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Dynamics of atmospheric turbidity in Nigeria: A geospatial analysis of Linke Turbidity Factor

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Abstract
Atmospheric turbidity plays a critical role in regulating surface solar radiation and has important implications for solar energy utilization, climate variability, and air quality. This study investigates the spatial and temporal dynamics of the Linke Turbidity Factor (TL) across Nigeria using a 13-year (2010–2022) satellite-derived dataset from the Copernicus Atmosphere Monitoring Service (CAMS). Four TL estimation models—Linke, Kasten, Louche, and Grenier—were evaluated to identify the most suitable model for Nigerian atmospheric conditions. Model performance was assessed using statistical metrics including mean bias error (MBE), root mean square error (RMSE), and coefficient of determination (R^2). Results indicate that the Linke model consistently outperformed the other models across the six geopolitical zones. Spatial analysis revealed a pronounced southeast–northwest gradient, with the highest mean TL values observed in the South-East (11.20) and the lowest in the South-West (6.27). Mann–Kendall trend analysis showed no statistically significant interannual trends across all zones. Elevated turbidity in southern Nigeria is associated with high atmospheric humidity and anthropogenic emissions, while northern patterns are influenced by Harmattan dust transport. These findings are relevant for solar resource assessment and atmospheric modeling in Nigeria.

Nomenclature and units

T_L	Linke Turbidity Factor
B_h	Horizontal Beam Irradiance (W/m²)
δ	Solar Declination (Degrees)
$\delta_R(m_r)$	Reyleigh Optical Air Mas
I_0	Solar Constant (W/m²)

1.0 Introduction

Atmospheric turbidity describes the attenuation of solar radiation as it passes through the Earth's atmosphere due to scattering and absorption by aerosols, water vapour, and trace gases. It is a key parameter in atmospheric physics, climate studies, and solar energy assessment (Gueymard, 2009). The Linke Turbidity Factor (TL), originally introduced by Linke (1922), expresses the integrated effect of atmospheric constituents on solar radiation transmission and remains one of the most widely applied turbidity indices (Kasten, 1996). Atmospheric turbidity usually tends to increase leading to increased attenuation of solar radiation with a resulting decrease in solar radiation beams' intensity. Precise measurement and characterization of air turbidity are significant across a broad array of disciplines such as Urban-rural pollution research, climate change research, and atmospheric chemistry research. It is also utilized in many applications such as climate and solar radiation extinction modeling, pollution research, and volcanic eruption fingerprint studies (Gueymard, 1998; Chaabane et al., 2004; Soneye, 2021).

In West Africa, atmospheric turbidity is strongly influenced by both natural and anthropogenic processes. Seasonal Harmattan winds transport large quantities of Saharan dust southward, significantly increasing aerosol optical depth during the dry season (Prospero et al., 2002; Knippertz & Todd, 2012). In contrast, the wet season is characterized by high humidity associated with the West African monsoon, which enhances aerosol hygroscopic growth and increases atmospheric optical thickness (Charlson et al., 1992; Seinfeld & Pandis, 2016).

Nigeria spans diverse climatic zones, ranging from arid and semi-arid regions in the north to humid tropical environments in the south. Anthropogenic activities such as urbanization, biomass burning, and industrial emissions further modify aerosol concentrations, particularly in southern Nigeria. Gas flaring in the Niger Delta has been identified as a major source of atmospheric pollutants and aerosol plumes, contributing to persistent degradation of atmospheric transparency in the South-South region (Elvidge et al., 2009; Anejionu et al., 2015).

Due to the scarcity of long-term ground-based radiation measurements in Nigeria, satellite-derived products have become essential for atmospheric studies. The Copernicus Atmosphere Monitoring Service (CAMS) provides physically consistent estimates of surface solar radiation through the McClear clear-sky model, which has been widely validated across different climatic regions (Lefèvre et al., 2013; Qu et al., 2017).

Several empirical formulations exist for estimating TL from clear-sky radiation data, including the Linke, Kasten, Louche, and Grenier models (Louche et al., 1991; Grenier et al., 1994). However, their relative performance under Nigerian atmospheric conditions has not been adequately assessed. This study therefore aims to (i) analyze the spatial and temporal variability of TL across Nigeria from 2010 to 2022 using CAMS data, (ii) evaluate the performance of four TL estimation models, and (iii) assess regional trends and implications for solar energy and atmospheric studies.

