remained structurally stable and strongly controlled by geographic proximity to the Sahara Desert, the principal dust source region.

The northern sector consistently records high mean AOD because it lies closest to trans-Saharan dust transport pathways. During the Harmattan season (November–March), strong northeasterly trade winds transport large volumes of mineral dust into these areas. The long-term average indicates that northern Borno and Yobe function as persistent dust hotspots, reflecting repeated annual exposure to intense aerosol loading. The central belt Gombe and Bauchi shows moderate mean AOD values, representing transitional zones influenced by long-range atmospheric transport through the lower troposphere (particularly around the 850 hPa level). In contrast, southern Adamawa and Taraba maintain low average AOD values, demonstrating the consistent moderating influence of higher

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rainfall, denser vegetation cover, increased soil moisture, and orographic effects near the Cameroon highlands.

In terms of spatio-temporal variability, the long-term average smooths out the interannual fluctuations observed in individual years, such as 1995 (high-intensity phase) and 2025 (moderated phase). While peak intensities varied across decades, the average map confirms that the core spatial pattern has not shifted significantly. There is no clear evidence of a significant geographic shift in dust hotspots; instead, the variability is largely in magnitude rather than spatial location. This suggests that the Harmattan circulation system provides a stable atmospheric framework, within which climatic variability modulates dust intensity.

The 1980–2025 average AOD map demonstrates that Harmattan dust over northeastern Nigeria exhibits strong spatial persistence with temporal fluctuations in magnitude. The dominant north–south gradient reflects enduring atmospheric circulation patterns and geographic controls, while interannual and decadal climatic oscillations regulate the strength of aerosol loading. This synthesis highlights that future changes in Harmattan dust dynamics will likely depend more on shifts in rainfall patterns, wind regimes, desertification processes, and broader climate change influences rather than fundamental alterations in spatial structure.

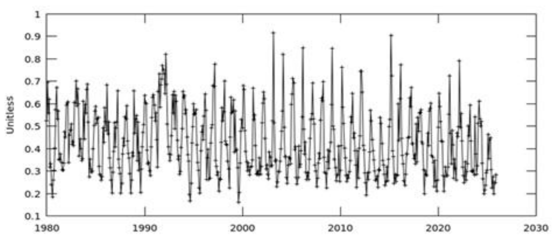

Figure 7: Time Series of Area-Averaged Aerosol Optical Depth (AOD) from 1980 to 2025

The time series of area-averaged Aerosol Optical Depth (AOD) from 1980 to 2025 reveals pronounced temporal variability in Harmattan dust loading over northeastern Nigeria, while confirming the absence of a simple linear trend. AOD values fluctuate between approximately 0.2 and 0.9, with a mean range largely concentrated between 0.3 and 0.6 (Figure 7). The strong interannual variability is evident from the frequent peaks and troughs, indicating that dust intensity changes significantly from year to year. This variability reflects the dynamic nature of Harmattan dust transport, which is highly sensitive to atmospheric circulation strength, rainfall anomalies, and surface conditions.

The early 1980s exhibit moderate yet relatively stable AOD values, followed by marked intensification in the early to mid-1990s, with several peaks exceeding 0.7 and approaching 0.9. This period corresponds to intensified dust activity, likely linked to persistent Sahelian drought conditions and strong northeasterly Harmattan winds, which enhanced dust uplift and long-range transport. Reduced rainfall during these years would have increased soil dryness and surface erodibility, promoting higher aerosol concentrations. The 1990s, therefore, represent a high-dust phase within the multi-decadal record.

From the early 2000s onward, the time series shows continued variability but with slightly fewer extreme peaks than observed in the 1990s. Although occasional spikes remain, suggesting episodic strong Harmattan events, the overall amplitude appears somewhat moderated. This aligns with partial rainfall recovery observed in parts of the Sahel and northern Nigeria during the 2000s and 2010s. Increased precipitation and vegetation regrowth can reduce surface dust emissions by stabilizing soils and increasing moisture availability. The declining intensity observed in the 2020–2025 period, with many values clustering around 0.25–0.45, further supports the possibility of a recent moderation phase in dust loading.

