

TREND ANALYSIS OF AOD AND AE IN ILORIN AND CAPO VERDO, WEST AFRICA

Sharafa Salihu Bolaji

Department of Physics, Usmanu Danfodiyo University Sokoto, Sokoto, Nigeria

Aliyu Rakiya

Physics Department, Kano State University of Science and Technology Wudil, Kano, Nigeria.

Ibrahim Bolaji Balogun

Physics/Electronics Unit, Kwara State Polytechnic, Ilorin, Nigeria

ABSTRACT

Analysis of atmospheric aerosols enhances confidence in the evaluation of its effects on both local and regional climate change. To accomplish this over West Africa, it is vital to be familiar with aerosols' temporal characteristics over the area. West Africa has witnessed more frequent and intensified dust storms in the past. Trend analysis of aerosols in this region requires observational data regarding its physical and optical properties. For this, the Statistical Package for the Social Sciences (SPSS) software has been used. Monthly averaged measurements of aerosol optical depth at 550 nm (AOD, τ) and Angstrom exponent at 470 – 660 nm (AE, α) data from Moderate Resolution Imaging Spectroradiometer (MODIS) over Capo Verdo and Ilorin Aerosol Robotic Network (AERONET) stations were analyzed in this study. The satellite dataset collected for a period from 2000 to 2015 were examined in relation to their trends. It was discovered that the Ilorin and Capo Verdo stations were dominated by fine mode and coarse mode particles, respectively. Also, an increasing trend in aerosol loading was noticed in Ilorin while a reduction was noticed in Capo Verdo. It was also deduced that fine mode aerosols are on the increase in the two stations. The analysis for the seasonal variation shows that during the dry season, both aerosol loading and fine mode aerosols are on the increase in both stations. In the rainy season, Ilorin station recorded increasing aerosol loading and an increase in dust pollution. On the other hand in Capo Verdo, a reduction in aerosol loading was noticed while fine mode aerosols are on the increase. Seasonal contribution of aerosols show that dry seasons has the highest pollution recorded in Ilorin while Capo Verdo record the least during the same dry season. The highest contribution of fine mode aerosols in both stations was noticed in the rainy season.

Keywords: Aerosol optical depth, Angstrom Exponent, MODIS, AERONET, West Africa.

INTRODUCTION

Aerosol particles influence climate by modifying the global energy balance through absorption and scattering of radiation (direct effects), and the reflectance and persistence of clouds and the development and occurrence of precipitation (indirect effects). Aerosols are stable, sparse suspension of microscopic or sub-microscopic solid and/or liquid particles in air. Aerosol particles contribute to many other climatically important processes, including fertilization of land and oceans through the deposition of nitrates, iron, and other nutrients, acidification of lakes and forests through the deposition of sulfates and nitrates, and the reduction of snow and ice albedo through the deposition of black carbon [1].

Reduction in the intensity of a direct solar beam during its propagation through the atmosphere is determined by absorption and scattering processes. These two different mechanisms contribute to extinction of light, a term that means the loss of light in the atmosphere from a directly transmitted beam [2].

Improvements in satellite measurement capability have increased the amount of aerosol parameters retrieved from space-borne sensors, from the initial aerosol optical depth (AOD, τ) at one wavelength to a list that, depending on sensor or combination, can include complex refractive index and depolarization of backscatter, each at several wavelengths; the wavelength dependences of extinction, scattering, absorption and backscatter; several particle size parameters for one or more size modes; and an indicator of particle shape.

To validate the aerosol retrieval parameters, ground-based measurement data are necessary. The aerosol optical properties retrieved using direct solar radiations from the sun-photometers of the Aerosol Robotic Network (AERONET) are free from surface reflectance error and cloud contamination. Therefore, AERONET dataset is widely used to evaluate the efficiency of satellite based aerosol retrieval algorithm as well as to develop new algorithm [3]. Several approaches have been proposed for the validation of MODIS aerosol retrieval algorithm for the purpose of renovating and improvement [4-6]. Kaufman *et al.* [8] proposed the first algorithm which was later modified by [9] and [10] by proposing two different methods for aerosol retrieval.

Massive dust plumes regularly propagate from the continent to the ocean and as far as America, particularly during the dry season in the so-called Saharan air Layer [11]. These mineral particles exert a strong influence on the radiative balance and the climate. The years of rainfall deficits over West Africa are marked by anomalies in the dynamics of the monsoon system and mineral dust has kept increasing during drought years [12]. But the cause of this continuous dust increase is still unknown because it may be linked to the increase in wind intensity during dry years and/or a decrease in vegetation.

To quantify the effect of atmospheric aerosols, it is necessary to increase our understanding of the subject by studying the spatial and temporal variability of its different properties [13].