2.0 Materials and Methods

2.1 Study Area and Data Source

Clear-sky solar radiation data were obtained from the CAMS Radiation Service using the McClear model. Daily direct normal irradiance (DNI) values were extracted for 18 locations across Nigeria and used to compute daily TL values. These values were aggregated into monthly and annual means.

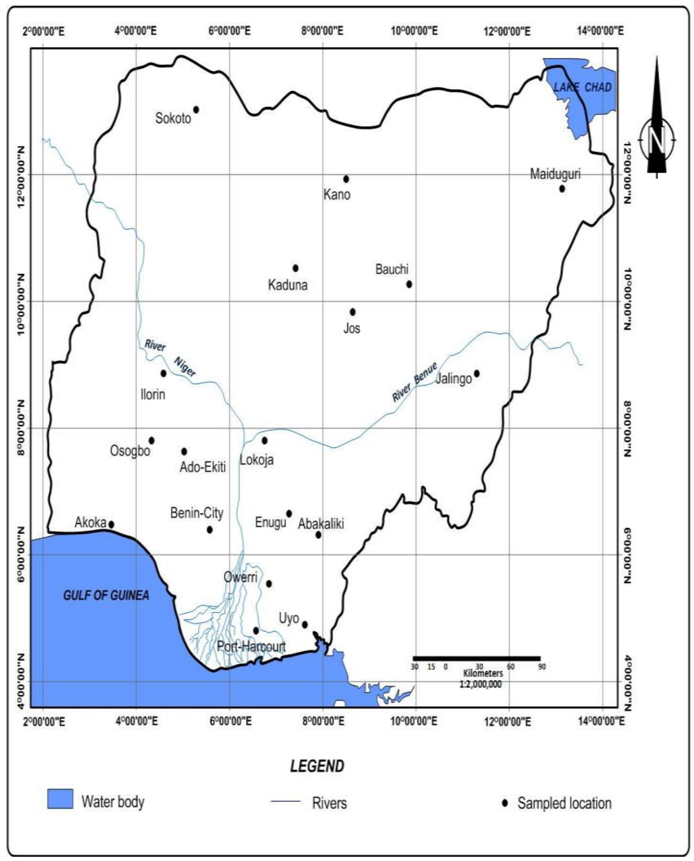

Figure 1 Map of Nigeria showing study locations

2.2 Calculation of Linke Turbidity Factor

The direct normal irradiance over the whole solar spectrum of the earth's surface is expressed in terms of Linke turbidity factor

$$T_L = \left(\frac{1}{\partial_R m}\right) . \ln\left(\frac{I_0 \varepsilon_0 \sin(\alpha)}{B_h}\right) \qquad (1)$$

Where $I_0\varepsilon_0$ is the solar constant normalized by the eccentricity factor because of sun-earth distance variation. I_0 = 1367 W/m2 (Danny and Joseph, 2002; Chaabane et al., 2003)

$$\varepsilon_0 = 1 + 0.033\cos\left(\frac{360dn}{365}\right) \quad (2)$$

$$\sin\alpha = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos w$$

φ= latitude

$$\delta = 23.45\sin\left[\frac{360}{365}(284+n)\right] \quad (3)$$

$$w = hourangle = 15*(hour - 12) \quad (4)$$

$$m = m_r \frac{P}{101325} \quad (5)$$

$$P = 101325\exp(0.0001184z) \quad (6)$$

Z = height above the sea level of the location (7)

$$m_r = \left[\cos\theta_z + 0.15(93.885 - \theta_z)^{-1.253}\right]^{-1} \quad (8)$$

2.3 Turbidity Models

2.3.1 Linke Model: Linke (Linke, 1922) came up with the integral Rayleigh optical thickness δ_R (m_r) as

$$\delta_R(m_r) = 0.128 - 0.054\log m_r \quad (9)$$

2.3.2 Kasten Model. For ease of determination of $T_L(m_r)$ from pyrheliometric measurements, Kasten (Kasten, 1980) proposed the following analytical simple formula for $\delta_R(m_r)$

$$\delta_R(m_r) = (9.4 + 0.9m_r)^{-1} \quad (10)$$

2.3.3 Louche *et al*. Model. (Louche et al, 1986) employed the most recent data available for extraterrestrial solar spectral radiation and for the spectral values of the absorption coefficients of the atmospheric gases, listed by Iqbal (Iqbal, 1976) to compute the enhanced numerical values of the integral Rayleigh optical thickness $\delta_R(m_r)$

$$\delta_R(m_r) = \left(6.5567 + 1.7513m_r - 0.1202m_r^2 + 0.0065m_r^3 - 0.00013m_r^4\right)^{-1} \quad (11)$$

