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Statistical Relationship Between Aerosol Optical Depth and Cloud Optical Properties over Kogi East, Nigeria

***[1]Abubakar Rasaq, [2]Egbunu Friday, [1]Aliyu Luqman Ugbede, [3]Abubakar Hamza, [3]Ugbede Akoh, [1]Maji Sunday Benjamin, [3]Ezejah Ofokaja, [3]Onuche Usman Paul and [4]Abubakar Abdulrazaq Ibrahim**

[1]Centre for Atmospheric Research (CAR), National Space Research and Development Agency (NASRDA), Anyigba, Kogi State, Nigeria.
[2]Department of Physics, Prince Abubakar Audu University, Anyigba, Kogi State, Nigeria.
[3]Bola Ahmed Tinubu Centre for Space Transport and Propulsion, National Space Research and Development Agency (NASRDA), Epe, Lagos State, Nigeria.
[4]Advanced Unmanned Aerial Vehicles Laboratory, Annex Building, Obasanjo Space Centre Airport Road, Abuja, FCT, Nigeria.

*Corresponding authors' email: abubakarrasaq71@gmail.com

ABSTRACT
Aerosol–cloud interactions are important components of the climate system because aerosols can modify cloud optical characteristics and influence atmospheric radiation and precipitation. This study investigated the statistical relationship between aerosol optical depth (AOD) and cloud optical depth (COD) over Kogi East, Nigeria, using monthly Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua observations from January 2019 to December 2025. Area-averaged monthly AOD at 550 nm from the Deep Blue land product and combined cloud optical thickness were obtained from the MODIS/Aqua MYD08_M3 Collection 6.1 product through NASA Giovanni. The matched dataset comprised 84 monthly observations. Descriptive statistics, Pearson product-moment correlation and simple linear regression were applied. AOD ranged from 0.3275 to 1.3678, with a mean of 0.6167 ± 0.2583 and a coefficient of variation of 41.89%. COD ranged from 1.9656 to 20.0880, with a mean of 8.2895 ± 4.5910 and a coefficient of variation of 55.38%. A moderate negative correlation was found between AOD and COD ($r = -0.4693$, $p < 0.001$). The fitted model was COD = 13.4322 − 8.3394AOD, with $R^2 = 0.2202$. Thus, AOD statistically accounted for about 22.02% of the observed variation in COD, while the remaining variation was associated with other atmospheric and cloud-related factors. The findings establish a quantitative baseline for aerosol–cloud studies over Kogi East, but the statistical association should not be interpreted as proof of a causal aerosol effect because meteorological conditions, aerosol type, cloud regime and satellite retrieval uncertainties can influence both variables.

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INTRODUCTION

Atmospheric aerosols are suspended solid and liquid particles that interact with solar and terrestrial radiation and influence atmospheric chemistry, clouds, precipitation, and climate. Their climatic effects occur through both direct interactions with radiation and indirect interactions with clouds. Aerosol–cloud interactions are particularly important because aerosols can influence the concentration and characteristics of cloud condensation nuclei and thereby modify cloud droplet number, droplet size, cloud optical properties, precipitation processes, and cloud lifetime (Twomey, 1977; Albrecht, 1989; Fan et al., 2016). The climatic importance of aerosols is therefore substantial, although the magnitude of aerosol radiative forcing remains uncertain because aerosol–cloud processes vary with aerosol composition, cloud regime, meteorological conditions, and atmospheric dynamics (Bellouin et al., 2020; Bender, 2020).

Aerosol optical depth (AOD) is a dimensionless measure of the extinction of radiation by aerosols integrated along an atmospheric column and is widely used as an indicator of atmospheric aerosol loading. Cloud optical depth (COD), also referred to as cloud optical thickness, describes the integrated optical attenuation produced by a cloud layer and is related to cloud water content, particle characteristics, and cloud microphysical structure (Platnick et al., 2003; King et al., 2013). The relationship between AOD and COD is therefore potentially useful for investigating aerosol–cloud interactions. Under the classical aerosol indirect effect, an increase in aerosol concentration can increase cloud condensation nuclei and cloud droplet number while reducing mean droplet size, thereby increasing cloud reflectivity and potentially altering cloud optical depth (Twomey, 1977). However, aerosol–cloud relationships are not necessarily linear or positive because they can be influenced by cloud dynamics, precipitation, entrainment, atmospheric humidity, aerosol type, cloud development, and atmospheric stability (Fan et al., 2016; Oreopoulos et al., 2020).

