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Seasonal Variability of Aerosol Optical Depth and Cloud Optical Depth over Kogi East, Nigeria Using MODIS Aqua Satellite Observations (2019–2025)

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ABSTRACT
Atmospheric aerosols and clouds are important components of the climate system because of their effects on radiation, precipitation, and atmospheric processes. However, limited information exists on the combined seasonal behaviour of aerosol and cloud optical properties over Kogi East, Nigeria. This study investigated the seasonal and interannual variability of Aerosol Optical Depth (AOD) and Cloud Optical Depth (COD) over Kogi East using MODIS Aqua satellite observations from January 2019 to December 2025. Monthly AOD and COD data were obtained through the NASA Giovanni platform and analysed using descriptive statistics, seasonal comparison, Pearson correlation, and linear regression. AOD ranged from 0.328 to 1.368, with a mean of 0.616 ± 0.259, while COD ranged from 1.966 to 20.088, with a mean of 8.290 ± 4.591. AOD generally recorded higher values during the dry season, associated with enhanced dust transport and reduced precipitation, whereas COD was generally higher during the wet season due to increased atmospheric moisture and cloud development. A moderate negative correlation was observed between AOD and COD ($r = -0.469$), while the regression model produced an R^2 of 0.2202. The findings indicate strong seasonal variability in both optical properties and suggest that their relationship is influenced by other atmospheric processes. The study provides a satellite-based baseline for further investigation of aerosol–cloud interactions over Kogi East and the Guinea Savannah region of Nigeria.

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INTRODUCTION

Atmospheric aerosols are suspended particles that influence radiation, cloud formation and climate. Their effects depend on concentration, size, composition and interactions with clouds and radiation (Andreae & Rosenfeld, 2008; Boucher et al., 2013; Twomey, 1974). Aerosol Optical Depth (AOD) provides a measure of column aerosol loading, while Cloud Optical Depth (COD) describes cloud optical thickness (Levy et al., 2013; Platnick et al., 2017).

West Africa experiences strong seasonal aerosol variability due to Saharan and Sahelian dust transport, biomass burning, anthropogenic emissions and changes in atmospheric circulation. During the dry Harmattan season, northeasterly winds transport mineral dust towards the region, whereas wet-season rainfall promotes aerosol removal through wet deposition (Ayanlade et al., 2019; Knippertz & Todd, 2012).

Satellite observations are valuable where ground-based measurements are limited. MODIS instruments aboard Terra and Aqua provide long-term aerosol and cloud observations and have been widely used to examine aerosol loading and cloud optical properties (Levy et al., 2013; Platnick et al., 2017; Remer et al., 2005).

Studies over Nigeria have reported substantial spatial and temporal aerosol variability. Ayanlade et al. (2019) identified humidity, wind and the Inter-Tropical Discontinuity as important controls, while Balarabe and Isah (2019) demonstrated seasonal variability in AOD over Ilorin. Khan et al. (2024) also reported variability in aerosol characteristics over Nigeria, including Kogi State.

Kogi East lies within the Guinea Savannah zone and has a tropical wet-and-dry climate. Dry-season Harmattan conditions may increase aerosol loading through transported mineral dust, while biomass burning and local human activities may provide additional sources. Because this study uses satellite-derived AOD and COD, individual aerosol sources cannot be quantitatively separated.

Aerosol–cloud relationships are complex because cloud properties are also controlled by moisture, cloud type, vertical motion, atmospheric stability and aerosol composition. Thus, a statistical association between AOD and COD should be interpreted as co-variability rather than proof of direct causation (Andreae & Rosenfeld, 2008; Taylor et al., 2019).

Despite increasing research on aerosols in Nigeria, the simultaneous seasonal behaviour of AOD and COD over Kogi East remains insufficiently documented. This study therefore uses MODIS Aqua observations from January 2019 to December 2025 to examine seasonal and interannual variability and the statistical relationship between AOD and COD.

The study objectives were to: (i) examine seasonal and interannual variations in AOD and COD; (ii) compare their wet- and dry-season characteristics; and (iii) evaluate their statistical relationship over Kogi East.

