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**DEVELOPING A TRIGONOMETRIC MODEL TO
ESTIMATE AEROSOL OPTICAL DEPTH IN ILORIN,
NIGERIA UTILIZING AERONET DATA**

BY

¹IBRAHIM, B.B. AND ²ZUBAIR, R.O.

¹Department of Science Laboratory Technology, Institute of Applied Sciences,
Physics/ Electronics unit

²Department of Mathematics, Institute of General Studies
Kwara State Polytechnic, Ilorin.

Corresponding author: ibb_fulani@yahoo.com,

Phone: +234 7063401453

ORCID NUMBER: 0000-0003-3679-6111

ABSTRACT

In the course of this research, we acquired Aerosol Optical Depth (AOD) data from the archive of AERosol Robotic NETwork (AeroNet) for Ilorin, Nigeria (latitude 8.32°N, longitude 4.34°E) spanning a period of 13 years from 2002 to 2014. We examined three distinct trigonometric models, namely Sine, Cosine, and Sine Cosine, using the R software package for analysis. To evaluate the performance of these models, we employed statistical error metrics, including the, root mean square error (RMSE), mean bias error (MBE) and mean percentage error (MPE). Additionally, we calculated the correlation coefficient (R) and coefficient of determination (R^2) for each model. After thorough evaluation, it was observed that the Sine Cosine model outperformed the other models, exhibiting the highest values for both R and R^2 , as well as the lowest RMSE. Therefore, we recommend the utilization of the Sine Cosine model for researchers engaged in air quality assessment and atmospheric studies.

Key Words: Aerosol, Aerosol Optical Depth, AERONET, Condensation Nuclei, Ilorin.

INTRODUCTION

Aerosols encompass combination of solid and liquid particles, including elements like mist, dust, fog, industrial emissions, Man-made (anthropogenic) pollutants, and biological particles. These particles have a substantial impact on the balance of energy within the Earth's atmosphere (Glantz et al., 2019). The scientific community places significant importance on understanding the climatic and ecological effects of atmospheric aerosols, as they have wide-ranging consequences for air quality, human health, climate change, and the Earth's radiation budget (Tan et al., 2016). On a global scale, aerosols are estimated to induce a cooling effect on the Earth's system (Putaud & Acqua, 2014; Sharafa et al., 2020; Tian & Sun, 2016). Recent research has indicated that implementing aggressive air pollution reduction measures could lead to an accelerated global warming of approximately +1.0°C by 2030, in addition to +1.2°C attributed to rise in long-lived greenhouse gas abundances (Chen et al., 2014; Nwoforet et al., 2007; Ruiz-Arias et al., 2014). To comprehend the immediate radiative influence of atmospheric aerosols, it is crucial to consider both their optical properties and non-aerosol characteristics, such as surface albedo and solar declination angle. These elements have a central role in shaping the Earth's radiation

equilibrium. Because of the diverse sources and relatively short life spans of aerosols, their properties can vary significantly both in terms of time and location. Moreover, aerosol optical properties exhibit variability on longer time scales, especially in regions closer to the equator (Lihavainen et al., 2017; More et al., 2013; Mu, 2014).

Emissions from burning agricultural biomass have become a noteworthy origin of different atmospheric contaminants, exerting adverse effects on quality of air at community, regional, and worldwide scales (Menut et al., 2016; Sharma et al., 2017; Zhu et al., 2017). These emissions occur over relatively short periods, spanning weeks to months, posing substantial challenges to quality of air and posing severe health risks to humans (Ibi et al., 2016; Shah et al., 2019; Sun et al., 2019). To evaluate the influence of human-made aerosols, including those arising from emissions resulting from the burning of agricultural biomass, on climate change and the radiation budget, researchers employ radiative forcing in coupled aerosol-chemistry-climate models (Butt et al., 2017; Tan et al., 2016; Zeb et al., 2019). These models aim to provide a more accurate representation of the physical, chemical, and optical properties of aerosols, which can differ

over both space and period. However, due to significant uncertainties surrounding factors such as emission levels, dispersion, optical characteristics, and blending conditions of these aerosols, achieving precise estimations of their direct radiative impacts on a regional to worldwide scale remains highly uncertain. Additionally, it's important to mention that aerosols from biomass burning can effectively act as cloud condensation nuclei. This can impact the creation and life span of clouds, thus influencing the radiation balance in the troposphere.