Within Nigeria, Balarabe and Isah (2019) demonstrated the usefulness of regression-based approaches for quantifying aerosol optical depth, supporting the application of statistical modelling to satellite-derived aerosol observations in the present study.

Satellite observations have provided important evidence of the relationship between aerosol loading and cloud properties. Using MODIS observations and global aerosol models, Myhre et al. (2007) demonstrated relationships between AOD and several cloud properties, including cloud optical depth, cloud cover, and cloud liquid water path. Their findings showed that satellite-derived aerosol–cloud relationships can provide useful evidence of aerosol effects on clouds, although interpretation is complicated by meteorological and retrieval-related factors. More recent global analyses have similarly shown that apparent aerosol–cloud responses vary substantially among cloud regimes and geographical locations, indicating that environmental conditions must be considered when interpreting satellite-derived relationships (Oreopoulos et al., 2020).

The African continent provides an important environment for investigating aerosol–cloud interactions because of the coexistence of natural and anthropogenic aerosol sources. Mineral dust from the Sahara and Sahel, biomass-burning emissions, urban and industrial emissions, traffic-related particles, and other anthropogenic sources contribute to atmospheric aerosol loading over different African regions. These aerosol sources interact with regional circulation, humidity, precipitation, and cloud development. Over West Africa, the interaction between aerosols, clouds, atmospheric chemistry, and meteorological processes is particularly important because the region experiences strong seasonal changes associated with the West African monsoon (Knippertz et al., 2015; Flamant et al., 2018).

The Dynamics–Aerosol–Chemistry–Cloud Interactions in West Africa (DACCIWA) project provided extensive evidence of the complexity of these processes. The project combined ground-based, aircraft, and atmospheric observations across several West African countries, including Nigeria, to investigate atmospheric composition, low-level clouds, weather, and aerosol–cloud interactions. The campaign demonstrated the importance of the coupled influence of natural and anthropogenic emissions, atmospheric dynamics, clouds, and radiation in southern West Africa (Flamant et al., 2018). The West African atmosphere is therefore characterized by a complex mixture of aerosol sources and atmospheric processes, making regional studies necessary for understanding aerosol–cloud relationships.

Seasonal variability further complicates the relationship between aerosol and cloud properties over Africa. During dry periods, mineral dust transport and biomass burning can contribute substantially to aerosol loading, while reduced rainfall limits wet removal of atmospheric particles. During the wet season, increased precipitation and atmospheric moisture can alter aerosol concentrations and support cloud development. Consequently, the relationship between AOD and cloud properties may change considerably between seasons. Nyasulu et al. (2020), using MODIS observations over Malawi, reported substantial seasonal variability in AOD and investigated its relationship with cloud properties over a ten-year period. Their study demonstrates the usefulness of long-term MODIS observations for examining aerosol–cloud relationships in African environments. Similarly, MODIS-based investigations over Africa have identified substantial spatial and temporal variability in aerosol and cloud optical and microphysical properties (Ntwali & Chen, 2018).

Recent regional investigations further demonstrate that aerosol–cloud interactions cannot be interpreted independently of atmospheric conditions. A decadal assessment over South Africa using MODIS, MISR, and meteorological observations showed substantial regional differences in aerosol and cloud properties and emphasized the complexity of aerosol–cloud interactions across different atmospheric environments (Chetty et al., 2022). At the global scale, satellite studies have also shown that meteorological conditions and cloud regimes can substantially influence apparent aerosol–cloud relationships (Oreopoulos et al., 2020). These findings suggest that statistical relationships observed between AOD and COD may reflect a combination of direct aerosol effects and common responses of both variables to meteorological and seasonal controls.

The use of satellite remote sensing is particularly valuable for regions where long-term ground-based observations are limited. The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites provides long-term observations of aerosol and cloud properties and has been widely used for regional and global atmospheric studies (King et al., 2013; Platnick et al., 2003). The MODIS Aqua MYD08_M3 Level-3 monthly atmosphere product provides monthly statistics of aerosol and cloud properties and therefore provides an appropriate dataset for investigating long-term temporal variability. Nevertheless, satellite retrievals are associated with uncertainties. Aerosol retrievals may be affected by surface reflectance, aerosol type, cloud contamination, and viewing geometry, while cloud optical-depth retrievals may be influenced by cloud phase, cloud heterogeneity, and aerosol above or near cloud layers (Remer et al., 2005; Alfaro-Contreras et al., 2014).