The study provides localized satellite-based information on aerosol and cloud optical variability and establishes a baseline for future work incorporating meteorological observations, ground measurements, aerosol composition and atmospheric modelling.

MATERIALS AND METHODS

Study Area

The study was conducted over Kogi East Senatorial District, Kogi State, Nigeria, within the Guinea Savannah ecological zone. The area extends approximately from 6.30°N to 8.50°N and 6.40°E to 7.50°E and comprises Ankpa, Dekina, Idah, Ibaji, Igalamela-Odolu, Ofu, Olamaboro and Omala LGAs. The wet season extends approximately from April to October and the dry season from November to March. These seasons are associated with the north–south movement of the Inter-Tropical Discontinuity, moist monsoon flow and dry Harmattan flow.

Dry-season Harmattan circulation can transport mineral dust from the Sahara and Sahel, while relatively low humidity and precipitation limit aerosol removal. Wet-season moisture, cloud development and rainfall favour aerosol removal through wet deposition. These contrasts provide the basis for seasonal comparison of AOD and COD.

During the dry season, Harmattan circulation can transport mineral dust from the Sahara and Sahel into the region, contributing to increased atmospheric aerosol loading. The dry period is also associated with relatively low humidity and limited precipitation. In contrast, the wet season is characterised by increased atmospheric moisture, enhanced cloud development and frequent rainfall, which promotes the removal of atmospheric aerosol particles through wet deposition. These seasonal contrasts provide an appropriate basis for examining variations in aerosol and cloud optical properties over Kogi East.

Data Sources

The study used MODIS Aqua Collection 6.1 Level-3 monthly AOD at 550 nm and COD observations. The dataset covered January 2019 to December 2025, giving 84 monthly observations. AOD represents column-integrated aerosol optical attenuation, while COD represents cloud optical thickness.

The study covered January 2019 to December 2025, corresponding to 84 monthly observations.

Two MODIS Collection 6.1 Level-3 monthly atmospheric products were used:

i. Aerosol Optical Depth (AOD) at 550 nm, representing the column-integrated optical attenuation associated with atmospheric aerosol particles; and
ii. Cloud Optical Depth (COD), representing the optical thickness of clouds and their attenuation of incoming solar radiation.

MODIS aerosol and cloud products have been widely applied in atmospheric studies (Levy et al., 2013; Platnick et al., 2017).

Data Acquisition

MODIS Aqua data were obtained through NASA Giovanni. A geographical bounding box covering Kogi East was specified, and monthly mean AOD and COD values for January 2019–December 2025 were downloaded as CSV files for analysis.

The downloaded data were screened, arranged chronologically by date, and organised by year, month, AOD and COD. This produced 84 paired monthly observations.

Data Processing

The downloaded data were screened, arranged chronologically and organised by year, month, AOD and COD. Monthly means were calculated where required using Equation (1).

The arithmetic mean was used where monthly values were calculated from individual observations. The monthly mean was calculated using Equation (1):

$$\bar{X} = \frac{\sum X_i}{N} \quad (1)$$

Where, $\bar{X}$ is monthly average mean, X_i represents individual observation and N is number of observations.

Observations were classified as dry season (November–March) or wet season (April–October), and seasonal means were calculated for AOD and COD.

Dry season

November, December, January, February and March.

Wet season

April, May, June, July, August, September and October.

Seasonal means were calculated to compare the behaviour of AOD and COD during the two seasons.

Descriptive Statistical Analysis

Descriptive statistics (mean, median, minimum, maximum, variance, standard deviation, coefficient of variation, skewness and kurtosis) were used to summarise AOD and COD.

The standard deviation (SD) was calculated using Equation (2):

$$SD = \sqrt{\frac{\sum(X_i - \bar{X})^2}{n-1}} \quad (2)$$

Where SD is the sample standard deviation, X_i is an individual observation, $\bar{X}$ is the arithmetic mean and n is the number of observations.