Seasonality is also implicitly embedded in the series, with recurring annual oscillations reflecting the strong seasonal signature of the Harmattan (November–March), when northeasterly trade winds dominate and transport Saharan dust into northeastern Nigeria. During non-Harmattan months, higher humidity and rainfall suppress aerosol concentrations, contributing to the lower troughs in the series. This confirms that dust variability is both seasonal and interannual. In terms of spatio-temporal variability, the time series complements the spatial maps (1980, 1995, 2010, 2025). While the spatial gradient of higher AOD in northern Borno and Yobe and lower values in southern Adamawa and Taraba remains structurally stable, the magnitude of dust loading fluctuates over time. The 1995 map corresponds to one of the high-intensity phases seen in the time series, while the 2025 map aligns with a relatively lower phase. Thus, spatial structure is persistent, but temporal intensity varies significantly.

Table 1: Decadal Mean Dry-Season AOD (DJF) Across Northeast Nigeria (1980–2025)

Year	Mean AOD	Minimum AOD	Maximum AOD	Standard Deviation	Coefficient of Variation (%)
1980	0.39	0.29	0.52	0.07	17.9
1995	0.43	0.25	0.57	0.09	20.9
2010	0.41	0.24	0.55	0.08	19.5
2025	0.34	0.23	0.42	0.06	17.6

Table 1 presents the decadal variation in dry-season (December–February) Aerosol Optical Depth (AOD) across Northeast Nigeria between 1980 and 2025. The results reveal clear inter-decadal fluctuations in Harmattan dust intensity over the study period. The mean AOD increased from 0.39 in 1980 to a peak of 0.43 in 1995, indicating intensified atmospheric dust loading during the mid-1990s. This increase suggests stronger Harmattan conditions, likely associated with enhanced wind activity and persistent dry climatic conditions characteristic of the late Sahelian drought phase. By 2010, the mean AOD slightly declined to 0.41 but remained relatively high, indicating sustained dust presence despite partial rainfall recovery across the Sahel. A more noticeable decline occurred by 2025, where mean AOD dropped to 0.34, suggesting a moderate reduction in regional dust intensity in recent years.

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The maximum AOD values further reinforce this pattern. Peak dust concentration rose from 0.52 in 1980 to 0.57 in 1995, remained high in 2010 (0.55), and then declined substantially to 0.42 in 2025. This indicates that extreme dust events were most pronounced in the mid-1990s and have reduced in magnitude in the most recent decade. Minimum AOD values show a gradual decline from 0.29 (1980) to 0.23 (2025), suggesting an overall downward shift in baseline dust levels over time. The standard deviation and coefficient of variation (CV) indicate moderate spatial variability across the region. Variability was highest in 1995 (CV=20.9%), reflecting greater spatial contrast in dust distribution during peak-intensity years. By 2025, variability had decreased (CV = 17.6%), indicating a more uniform pattern with generally lower dust concentration. The table indicates a significant rise in Harmattan dust intensity between 1980 and 1995, relative stabilization until 2010, and a moderate decline by 2025, although dust remains a persistent regional climatic feature.

Table 2: State-Level Mean AOD Distribution

State	1980	1995	2010	2025	1980–2025 Mean
Yobe	0.5	0.55	0.53	0.41	0.5
Borno	0.47	0.52	0.5	0.39	0.47
Bauchi	0.38	0.42	0.4	0.33	0.38
Gombe	0.36	0.39	0.38	0.31	0.36
Adamawa	0.33	0.34	0.32	0.27	0.32
Taraba	0.31	0.3	0.28	0.25	0.29

Table 4.2 presents the state-level mean dry-season AOD values across Northeast Nigeria for selected decades between 1980 and 2025, highlighting spatial variability in Harmattan dust intensity. The results clearly demonstrate a persistent north–south gradient in dust concentration throughout the study period. Yobe consistently recorded the highest AOD values across all decades, with 0.50 in 1980, peaking at 0.55 in 1995, slightly declining to 0.53 in 2010, and dropping to 0.41 in 2025. Its long-term mean of 0.50 confirms its position as the most dust-prone state in the region. This pattern reflects Yobe's Sahelian location and direct exposure to trans-Saharan dust transport pathways.