The interpretation of satellite-derived AOD–COD relationships therefore requires caution. A negative statistical relationship does not necessarily imply that increasing aerosol loading directly suppresses cloud optical depth. Likewise, a positive relationship does not necessarily provide direct evidence of the classical aerosol indirect effect. Meteorological variables such as relative humidity, temperature, precipitation, wind, atmospheric stability, and vertical motion can influence both aerosol loading and cloud properties and may therefore produce apparent statistical relationships between them (Engström & Ekman, 2010; Oreopoulos et al., 2020). This consideration is particularly important for monthly area-averaged observations, where short-term variations and sub-grid-scale processes are not explicitly resolved.

Despite increasing satellite-based research on aerosol and cloud properties across Africa, quantitative information on the long-term relationship between AOD and COD remains limited for several inland regions of Nigeria. This is particularly relevant to Kogi East, where seasonal changes in atmospheric circulation, rainfall, humidity, dust transport, biomass burning, convection, and anthropogenic activities may influence aerosol and cloud conditions. Although studies associated with West African aerosol and cloud processes have provided important regional information, the specific statistical relationship between long-term satellite-derived AOD and COD over Kogi East remains insufficiently documented. This creates a need for a regional assessment using a consistent multi-year satellite dataset.

The present study addresses this gap by investigating the temporal variability and statistical relationship between aerosol optical depth and cloud optical depth over Kogi East, Nigeria, using monthly MODIS Aqua observations from January 2019 to December 2025. Area-averaged AOD at 550 nm from the Deep Blue land product and combined cloud optical thickness from the MODIS/Aqua MYD08_M3 Collection 6.1 product were obtained through NASA Giovanni. The study uses descriptive statistics, Pearson product-moment correlation, and simple linear regression to characterize the variability of AOD and COD and quantify their statistical association. The analysis is interpreted as an assessment of statistical association rather than direct proof of causality because meteorological conditions, aerosol characteristics, cloud regimes, and satellite retrieval uncertainties may influence both variables.

The objectives of this study were to: (i) determine the statistical characteristics of AOD and COD over Kogi East from 2019 to 2025; (ii) determine the strength and direction of the relationship between AOD and COD; and (iii) develop a simple linear regression relationship between AOD and COD.

MATERIALS AND METHODS

Study Area

The study was conducted over Kogi East, Nigeria. The MODIS Giovanni extraction used a user-defined bounding box extending from 6.4°E to 7.5°E longitude and 6.3°N to 8.5°N latitude. The Giovanni output reported a data bounding box of 6.5°E–7.5°E and 6.5°N–8.5°N. The region has distinct wet and dry seasons. For broad seasonal interpretation, November–March was treated as the dry season and April–October as the wet season.

Data Sources

Two monthly MODIS Aqua datasets were used: (1) Aerosol Optical Depth 550 nm (Deep Blue, Land-only), monthly; and (2) Combined Cloud Optical Thickness: Mean of Daily Mean, monthly. Both variables were obtained from the MODIS/Aqua MYD08 M3 Collection 6.1 product through NASA Giovanni. The downloaded files covered 1 January 2019 to 31 December 2025.

Data Processing

The two CSV files were read, chronological dates were retained, and the AOD and COD records were matched by month. The resulting analytical dataset contained 84 paired observations from January 2019 to December 2025, with no missing paired observations after matching. Descriptive statistics included minimum, maximum, arithmetic mean, sample standard deviation and coefficient of variation.

The coefficient of variation was calculated as:

The coefficient of variation (CV) used to quantify relative variability was calculated using Equation (1):

$$CV = \frac{SD}{\bar{X}} \times 100 \quad (1)$$

Statistical Analysis

Pearson's product-moment correlation coefficient was used to quantify the direction and strength of the linear association between AOD and COD. Simple linear regression was then fitted with COD as the dependent variable and AOD as the explanatory variable:

The linear association between AOD and COD was modelled using the simple linear regression form given in Equation (2):

$$COD = a + b(AOD) \quad (2)$$

The coefficient of determination (R^2) was used to quantify the proportion of variance in COD statistically associated with AOD in the fitted linear model. A two-tailed significance level of 0.05 was adopted.