Instrument failures are a common occurrence when dealing with AERONET data, and this frequently results in significant gaps in the series of Aerosol Optical Depth (AOD) data in Sub-Saharan West Africa, specifically at the Ilorin station. These gaps, sometimes spanning many days or even months, occur due to the need for equipment maintenance or servicing, which makes continuous data unattainable for meteorological and atmospheric studies (Nwofor and Chineke, 2007). To address the issues of instrument failures and data gap, we develop a model using available data from the AERONET archive to estimate AOD for the region to solve the persistent problems of the data series. The approach involved utilizing a

Trigonometric Model for predicting AOD over the study area, allowing for a more comprehensive evaluating aerosol optical properties remains possible even when dealing with occasional data interruptions.

MATERIALS AND METHODS

Overview of the research location

The study site is located at the University of Ilorin in Nigeria, with specific coordinates of 8.50 degrees north latitude and 4.50 degrees east longitude, at an elevation of approximately 375 meters above sea level. Ilorin is situated in the Guinea Savannah area of West Africa., serving as a shift area located amidst the Guinea coast and the Sahel region of West Africa. Ilorin is positioned in the intermediary zone between the Sahara Desert and the savanna region of northern Nigeria, which leads to the presence of the dry and dusty Harmattan winds influencing the area. (Ginoux et al., 2010). To be more specific, Ilorin is located at the northern boundary of the Guinea savanna region, where the typical monthly temperature averages around 30.2 degrees Celsius, and the annual rainfall averages approximately 873 millimeters. (Falaiye et al., 2013).

Figure 1 shows (a) the map of Nigeria, (b) map of Ilorin and (c) map of the site respectively.

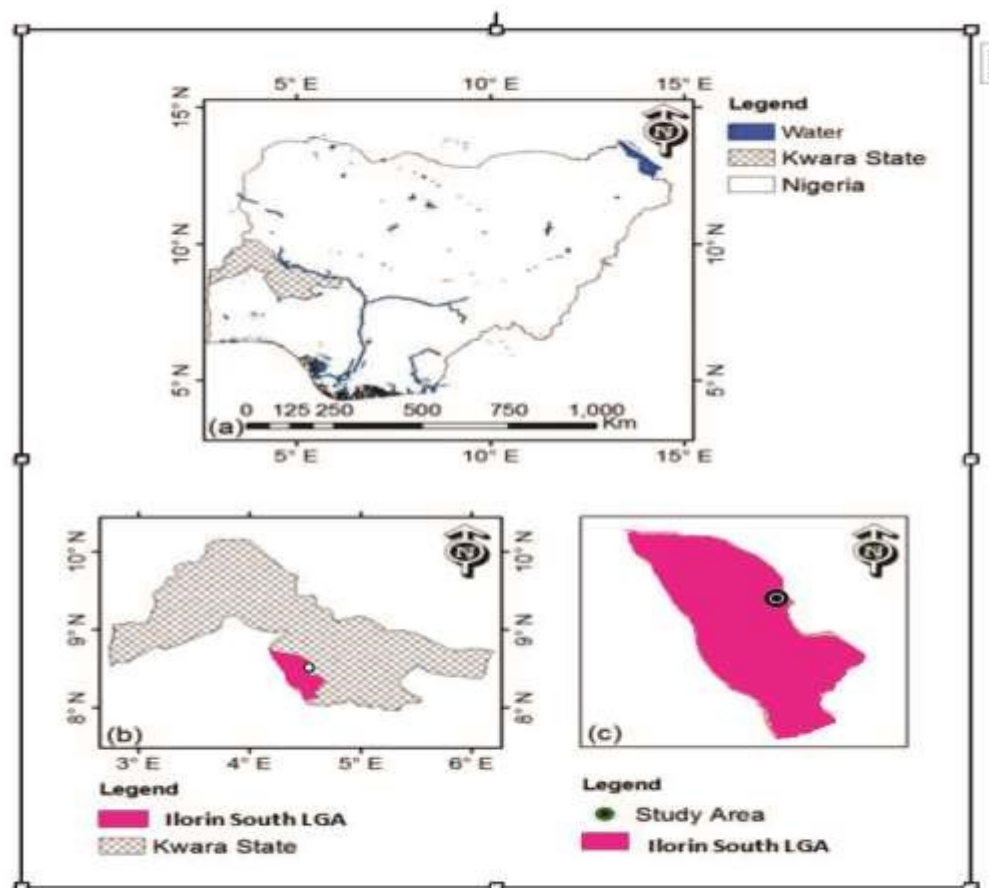


Figure 1 Digitized maps: (a) Nigeria with Kwara State, (b) Kwara State with Ilorin South LGA, and (c) Ilorin South LGA with the study area.