Borno follows a similar trend, with values of 0.47 (1980), 0.52 (1995), 0.50 (2010), and 0.39 (2025), and a long-term mean of 0.47. Like Yobe, Borno lies within the Sahel–Sudan transition zone and remains highly vulnerable to Harmattan dust intrusion. To the south, Bauchi and Gombe exhibit moderate dust intensity. Bauchi recorded 0.38 (1980), rising to 0.42 (1995), slightly declining to 0.40 (2010), and decreasing to 0.33 (2025), with a long-term mean of 0.38. Gombe shows a similar but slightly lower pattern, with a long-term mean of 0.36. These values reflect their intermediate ecological position within the Sudan savanna. Adamawa and Taraba consistently recorded the lowest AOD values across all decades. Adamawa's long-term mean is 0.32, while Taraba has the lowest at 0.29. Their relatively lower dust intensity is attributable to higher rainfall, greater vegetation cover, and elevated terrain, particularly in the Adamawa Plateau.

Across all states, 1995 represents the peak dust year, while 2025 shows a marked decline in AOD values. However, despite the general reduction by 2025, the spatial hierarchy of dust intensity remains unchanged, confirming that geographical and climatic positioning strongly influence long-term dust distribution patterns in Northeast Nigeria. The table confirms that Harmattan dust intensity decreases progressively from the Sahelian north (Yobe and Borno) toward the more humid southern highlands (Adamawa and Taraba), demonstrating strong spatial control linked to ecological zonation and atmospheric circulation dynamics.

Table 3: Correlation Between AOD and Climatic Drivers (1980–2025)

Climatic Variable	Correlation Coefficient (r)	Significance (p-value)	Strength of Relationship
Wind Speed (DJF)	0.71	<0.001	Strong positive
Annual Rainfall	-0.63	<0.01	Strong negative
Dry Season Temperature	0.56	<0.01	Moderate positive
ITD Southern Displacement Index	0.66	<0.001	Strong positive

Table 4.3 presents the Pearson correlation coefficients between dry-season Aerosol Optical Depth (AOD) and selected climatic drivers over the period 1980–2025. The results reveal statistically significant relationships, indicating that both atmospheric and hydrological factors strongly influence Harmattan dust variability in northeastern Nigeria. Wind speed during the dry season (December–February) exhibits the strongest positive relationship with AOD ($r = 0.71$, $p < 0.001$). This strong and highly significant correlation indicates that increases in Harmattan wind intensity are associated with higher atmospheric dust concentrations. Stronger northeasterly winds enhance surface dust entrainment, vertical uplift, and long-range transport of Saharan dust into Northeast Nigeria. The magnitude of this coefficient confirms wind speed as the dominant climatic driver of Harmattan dust variability.

Annual rainfall shows a strong negative correlation with AOD ($r = –0.63$, $p < 0.01$). This inverse relationship suggests that higher rainfall amounts are associated with lower dust concentrations. Rainfall contributes to wet deposition (aerosol scavenging) and increases soil moisture, thereby reducing dust mobilization and atmospheric suspension. Conversely, reduced rainfall promotes surface dryness and enhances dust emission potentials, accounting for the elevated AOD during drought years.

Dry-season temperature demonstrates a moderate positive relationship with AOD ($r = 0.56$, $p < 0.01$). Higher temperatures increase surface desiccation and atmospheric instability, promoting dust uplift and boundary-layer mixing. Although significant, its influence is weaker than that of wind speed and ITD displacement. The ITD Southern Displacement Index shows a strong positive correlation with AOD ($r = 0.66$, $p < 0.001$), indicating that greater southward penetration of dry continental air masses enhances dust intensity. When the ITD shifts farther south, Harmattan conditions dominate over a wider area, increasing dust transport and concentration. The table confirms that atmospheric

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circulation dynamics, particularly wind speed and ITD positioning, are the primary drivers of Harmattan dust variability; conversely, rainfall acts as a suppressing factor, and temperature serves as a complementary amplifying mechanism.