RESULTS AND DISCUSSION

Descriptive Statistics

The descriptive statistics for AOD and COD are summarized in Table 1.

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

Parameter	N	Minimum	Maximum	Mean	SD	CV (%)
AOD	84	0.327531	1.367819	0.616674	0.258336	41.89
COD	84	1.965602	20.087991	8.289518	4.590975	55.38

The higher CV for COD indicates that cloud optical thickness responded more strongly to temporal and seasonal changes than aerosol loading over the study domain. This difference is expected because cloud optical properties can change rapidly with moisture availability, convection and cloud development, whereas monthly area-averaged AOD reflects the combined influence of aerosol emission, transport and removal processes.

AOD varied from 0.327531 to 1.367819, with a mean of 0.616674 and standard deviation of 0.258336. The coefficient of variation of 41.89% indicates substantial temporal variability in aerosol loading. COD ranged from 1.965602 to 20.087991, with a mean of 8.289518 and standard deviation of 4.590975. Its coefficient of variation was 55.38%, which was higher than that of AOD, indicating greater relative variability in retrieved cloud optical thickness during the study period.

The monthly AOD time series is presented in Figure 1.

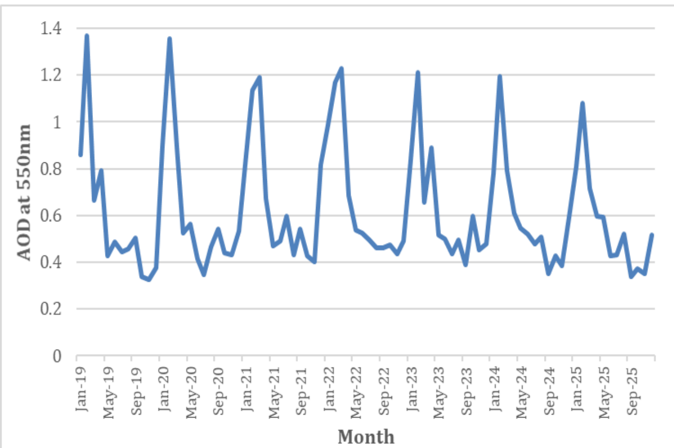

Figure 1: Monthly Variation of Aerosol Optical Depth (AOD) at 550 nm over Kogi East, January 2019-December 2025

Figure 1 shows pronounced month-to-month changes in AOD. The largest values occur mainly during portions of the dry-season period, while lower values are generally observed during wetter months. This pattern is physically consistent with reduced wet removal and enhanced dust or biomass-burning influence during dry conditions, although the present dataset alone cannot attribute individual peaks to a specific aerosol source.
The corresponding monthly COD variation is shown in Figure 2.

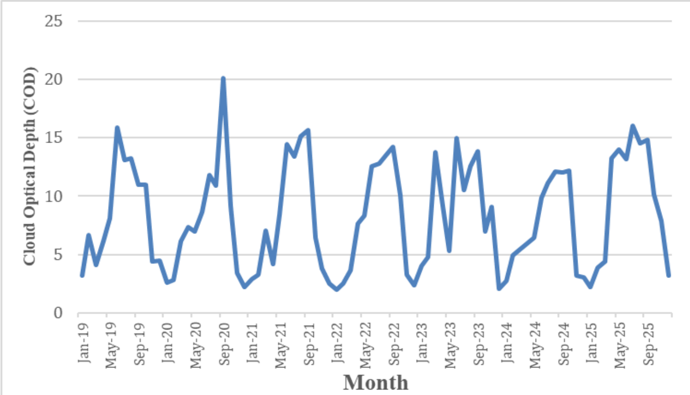

Figure 2: Monthly Variation of Cloud Optical Depth (COD) over Kogi East, January 2019–December 2025

COD also exhibited strong temporal variability. The time series shows relatively low optical thickness during several dry-season months and higher values during many wet-season months. This seasonal contrast is consistent with the greater availability of atmospheric moisture during the rainy season, although cloud optical thickness is also controlled by cloud type, liquid-water content, cloud development and atmospheric dynamics.

Annual and Seasonal Variability
The annual mean values of AOD and COD are presented in Table 2.