The coefficient of variation (CV) was calculated using Equation (3):

$$CV(\%) = \left(\frac{SD}{\bar{X}}\right) \times 100 \quad (3)$$

The descriptive statistics were used to assess the magnitude and temporal variability of aerosol and cloud optical properties during the study period.

Trend Analysis

Simple linear regression was used to assess temporal trends in AOD and COD using Equation (4), where Y is AOD or COD, X is time, a is the intercept and b is the slope.

$$Y = a + bX \quad (4)$$

Where (Y) is AOD or COD, (X) is time, (a) is the intercept, and (b) is the slope. A positive slope indicates an increasing trend, while a negative slope indicates a decreasing trend.

Pearson Correlation Analysis

Pearson correlation was used to determine the relationship between AOD and COD using Equation (5). Positive and negative values indicate positive and negative associations, respectively.

$$r = \frac{\sum(X-\bar{X})(Y-\bar{Y})}{\sqrt{\sum(X-\bar{X})^2 \sum(Y-\bar{Y})^2}} \quad (5)$$

Where (r) is the correlation coefficient, (X) is AOD, (Y) is COD, and (n) is the number of paired observations. Positive values indicate a positive relationship, while negative values indicate a negative relationship.

Linear Regression between AOD and COD

Simple linear regression was used to examine AOD–COD association, with COD as the dependent variable and AOD as the independent variable, using Equation (6). R^2 indicates the proportion of COD variability statistically explained by AOD; the result was interpreted as association rather than causation.

$$COD = a + b\,(AOD) \qquad (6)$$

Where (a) is the intercept and (b) is the regression coefficient. The coefficient of determination (R^2) was used to assess the proportion of COD variability explained statistically by AOD. The regression was interpreted as an association and not as evidence of direct causation.

Software and Analytical Tools

NASA Giovanni and MODIS Aqua Collection 6.1 Level-3 products were used for data extraction. Microsoft Excel was used for data organisation, descriptive statistics, correlation, regression and graphical presentation.

Quality Assurance and Study Limitations

MODIS retrievals may be affected by cloud contamination, surface reflectance, viewing geometry and atmospheric conditions (Levy et al., 2013; Platnick et al., 2017). Long-term ground-based aerosol measurements were unavailable; therefore, aerosol composition and individual emission sources could not be determined. Seasonal and meteorological controls may also influence the AOD–COD relationship, so the correlation does not establish causation.

The study relied on satellite observations because long-term ground-based aerosol measurements were unavailable for the study area. Therefore, the study could not directly determine aerosol chemical composition or individual emission sources. The AOD–COD relationship may also be influenced by common seasonal and meteorological conditions. Therefore, the correlation does not establish direct causation. Future studies should incorporate meteorological variables, aerosol composition and ground-based observations to improve the assessment of aerosol–cloud interactions.

RESULTS AND DISCUSSION

Temporal Variation of Aerosol Optical Depth

The monthly variation of AOD over Kogi East is presented in Figure 1. AOD ranged from 0.328 to 1.368, with a mean of 0.616 ± 0.259 and coefficient of variation of 42.02% (Table 1). Values were generally higher in the dry season and lower in the wet season, consistent with Harmattan dust transport and reduced precipitation. Wet-season rainfall and moisture favour aerosol removal through wet deposition.

The temporal pattern shows enhanced dry-season aerosol loading, while wet-season precipitation and moisture generally reduced AOD. Biomass burning and anthropogenic activities may contribute additional particles, but their individual contributions cannot be quantified from the dataset.

The seasonal pattern is consistent with reported aerosol variability across Nigeria and West Africa (Ayanlade et al., 2019; Knippertz & Todd, 2012).