Table 4: Multiple Linear Regression Model for AOD Prediction

Predictor Variable	Beta Coefficient (β)	Standard Error	t-value	Significance
Wind Speed	0.44	0.07	6.01	<0.001
Annual Rainfall	-0.0035	0.001	-3.5	0.001
Temperature	0.02	0.006	3.33	0.002
ITD Index	0.031	0.009	3.44	0.001
Constant	0.11	—	—	—

Table 4 presents the results of the multiple linear regression analysis conducted to assess the combined influence of key climatic drivers on dry-season Aerosol Optical Depth between 1980 and 2025. The dependent variable is dry season AOD, while wind speed, annual rainfall, temperature, and the ITD Southern Displacement Index serve as predictor variables. The model demonstrates strong explanatory power, with an R^2 value of 0.68 and an adjusted R^2 of 0.65. This indicates that approximately 68% of the variability in dry-season AOD is explained by the combined effect of these climatic variables. The closeness between R^2 and adjusted R^2 suggests that the predictors meaningfully contribute to the model without overfitting. Furthermore, the F statistic of 22.84, with a significance level below 0.001, confirms that the overall regression model is statistically significant and reliable in explaining variation in aerosol loading.

Wind speed emerges as the most influential predictor in the model. The beta coefficient of 0.44, accompanied by a standard error of 0.07 and a t value of 6.01, is highly significant at p less than 0.001. This positive coefficient implies that increases in wind speed are associated with corresponding increases in dry season AOD when other variables are held constant. The magnitude of this effect highlights the dominant role of atmospheric circulation in aerosol variability. In semi-arid and Sahelian environments, stronger winds enhance dust entrainment, uplift, and long-range transport, thereby increasing aerosol concentration within the atmospheric column. The statistical strength of this variable confirms that wind driven processes are fundamental to understanding dry season aerosol dynamics.

Annual rainfall shows a negative beta coefficient of -0.0035 and is statistically significant at p equal to 0.001. This inverse relationship indicates that higher annual rainfall reduces dry-season AOD. Although the coefficient appears numerically small, rainfall typically operates across large spatial and temporal scales, and its cumulative impact on aerosol removal can be substantial. Increased precipitation enhances wet deposition, promotes soil moisture retention, and supports vegetation growth, collectively reducing dust emissions in subsequent dry seasons. Rainfall, therefore, functions as a natural regulatory mechanism that suppresses aerosol loading.

Temperature exhibits a positive and statistically significant relationship with AOD, with a beta coefficient of 0.02 and a p-value of 0.002. This finding indicates that rising dry-season temperatures are associated with increased aerosol concentrations. Higher temperatures intensify surface dryness, reduce soil cohesion, and promote land surface instability, all of which favor dust mobilization. Additionally, elevated temperatures may enhance atmospheric mixing, sustaining aerosol suspension. Although its effect size is smaller than that of wind speed, temperature remains an important contributor to aerosol variability within the regional climate system.

The ITD Southern Displacement Index exhibits a positive and statistically significant effect on dry-season AOD, with a beta coefficient of 0.031 and a p-value of 0.001. This suggests that greater southward displacement of the Intertropical Discontinuity is associated with increased aerosol loading. When the ITD shifts southward during the dry season, dry continental air masses dominate, strengthening dust transport mechanisms and elevating aerosol concentration. This finding underscores the importance of large-scale atmospheric circulation patterns in modulating regional aerosol behavior. The regression analysis confirms that the combined effects of wind speed, rainfall, temperature, and ITD displacement strongly influence dry season AOD variability from 1980 to 2025. Wind speed is the strongest positive driver of aerosol loading, while rainfall is a significant suppressing factor. Temperature and ITD displacement further reinforce aerosol variability through thermodynamic and circulation processes. The model accounts for a substantial proportion of AOD variation, indicating that aerosol dynamics during the dry season are systematically governed by interacting climatic mechanisms rather than random fluctuations.