Table 2: Annual Mean AOD and COD over Kogi East, 2019–2025

Year	Mean AOD	Mean COD
2019	0.5872	8.4298
2020	0.6176	7.6660
2021	0.6661	8.0987
2022	0.6630	7.7224
2023	0.6218	8.9166
2024	0.5982	7.4149
2025	0.5629	9.7782

Annual means show that AOD was highest in 2021 (0.6661) and lowest in 2025 (0.5629), whereas COD was highest in 2025 (9.7782) and lowest in 2024 (7.4149). These annual variations indicate that the seven-year record does not follow a simple monotonic pattern for either variable. The annual contrast between AOD and COD is illustrated in Figure 3.

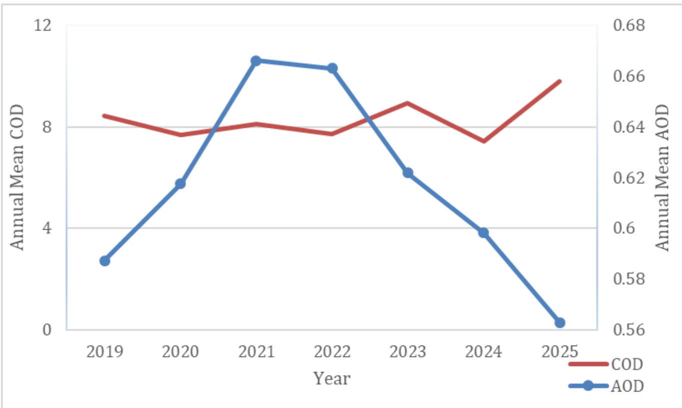

Figure 3: Annual Mean AOD and COD over Kogi East, 2019–2025

The seasonal contrast is consistent with earlier MODIS-based observations over African environments, where aerosol and cloud properties exhibit strong seasonal dependence. Nyasulu et al. (2020), for example, reported marked seasonal variability in AOD and cloud properties over Malawi. The present Kogi East results similarly indicate that seasonality is an important background control that should be considered when interpreting the AOD–COD relationship.
For seasonal interpretation, the dry-season observations had a mean AOD of 0.7782, compared with 0.5013 during the wet

season. Conversely, mean COD was substantially higher during the wet season. This contrast provides a plausible meteorological context for the negative overall AOD–COD association, but it should not be interpreted as independent proof of aerosol causality because both variables respond to seasonal atmospheric conditions.

Pearson Correlation between AOD and COD

Pearson correlation analysis yielded r = -0.469265 with p = 6.709e-06. The negative sign indicates an inverse linear association, while the magnitude indicates a moderate relationship. Thus, months with relatively high AOD tended, on average, to have lower retrieved COD values in the paired dataset.

The Pearson correlation result is summarized in Table 3.

Table 3: Pearson Correlation Between AOD and COD

Variables	Pearson r	p-value	Interpretation
AOD vs COD	-0.469265	<0.001	Moderate negative relationship

Linear Regression Relationship

The fitted simple linear regression model was COD = 13.432233 − 8.339443AOD, with R^2 = 0.220209. The slope was statistically significant (p = 6.709e-06) and its 95% confidence interval was -11.787 to -4.892. The model therefore indicates that, within the observed data range, an increase of one AOD unit is associated with an estimated decrease of about 8.34 COD units.

The fitted regression coefficients are summarized in Table 4.

The AOD–COD scatter plot and fitted regression line are shown in Figure 4.

Table 4: Simple Linear Regression of COD on AOD

Parameter	Estimate	Standard error	R^2	p-value
Intercept	13.432233	—	0.220209	6.709e-06
AOD slope	-8.339443	1.733011	0.220209	6.709e-06

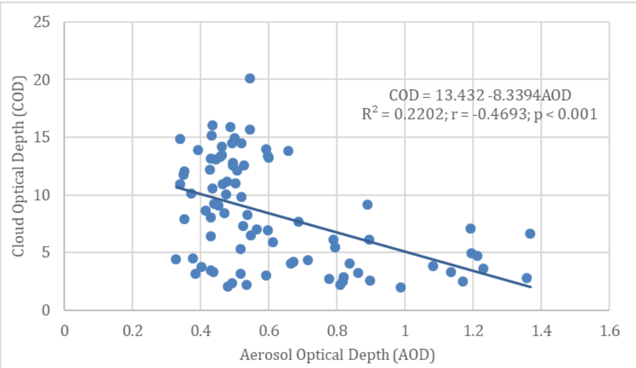

Figure 4: Scatter Plot and Fitted Linear Regression Between AOD and COD over Kogi East, 2019–2025