Studies have reported on the aerosol climatology in West Africa, but aerosol observations in this region are still scarce. The years of rainfall deficits over West Africa are marked by anomalies in the dynamics of the rainy season and mineral dust has kept increasing [12]. But the cause of this continuous dust increase is still unknown. Dust particles were investigated during the Saharan Dust Experiment (SHADE) campaign over West Africa, while their radiative effects were measured in the solar spectrum by ground-based measurements [14]. The particles found during field measurements were only dust with relatively low absorption properties. Modeling approaches have also been used by some authors [15-17] to study aerosols spatio-temporal distribution and their impacts on the climate. Despite these studies, the spatio-temporal distribution of aerosols and their radiative impacts on the climate is still being explored. Surface networks, such as the Aerosol Robotic Network (AERONET), provide a needed long term coverage, while measurements by satellite instruments like Moderate resolution imaging spectroradiometer (MODIS) provide extensive spatial coverage [18]. But insufficient information on the aerosol features at local and regional levels as well as the inadequacy with which the existing models represent the spatio-temporal heterogeneity is a concern [19,20]. A better understanding of aerosol optical, microphysical and radiative properties is a crucial challenge for climate change studies [21].

Understanding the microphysical and optical properties of aerosols is important in investigations of climate change, since aerosols have a major impact on the radiative energy balance [14]. However, analyzing the impacts of aerosols on climate is challenging, and large uncertainties still exist due to the diversity, not only about the particle size, composition, sources, and lifetime variation, but also in their spatial and temporal distributions. Aerosol parameters can be measured from ground sensors or from aircraft or satellites. Most especially, satellite-based aerosol observation constitutes a recent and powerful tool for assessing aerosol spatial distribution and their properties. The data from satellite sensors can be used to improve the current understanding of climate prediction and the impacts of aerosols on climate change [19,22-23].

Aerosols can affect the Earth's climate directly by scattering and absorbing both shortwave and longwave radiation (direct effects) or indirectly by altering the microphysical and hence radiative properties of clouds (indirect effects) as seen in Figure 1. There are several mechanisms by which aerosols can influence clouds, however, the most studied is the first indirect effect or cloud albedo effect which describes a change in cloud albedo due to an increase in cloud condensation nuclei (CCN) under fixed liquid water content [24].

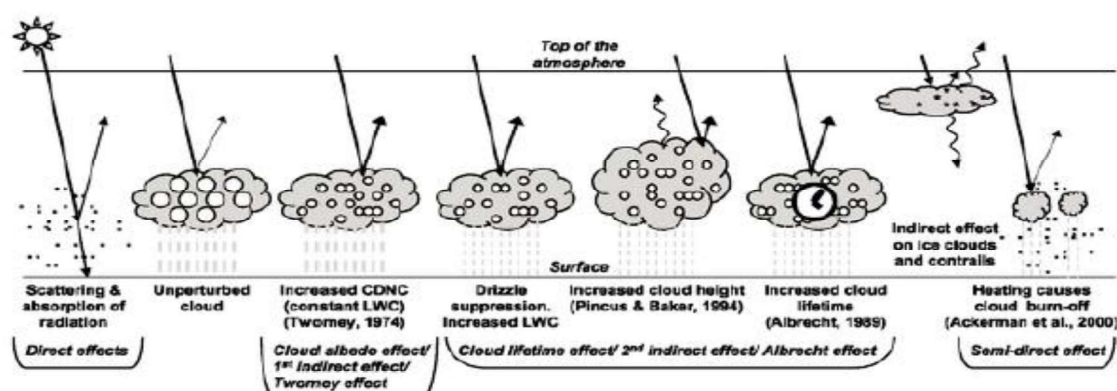


Figure 1: Schematic diagram of the various radiative mechanisms associated with aerosol indirect effects on clouds. The small black dots represent aerosols while the larger open circles represent cloud droplets. Straight lines represent incident and reflected shortwave radiation and wavy lines represent longwave radiation. CDNC stands for cloud droplet number concentration. The unperturbed cloud contains larger droplets while the perturbed cloud contains a greater number of small cloud droplets. [24]

Global-scale atmospheric models, which predict the transport and evolution of aerosols in space and time, play an important role in assessing the radiative forcing of aerosols [24]. For global simulations, models are run with much coarser resolution than processes important for aerosol predictions. As a result, aerosol processes must be parameterized. There is significant diversity in how aerosols are treated across the available atmospheric models [25]. This includes the representation of the size and mass of aerosols within the model (bulk versus modal treatment), the chemical state of aerosols (internal versus external mixtures) and the microphysical processes (nucleation, condensation, coagulation, aging, activation). In addition, emissions of primary aerosol and precursor gases for secondary aerosol formation and model chemistry vary. The vertical transport of aerosols and the removal of aerosols by precipitation is particularly uncertain. This combination of factors leads to a large spread in aerosol predictions and a large uncertainty in aerosol radiative forcing calculations [25]. A better understanding of aerosol optical and microphysical properties is a crucial challenge for climate change studies [21].