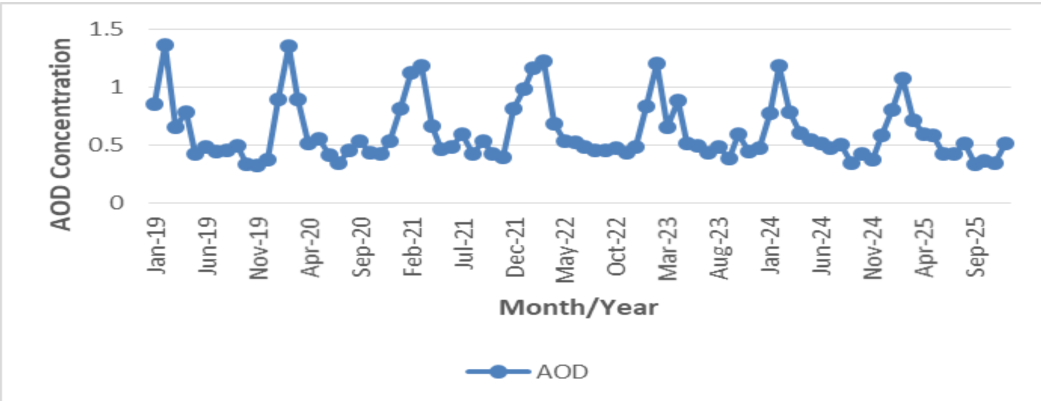

Figure 1: Monthly variation of Aerosol Optical Depth (AOD) over Kogi East, Nigeria, January 2019 to December 2025

Temporal Variation of Cloud Optical Depth

The monthly variation of COD is presented in Figure 2. COD ranged from 1.966 to 20.088, with a mean of 8.290 ± 4.591 and coefficient of variation of 55.38% (Table 1), indicating greater relative variability than AOD. COD was generally higher during the wet season, when moisture and convection favour cloud development, and lower during the dry season. Cloud type, water or ice content, particle size, stability and vertical motion also influence COD.

The higher wet-season COD is consistent with increased atmospheric moisture and convective activity. However, the pattern should not be attributed to rainfall alone because several atmospheric processes control cloud optical depth.

The seasonal behavior therefore reflects the combined influence of moisture and atmospheric dynamics on cloud properties.

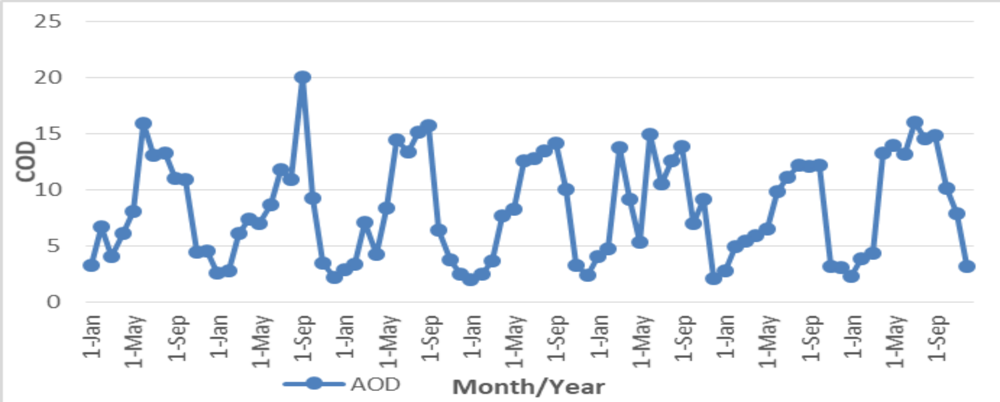

Figure 2: Monthly variation of Cloud Optical Depth (COD) over Kogi East, Nigeria, January 2019 to December 2025

Descriptive Statistics of AOD and COD

Table 1 summarises the descriptive statistics of AOD and COD for the 84 monthly observations.

Table 1: Descriptive statistics of AOD and COD over Kogi East, Nigeria, 2019–2025.

Parameter	AOD	COD
Number of observations	84	84
Mean	0.616	8.290
Median	0.517	7.752
Minimum	0.328	1.966
Maximum	1.368	20.088
Standard deviation	0.259	4.591
Variance	0.067	21.077
Coefficient of variation (%)	42.02	55.38
Skewness	1.379	0.300
Kurtosis	1.059	−1.086

Table 1 shows substantial variability in both parameters. COD had the larger coefficient of variation (55.38%) compared with AOD (42.02%), while AOD had positive skewness (1.379), indicating occasional high aerosol-loading months. COD was less positively skewed (0.300).