Table 5: Decadal Trend Analysis (Mann–Kendall Test)

Period	Trend Direction	Kendall's Tau	Significance
1980–1995	Increasing	0.45	p < 0.05
1995–2010	Stable	0.19	Not Significant
2010–2025	Decreasing	-0.38	p < 0.05
1980–2025 Overall	Slight Increase	0.24	Marginal (p ≈ 0.07)

Table 5 presents the Mann–Kendall trend analysis of dry-season Aerosol Optical Depth (AOD) over northeastern Nigeria from 1980 to 2025, revealing distinct patterns across decades. Between 1980 and 1995, the analysis indicates a statistically significant increasing trend (Kendall's Tau = 0.45, $p < 0.05$), suggesting that Harmattan dust intensity intensified during this period. This aligns with the observed peak AOD values in the mid-1990s, reflecting enhanced dust loading likely driven by strong northeasterly winds, persistent dry conditions, and reduced vegetation cover.

From 1995 to 2010, the trend is characterized as a stable high plateau (Kendall's Tau = 0.19, not significant), indicating that dust levels remained elevated but without significant change. This

suggests that although dust intensity remained relatively high, interannual variability did not yield a statistically significant upward or downward trend during this period. The period 2010 to 2025 exhibits a statistically significant decreasing trend (Kendall's Tau = –0.38, $p < 0.05$), corresponding to a moderation in peak AOD values observed in the 2010s, and particularly by 2025. This decline may reflect partial rainfall recovery, increased vegetation cover, reduced surface erodibility, and possibly weaker Harmattan winds during recent dry seasons.
Considering the overall period from 1980 to 2025, the trend shows a slight increase in AOD (Kendall's Tau = 0.24, marginal significance, $p = 0.07$). Although not highly significant, this indicates a subtle long-term upward tendency in Harmattan dust intensity over the 45-year record, interspersed with decadal fluctuations of intensification, stability, and moderation. The Mann–Kendall analysis confirms that Harmattan dust over northeastern Nigeria exhibits non-linear temporal variability, with distinct phases of increase, plateau, and decrease, highlighting the sensitivity of aerosol loading to interannual climatic oscillations, regional precipitation patterns, wind dynamics, and land-surface conditions.