2.3.4 Grenier *et al*. Model. (Grenier et al, 1994) () introduced a fourth-order polynomial for the function ($\delta_R(m_r)$) which is just like Louche et al. (Louche et al, 1986) but with coefficients that marginally vary

$$\delta_R(m_r) = \left(5.4729 + 3.0312m_r - 0.6329m_r^2 + 0.0910m_r^3 - 0.00512m_r^4\right)^{-1} \quad (12)$$

The yearly change of the Linke turbidity factor was studied during the 13-year period from January 2010 to December 2022. The graphs of the turbidity factor were constructed taking into account the change of the mean monthly values. The turbidity factor was calculated using the four models described above

2.4 Statistical Analysis

2.4.1 Mann–Kendall Trend Test

The non-parametric Mann–Kendall (MK) test was employed to detect monotonic trends in annual and seasonal TL time series for each geopolitical zone over the 2010–2022 period. The MK test is widely used in climatological and environmental studies because it does not require data normality and is robust against outliers.

The null hypothesis (H_0) assumes no trend in the time series, while the alternative hypothesis (H_1) indicates the presence of a statistically significant increasing or decreasing trend. Trend significance was evaluated at the 95% confidence level ($p < 0.05$). The direction and magnitude of trends were assessed using Sen's slope estimator.

2.4.2 Analysis of Variance (ANOVA)

A one-way Analysis of Variance (ANOVA) was conducted to test whether mean T_l values differed significantly among Nigeria's six geopolitical zones. Prior to analysis, zonal mean T_l values were examined for homogeneity of variance. The ANOVA null hypothesis assumes no statistically significant difference in mean T_l among zones. Statistical significance was assessed at $p < 0.05$.

2.5 Spatial Analysis

Spatial interpolation was carried out using the IDW method within a GIS environment.

3.0 Results and Discussions

3.1 Model Performance Comparison

Table 2 Mean estimation errors of the Linke turbidity factor

Errors/Models	Linke	Kasten	Louche	Grenier
MBE	0.88	2.12	1.45	2.00
MPE (%)	10.19	25.55	17.29	24.48
RMSE	1.87	2.94	2.24	2.45

Figure 2 Spatial Distribution of Linke Turbidity Factor for North-Central and North-East

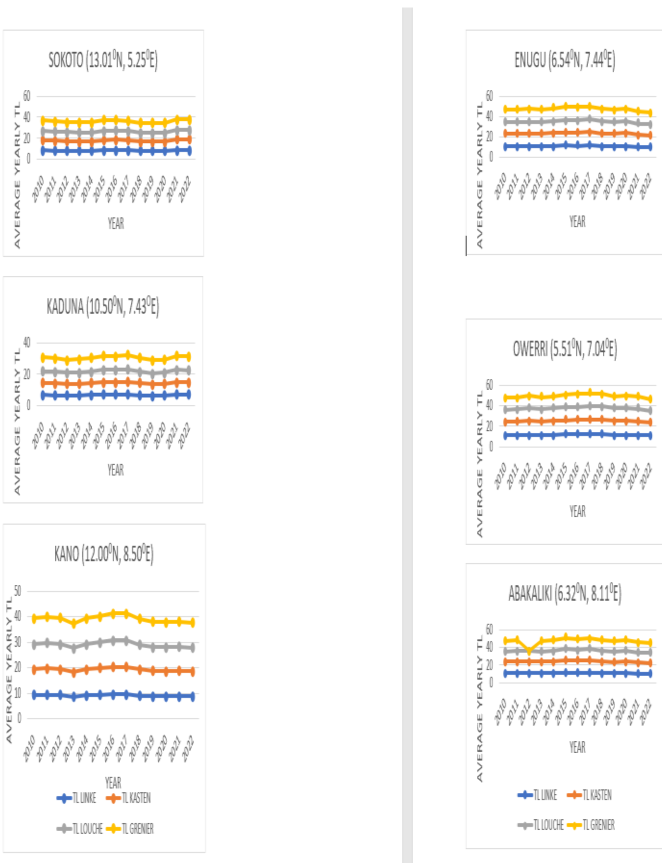

Figure 3 Spatial Distribution of Linke Turbidity Factor for North-West and South East

Figure 4 Spatial Distribution of Linke Turbidity Factor for South-South and South-West