The positive AOD skewness is consistent with occasional enhanced aerosol loading, potentially during Harmattan periods.

Seasonal Variation of AOD and COD

Seasonal mean AOD and COD are presented in Figures 3 and 4, respectively. The results show contrasting seasonal behaviour between aerosol and cloud optical properties.

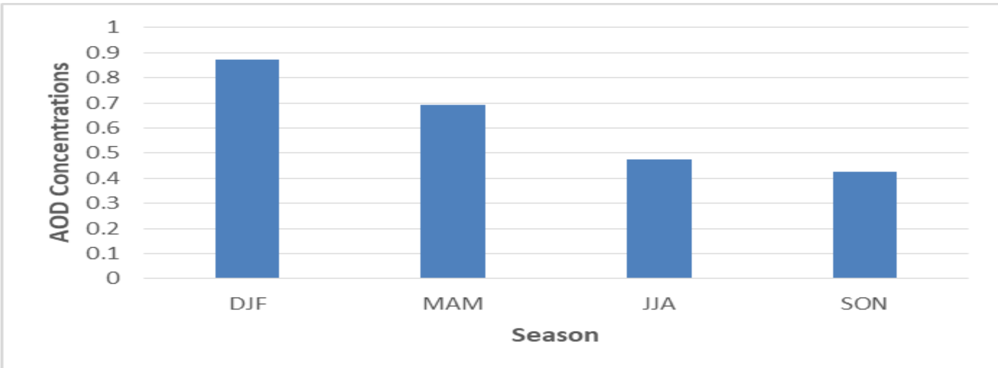

Figure 3: Seasonal mean Aerosol Optical Depth (AOD) over Kogi East, Nigeria

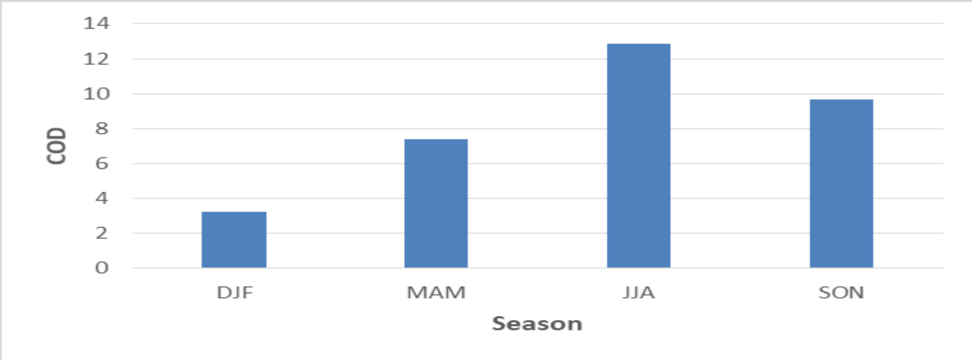

Figure 4: Seasonal mean Cloud Optical Depth (COD) over Kogi East, Nigeria

Figures 3 and 4 show contrasting seasonal behaviour. AOD was generally higher in the dry season because of Harmattan dust transport and limited rainfall, whereas COD increased during the wet season as moisture and convection favoured cloud development. The contrast may produce an inverse AOD–COD relationship through shared seasonal controls rather than a direct aerosol effect.

Wet-season moisture and convective activity favoured higher COD, while dry-season conditions generally limited cloud development.

The seasonal contrast represents co-variability and does not independently establish causal aerosol–cloud interaction.

Pearson Correlation between AOD and COD

The relationship between AOD and COD is presented in Figure 5. Pearson analysis gave a moderate negative correlation ($r = -0.469$). Months with higher AOD tended to have lower COD, consistent with their contrasting seasonal cycles.