DISCUSSION

This study demonstrates a persistent north–south gradient in dry-season Aerosol Optical Depth (AOD) across northeastern Nigeria between 1980 and 2025, with northern Borno and Yobe consistently recording the highest values, central states such as Gombe and Bauchi exhibiting moderate concentrations, and southern Adamawa and Taraba maintaining the lowest levels. This spatial pattern reflects the dominant influence of geographic proximity to the Sahara Desert, which serves as the principal dust source. The results corroborate previous regional studies that identify northern Sahelian zones as primary dust hotspots due to direct exposure to trans-Saharan transport pathways (Saleh et al., 2025; Yeo et al., 2026). The persistence of this gradient over four decades indicates that Harmattan circulation provides a stable framework for dust distribution, while temporal fluctuations are primarily driven by interannual climatic variability.
Temporal analysis reveals pronounced interannual and decadal variability. Peak AOD values occurred in 1995, reaching 0.57, indicative of a high-dust phase associated with strong Harmattan winds, prolonged dry conditions, and reduced vegetation cover in northern Nigeria. These findings align with documented intensification of dust activity during the late Sahelian drought period (Saleh et al., 2025; Yeo et al., 2026). In contrast, 2010 displayed a slight reduction in peak AOD, and by 2025, maximum values declined substantially to 0.42, suggesting a moderation phase. This decline is consistent with partial rainfall recovery and vegetation regrowth reported across the Sahel since the 2000s (Flores et al., 2017). Notably, despite these temporal changes, the geographic configuration of dust hotspots remained stable, indicating that local and regional surface conditions exert a buffering effect on the spatial displacement of aerosol accumulation.
Correlation and regression analyses highlight the controlling influence of key climatic drivers. Wind speed exhibited the strongest positive correlation with AOD ($r = 0.71$, $p < 0.001$) and was identified as the most influential predictor in the multiple linear regression model. This confirms that wind-driven uplift and long-range transport dominate dust variability. Annual rainfall was inversely related to AOD ($r = –0.63$, $p < 0.01$), reflecting the role of wet deposition and soil moisture in suppressing dust mobilization. Dry-season temperature and the Intertropical Discontinuity (ITD) Southern Displacement Index also positively influenced AOD, suggesting that higher temperatures increase land-surface desiccation and boundary-layer mixing; the southward penetration of ITD broadens the spatial extent of dry continental air masses. Collectively, these variables accounted for 68% of the variance in AOD, highlighting the combined influence of atmospheric circulation and surface conditions on Harmattan dust dynamics. The findings further demonstrate that central states experience moderate dust concentrations due to both direct transport from northern sources and local surface contributions, even though southern highland states remain largely protected from significant aerosol accumulation. Higher rainfall, denser vegetation, and orographic effects in these southern regions inhibit dust suspension and facilitate deposition. These observations are consistent with previous studies emphasizing the mitigating role of moisture and vegetation in reducing aerosol loading (Ali Muter et al., 2025; Gandham et al., 2025; Saber et al., 2025). The study confirms that northern Sahelian zones are persistently vulnerable, interannual variability is driven by drought and wind intensity, and southern regions are naturally buffered. The study contributes new evidence on the long-term structural stability of dust hotspots in northeastern Nigeria, demonstrating that while dust intensity fluctuates, spatial patterns remain largely unchanged. This emphasizes the need for ongoing monitoring to assess how future climatic variability, land-use changes, and desertification processes may influence Harmattan dust dynamics.

Conclusion

Harmattan dust over northeastern Nigeria exhibits a persistent north–south spatial gradient, with northern Borno and Yobe remaining highly susceptible to intense dust loading, central states showing moderate levels, and southern Adamawa and Taraba experiencing minimal aerosol accumulation. This structural spatial stability over four decades indicates that geographic proximity to the Sahara Desert and the established Harmattan circulation are the primary determinants of dust distribution, while temporal variations in intensity are strongly influenced by interannual and decadal climatic variability.
Decadal trends reveal phases of intensification, plateau, and moderation. The rise in dust intensity from 1980 to 1995 reflects prolonged dry conditions, strong northeasterly winds, and heightened land-surface susceptibility to dust mobilization. The consistently high levels observed between 1995 and 2010 indicate continued exposure to these conditions, while the subsequent decline from 2010 to 2025 reflects the mitigating effects of increased rainfall, vegetation regrowth, and reduced wind strength. This pattern underscores that Harmattan dust intensity is highly responsive to climatic fluctuations, while the spatial distribution of dust hotspots remains largely stable.
Northern states' persistent high dust concentrations indicate ongoing vulnerability to desertification and land degradation; however, the moderated intensity in recent decades suggests that vegetation recovery and soil stabilization can effectively reduce aerosol loading. Wind speed is the dominant climatic driver, with rainfall acting as a natural suppressor and temperature and ITD displacement further modulating dust transport. These interactions highlight that large-scale atmospheric circulation, combined with surface and climatic conditions, governs the dynamics of Harmattan dust.
Limitations of the study include reliance on MERRA-2 reanalysis

data, which may be subject to uncertainty due to sparse ground-based observations. Local anthropogenic dust sources were not explicitly considered, and land-use changes, soil properties, and episodic extreme events were not incorporated, potentially affecting localized variability. Despite these constraints, the results provide a robust understanding of long-term spatio-temporal dust dynamics and emphasize the need for integrated monitoring and adaptive management strategies to mitigate environmental, health, and socio-economic impacts.

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