AERONET is short for the AERosol Robotic NETwork, which consists of a network of CIMEL Sun Photometers. Since 1995, about twenty (20) stations have been set up in West Africa as part of the PHOTONS segment of the AERONET network. Each of these stations has been conducting observations for different periods and durations. (Dubovik et al., 2010). A CIMEL Sun photometer is an

automated radiometer designed for sun-sky scanning with filter capabilities. It allows for the measurement of direct solar irradiance at precise wavelengths: 340, 380, 440, 500, 675, 870, 940, and 1020 nm.. These photometers are solar-powered, sturdy, and capable of robotic pointing. The data gathered is sent to the NASA Goddard Space Flight Center using a satellite data telemetry antenna.

NASA performs initial processing of the real-time data, including the daily Aerosol Optical Depth (AOD) patterns at all operational wavelengths. The Aerosol Optical Depth (AOD) data is obtained using the ASTPwin software, developed by Cimel Ltd. Co, and is presented at various levels: Level 1.0 AOD (raw data without cloud screening), Level 1.5 AOD (AOD after cloud screening, following the method outlined by Smirnov et al., 2002), and Level 2 AOD (a quality-assured dataset). Additionally, the Angstrom Exponent is computed between 440 and 870 nm. The

information stored in the photometer's control box microprocessor is subsequently transmitted using a conical-shaped antenna to one of three geosynchronous satellites: GOES, METEOSTAT, or GMS. Afterward, this data is relayed to the relevant ground station for processing and is subsequently made available to the public on the internet at <http://aeronet.gsfc.nasa.gov/>. Figure 2 offers a visual depiction of a standard AERONET CIMEL Sun-Photometer setup on a rooftop.



Figure 2: AERONET CIMEL Sun-photometer at block 9 of the faculty of physical science, University of Ilorin, Nigeria.

Model Development

We developed a straightforward mathematical model to estimate the monthly Aerosol Optical Depth (AOD) for Ilorin. This model is based on a trigonometric function and was designed to replicate the measured data over a 13-year span from 2002 to 2014. The function involves just one independent parameter, which is the month of the year. You can estimate the monthly AOD using the equation provided below:

$$Y = \bar{Y} + A \sin\left(\frac{2\pi t}{12}\right) + K \quad (1)$$

$$Y = \bar{Y} + A \cos\left(\frac{2\pi t}{12}\right) + K \quad (2)$$

$$Y = \bar{Y} + A \left[\left(\sin\frac{2\pi t}{12} \right) + \left(\cos\frac{2\pi t}{12} \right) \right] + K \quad (3)$$

where t is the number of month starting from $t = 1$ for January 2002 and $t = 168$ for December 2014. $\bar{Y}$ Represents the monthly mean AOD for the whole period of years studied,

$$A = \frac{Y_{max} - Y_{min}}{2} \quad (4)$$

$$K = \frac{Y_{max} + Y_{min}}{2} \quad (5)$$

12 in the equations 1 to 3 represents the total number of months in a year.

To fit the trigonometric functions and optimize their performance, we employed a computer software package called R. This involved making adjustments by subtracting a specific value from K and multiplying A by another value until we achieved the best possible fitness, as outlined in a custom-written R program (Husamettin, 2007). Subsequently, we utilized this model to make predictions for the data in the year 2015.

RESULTS and DISCUSSIONS

The model comprising the three trigonometric functions is expressed in the following equations;

$$Y = \bar{Y} + 0.75A \sin\left(\frac{2\pi t}{12}\right) + (K - 0.78) \quad (6)$$

$$Y = \bar{Y} + 0.75A \cos\left(\frac{2\pi t}{12}\right) + (K - 0.78) \quad (7)$$

$$Y = \bar{Y} + 0.6A \left[\left(\sin \frac{2\pi t}{12} \right) + \left(\cos \frac{2\pi t}{12} \right) \right] + (K - 0.78) \quad (8)$$

where $\bar{Y} = 0.7744$, $A = 0.6905$, $K = 0.9841$.

The plots of the measured and predicted data for the three trigonometric functions is presented in Figure 3 to 5 for sine, cosine and sine + cosine model respectively. Table 1 presents the observed and forecasted data for the three trigonometric models in 2015.