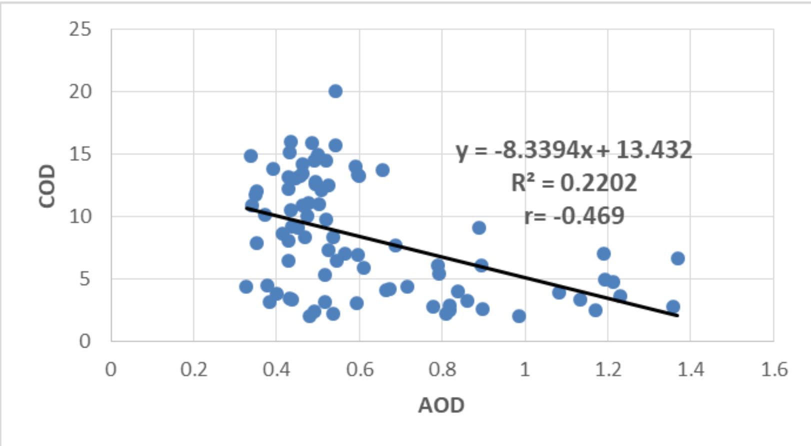

Figure 5: Scatter plot showing the relationship between AOD and COD over Kogi East, Nigeria, 2019-2025

The negative association indicates that higher AOD generally coincided with lower COD, but this does not demonstrate that aerosol loading directly reduced cloud optical depth.

Both AOD and COD are affected by seasonal moisture, precipitation, cloud development and Harmattan circulation. Other controls include relative humidity, temperature, stability, vertical motion, cloud type, water content and wind fields (Andreae & Rosenfeld, 2008; Taylor et al., 2019).

Linear Regression between AOD and COD

The simple linear regression produced COD = 13.432 − 8.3394(AOD), with $R^2 = 0.2202$. The negative slope indicates an inverse statistical association, while R^2 shows that AOD explains approximately 22.02% of COD variability.

$$COD = 13.432 - 8.3394(AOD)$$

The fitted slope indicates that a one-unit increase in AOD corresponds to an estimated 8.34-unit decrease in COD. The remaining 77.98% of COD variability is not explained by this one-variable model, highlighting the role of other atmospheric processes.

Because cloud optical properties depend on multiple atmospheric processes, AOD alone has limited explanatory power.

The regression therefore represents a statistical association rather than direct aerosol causation. Additional variables such as relative humidity, precipitation, temperature, wind, cloud fraction and atmospheric stability would improve interpretation.

Discussion

Overall, the results show pronounced seasonal variability in AOD and COD over Kogi East during 2019–2025. AOD generally increased during the dry Harmattan season, whereas COD generally increased during the wet season.

The AOD pattern agrees with the seasonal influence of Saharan and Sahelian dust transport and reduced aerosol removal during dry conditions (Ayanlade et al., 2019; Knippertz & Todd, 2012).

Higher wet-season COD is consistent with increased moisture and convective cloud development. The opposing seasonal cycles contributed to the observed negative AOD–COD correlation.

The correlation (r = −0.469) and R^2 (0.2202) indicate moderate association and limited explanatory power. The result supports co-variability but not direct causation.
The findings highlight the need to consider meteorological conditions when interpreting aerosol–cloud relationships. Future studies should combine MODIS observations with meteorological and ground-based measurements where available.

CONCLUSION

This study examined seasonal and interannual variability in AOD and COD over Kogi East using 84 monthly MODIS Aqua observations from January 2019 to December 2025. AOD ranged from 0.328 to 1.368 (0.616 ± 0.259), while COD ranged from 1.966 to 20.088 (8.290 ± 4.591). AOD was generally higher in the dry season, whereas COD increased during the wet season.
A moderate negative AOD–COD relationship was observed (r = −0.469). The regression, COD = 13.432 − 8.3394(AOD), gave R^2 = 0.2202, showing that AOD statistically explained about 22.02% of COD variability but did not establish direct causation.
The contrasting seasonal behaviour reflects the influence of dust transport, precipitation, moisture and cloud development. The study provides a satellite-based baseline for Kogi East. Future work should incorporate precipitation, humidity, temperature, wind, cloud fraction, aerosol composition and ground-based observations to better separate seasonal co-variability from direct aerosol effects.

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