The relatively modest R^2 is important for interpretation: AOD alone is not sufficient to explain most of the month-to-month variability in COD. Similar caution is emphasized in satellite aerosol–cloud studies because meteorological covariation and cloud-regime selection can generate apparent relationships between aerosol and cloud properties. Therefore, the fitted equation is best regarded as an empirical statistical relationship for the study domain and period rather than a predictive causal law.

The R^2 value of 0.2202 means that approximately 22.02% of the observed variability in COD is statistically associated with AOD in this one-predictor model. Consequently, about 77.98% remains unexplained by AOD alone. The result emphasizes that cloud optical properties are controlled by multiple interacting processes, including humidity, precipitation, temperature, vertical motion, cloud type and microphysical characteristics.

Physical Interpretation and Comparison with Aerosol–Cloud Theory

The inverse relationship observed in Kogi East does not necessarily contradict aerosol–cloud theory. Aerosol particles may influence clouds by acting as cloud condensation nuclei, but the sign and magnitude of the observed relationship depend on aerosol composition, particle size, cloud regime, moisture, atmospheric stability and vertical overlap between aerosol and cloud layers. In West Africa, mineral dust, biomass-burning particles and anthropogenic aerosols may coexist, and their cloud interactions can differ.

A plausible interpretation of the present result is that seasonal meteorological conditions act on both variables. During relatively dry periods, aerosol loading may increase because of dust transport, biomass burning and reduced wet removal, while reduced moisture can limit cloud development and optical thickness. During wetter periods, enhanced moisture can support thicker clouds while rainfall removes aerosol through wet deposition. This shared seasonal control can generate a negative statistical association even when a direct aerosol-induced reduction in COD is not established.

Satellite Retrieval Considerations and Limitations

The use of MODIS Aqua MYD08 M3 provides a consistent seven-year monthly record and makes it possible to investigate regional variability where continuous ground-based observations are limited. However, satellite retrievals are subject to uncertainty. AOD retrievals can be affected by surface reflectance, cloud contamination, aerosol type and viewing geometry, while cloud optical-property retrievals can be affected by cloud phase, cloud heterogeneity and aerosol–cloud vertical structure.

The principal limitation of the present analysis is that it uses only two remotely sensed variables and a simple bivariate statistical model. The analysis therefore quantifies association rather than causation. The use of monthly area-averaged data also removes some short-term and sub-grid variability. Future studies should incorporate precipitation, relative humidity, temperature, wind, cloud fraction, aerosol type and atmospheric stability and should consider seasonal or multivariate analyses.

CONCLUSION

This study quantified the statistical relationship between AOD and COD over Kogi East, Nigeria, using 84 paired monthly MODIS Aqua observations from January 2019 to December 2025. AOD ranged from 0.327531 to 1.367819, with a mean of 0.616674 ± 0.258336 and CV of 41.89%, whereas COD ranged from 1.965602 to 20.087991, with a mean of 8.289518 ± 4.590975 and CV of 55.38%. COD therefore showed greater relative variability than AOD.

A moderate negative correlation was found between AOD and COD ($r = -0.469265$, $p < 0.001$). The regression equation was $COD = 13.432233 - 8.339443 AOD$, with $R^2 = 0.2202$, indicating that approximately 22.02% of COD variability was statistically associated with AOD in the simple model. The result provides a useful regional baseline but does not establish a direct causal aerosol effect.

The study recommends that subsequent research combine satellite aerosol and cloud products with meteorological variables and aerosol-type information. Seasonally stratified and multivariate approaches, together with independent ground-based observations where available, would provide a stronger basis for identifying the physical mechanisms responsible for aerosol–cloud variability over Kogi East and central Nigeria.

DATA AVAILABILITY

The analysis was based on the two MODIS Aqua MYD08_M3 Collection 6.1 monthly area-averaged CSV datasets supplied for this study through NASA Giovanni. A merged analysis dataset and annual-mean table are provided with the manuscript for reproducibility.

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