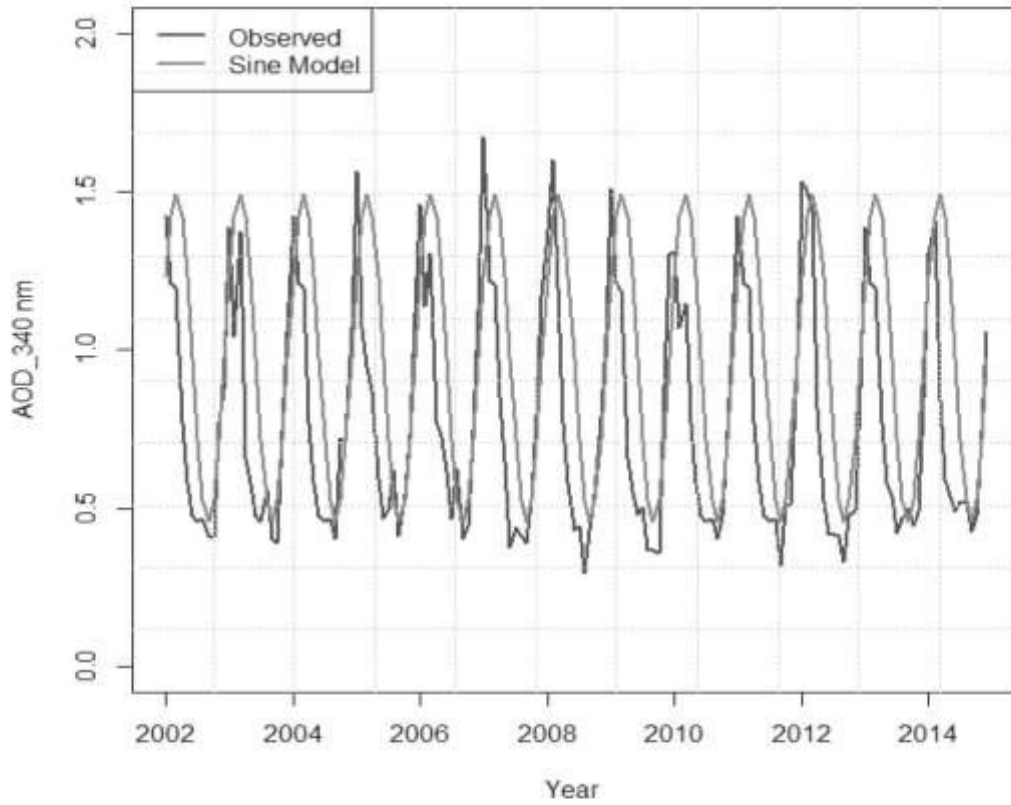


Figure 3: Time series chart illustrating the measured and forecasted AOD at 340 nm for the sine model.

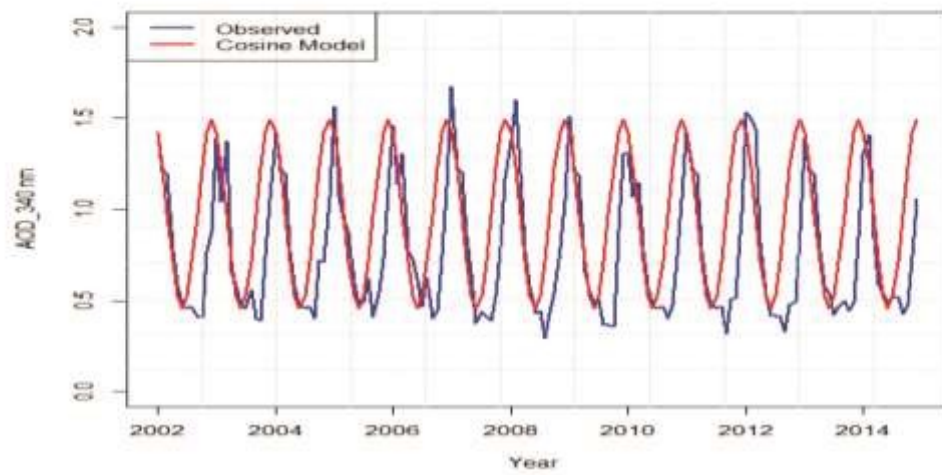


Figure 4: Time series chart illustrating the measured and forecasted AOD at 340 nm for the Cosine model.