Table 2 Zonal mean TL ± SD of the models

Location	Linke Model	Kasten Model	Louche Model	Grenier Model	F(p)
North Central	7.07 ± 1.66	7.99 ± 1.87	7.54 ± 1.77	8.05 ± 1.76	18.297 (<0.001)
North East	9.41 ± 1.88	10.27 ± 2.11	10.03 ± 2.01	10.46 ± 2.3	10.745 (<0.001)
North West	8.09 ± 1.53	9.12 ± 1.74	8.64 ± 1.65	9.51 ± 2.44	15.709 (<0.001)
South East	11.2 ± 2.18	13.03 ±2.55	11.98 ± 2.28	12.3 ± 2.26	2.619 (<0.001)
South South	10.57 ± 2.48	12.27 ± 2.87	11.18 ± 2.61	11.38 ± 2.5	2.619 (<0.001)
South West	6.26 ±1.63	6.96 ±1.78	6.71 ± 1.73	7.63 ± 2.12	2.619 (<0.001)

3.3 Temporal Variability and Trends

Table 4 Mann-Kendall Test Results for Annual TL

LOCATION	MK Z-Value	Sen's Slope	P-Value	Trend
North Central	-0.666	-0.018	0.561	Decreasing
North East	-0.071	-0.004	0.692	Decreasing
North West	-0.203	-0.002	0.553	Decreasing
South East	-0.031	-0.002	0.577	Decreasing
South South	0.657	0.023	0.575	Increasing
South West	0.138	0.002	0.526	Increasing

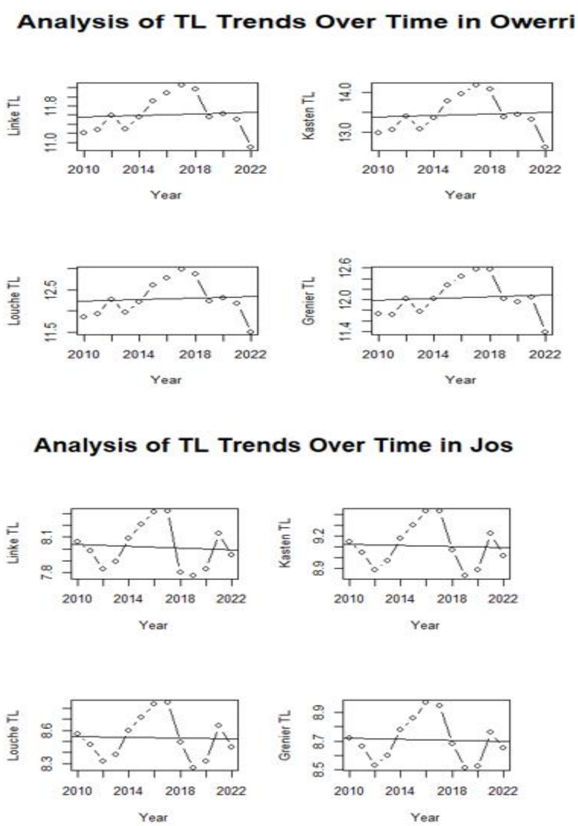

Figure 5 Mann-Kendall Trend Results for Owerri (South East) and Jos (North Central

5.0 Conclusions

This study analyzed the spatial and temporal variability of the Linke Turbidity Factor across Nigeria from 2010 to 2022 using satellite-derived data. Among the evaluated models, the Linke model showed the best performance across all regions. Results revealed a clear spatial gradient, with higher turbidity in southern Nigeria due to moisture and anthropogenic emissions, and relatively lower values in the north influenced by Harmattan dust. Trend analysis indicated no statistically significant long-term changes, although slight increasing tendencies were observed in southern zones. These turbidity patterns have important implications for solar energy generation, as higher turbidity reduces solar radiation availability and may impact photovoltaic system performance.

The findings provide useful insights for solar energy planning, atmospheric modeling, and climate studies in Nigeria. Continuous monitoring and improved turbidity modeling are recommended for better solar resource assessment and energy system optimization.

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Declaration of conflict of interest

The authors have contributed to the conceptualization, design, and execution of this journal. The authors have all contributed to the writing and revising of the manuscript for inclusion of significant intellectual content. The manuscript has not been previously submitted or reviewed by any other journal or publishing site. Moreover, the authors have no affiliation with any organization that has a direct or indirect financial interest in the subject matter discussed in this manuscript.

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