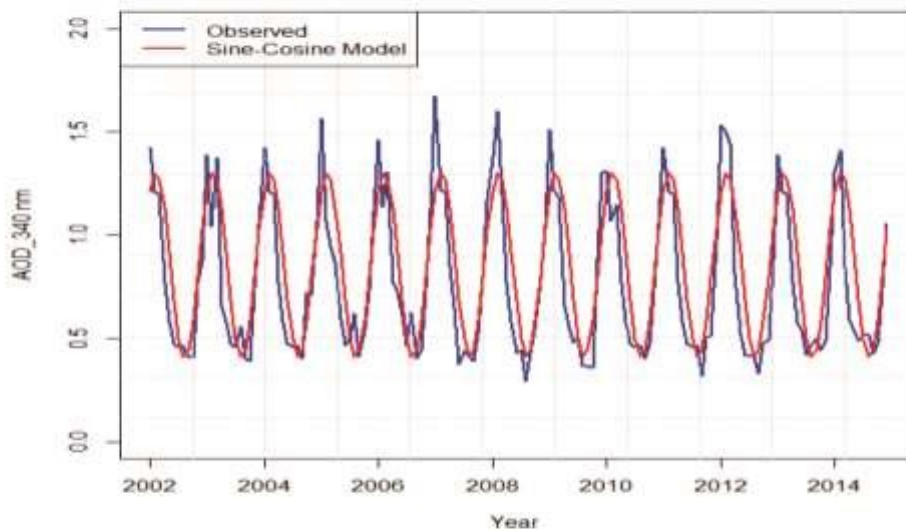


Figure 5: Time series chart illustrating the measured and forecasted AOD at 340 nm for the sine-cosine model.

Table I: Measured and Predicted AOD at 340 nm for 2015 for Ilorin

2015 Forecast	Sine Model	Cosine Model	SineCosine Model	Measured 2015
Jan	1.2347256	1.5737983	1.2786702	1.119353
Feb	1.424292	1.3210431	1.3393314	1.053027
Mar	1.4936781	0.9757731	1.2705431	1.120758
Apr	1.424292	0.6305031	1.090737	1.122485
May	1.2347256	0.377748	0.848092	0.639123
Jun	0.9757731	0.2852331	0.6076247	0.547588
Jul	0.7168206	0.377748	0.433768	0.474944
Aug	0.5272543	0.6305031	0.3731068	0.487607
Sep	0.4578681	0.9757731	0.4418951	0.364249
Oct	0.5272543	1.3210431	0.6217012	0.432197
Nov	0.7168206	1.5737983	0.8643462	0.581512
Dec	0.9757731	1.6663131	1.1048135	1.164366

Table 2: Regression Equation and Statistical Metrics

Equations	R	R ²	MBE	MPE	RMSE
$Y = \bar{Y} + 0.75A \sin\left(\frac{2\pi t}{12}\right) + (K - 0.78)$	0.835	0.914	0.019	-2.72	0.296
$Y = \bar{Y} + 0.75A \cos\left(\frac{2\pi t}{12}\right) + (K - 0.78)$	0.404	0.636	0.217	43.05	0.259
$Y = \bar{Y} + 0.6A \left[\left(\sin \frac{2\pi t}{12} \right) \left(\cos \frac{2\pi t}{12} \right) \right] + (K - 0.78)$	0.924	0.962	0.097	-14.35	0.163

The results, as shown in Table 2, reveal important statistical indicators for our models. For the sine model, we observed a correlation

coefficient of 0.835 between AOD and the months of the year, with a coefficient of determination (R^2) of 0.914. This signifies

that 91.4% of the AOD can be explained by considering the months of the year. On the other hand, the cosine model demonstrated a lower correlation coefficient of 0.404 between AOD and the months of the year, with an R^2 value of 0.636. This suggests that 63.6% of the AOD variation can be attributed to the months of the year when using the cosine model. However, the sine cosine model exhibited the most promising results, with a high coefficient of determination (R^2) of 0.962. This implies that a substantial 96.2% of the AOD can be accounted for by considering the months of the year within this

CONCLUSION

We collected monthly Aerosol Optical Depth (AOD) data spanning a period of thirteen years, from 2002 to 2014, from the AERONET archive for Ilorin. Subsequently, we employed the R software package to fit various trigonometric functions to this dataset. Through our analysis, we developed three simple trigonometric models, all of which demonstrated excellent predictive capabilities when compared to the actual

model. These findings indicate that the sine and sine cosine models are the most suitable for describing the data. Furthermore, it's important to note that the sine cosine model outperforms the sine model, as the R^2 value for the former is greater, and the root mean square error (RMSE) is lower. Nevertheless, it's worth mentioning that the mean bias error (MBE) and mean percentage error (MPE) for the sine model are closer to zero compared to the sine cosine model. Visualizing the results in Figure 6 to 8, it becomes evident that the sine cosine model provides the best fit for the AOD data for Ilorin in 2015.

measured data. After a thorough assessment using statistical indicators, it became evident that the Sine Cosine Model provided the most accurate description of the correlation between AOD and the months of the year.

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