The goal of this research is to investigate aerosols and their trend using MODIS data over Ilorin and Capo Verdo.

The objective associated with this work is the analysis of aerosol trend from MODIS measurements over the study stations. This is to analyze the changes in each parameter, per station, over the study period.

The analysis was conducted on aerosol optical depth at 550 nm (AOD, τ_{550}) and Angstrom exponent at 470 – 660 nm (AE, $\alpha_{470-660}$).

Aerosol optical depth, τ , is a measure of aerosol loading. Unpolluted atmospheric conditions should have τ values between 0.04 and 0.06 [26]. Ångström exponent (α) provides first-hand information on the aerosol size distribution trend while the Ångström turbidity coefficient (β), corresponding to τ at unit λ (1 μm), is linked to the columnar mass loading of coarse-mode aerosols.

High α and low β indicate higher quantity of fine mode aerosol concentration. The α value varies from 1 to 3 for fresh and aged smoke, and urban aerosol particles, while it is nearly zero for coarse mode aerosols such as dust and sea salt [27]. β ranges between 0 and 1, and is an indicator of the amount of aerosols present in the atmospheric column [28].

The impact of the connection of two air masses which varies during the year with the north–south displacement of the intertropical convergence zone (ITCZ) controls the climate in West Africa. During November–February, hot and dry continental air masses departing from the high-pressure system over the Sahara Desert offer ascent to dusty harmattan twists over the majority of West Africa. Moist central air masses which originate over the Atlantic Ocean bring annual rainfalls during the months of April to October [29].

THEORETICAL BACKGROUND

The simplest method to quantify the changes in spectral τ is to estimate Ångström parameters (α and β) using Eqn. (1) [30-32],

$$\tau(\lambda) = \beta \lambda^{-\alpha} \quad (1)$$

τ is a measure of aerosol loading. Pure atmospheric conditions should be between 0.04 and 0.06 [31]. Ångström exponent (α) provides information on the aerosol size distribution while the Ångström turbidity coefficient (β) is linked to the columnar mass loading of coarse-mode aerosols.

High α and low β indicate higher quantity of fine mode aerosol concentration. The α value depends on aerosol size distribution and varies from 1 to 3 for fresh and aged smoke, and for urban aerosol particles, while it is nearly zero for coarse mode aerosols such as dust and sea salt [27]. The α can be calculated using Eqn. (2) [32-34]:

$$\alpha = - \frac{\ln\left(\frac{\tau_1}{\tau_2}\right)}{\ln\left(\frac{\lambda_1}{\lambda_2}\right)} \quad (2)$$

where τ_1 is the aerosol optical depth (AOD) at a reference wavelength λ_1 and τ_2 is the AOD at another wavelength λ_2 .

For each wavelength, β is determined as.

$$\beta = \frac{\tau(\lambda_1)}{\lambda_1^{-\alpha}} = \frac{\tau(\lambda_2)}{\lambda_2^{-\alpha}} \quad (3)$$

where λ must be expressed in microns ($550 \text{ nm} = 0.550 \mu$). β values of less than 0.1 are associated with a relatively clear atmosphere, and values greater than 0.2 are associated with a relatively hazy atmosphere [35].

The datasets used in this research are described below.

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Anthropogenic aerosols, which contribute about 20 - 40% to the global τ , are smaller in size and more absorbing than natural aerosols [16].

The Moderate-resolution Imaging Spectroradiometer (MODIS) level II collection 06 aerosol product aqua (MYD04 C006) and terra (MOD04 C006) retrievals are the best aerosol optical depth product suitable for near-real-time aerosol data assimilation [37]. MODIS currently provides the most extensive aerosol retrievals on a global basis, but validation is limited to a small number of ground stations [38].

MATERIALS AND METHOD

Data Collection

Aerosol Robotic Network (AERONET) and Moderate Resolution Imaging Spectroradiometer (MODIS) data were used in this work. Long-term (2000 – 2015) daily data from MOD04_L2/MYD04_L2 Deep Blue (DB) collection 6 of aerosol optical properties were downloaded from the website of Multi-sensor Aerosol Products Sampling System (MAPSS) (<http://giovanni.gsfc.nasa.gov/mapss/>) for analysis in this work. It provides a consistent sampling approach that enables easy and direct inter-comparison and ground-based validation of the diverse aerosol products from different satellite sensors in a uniform and consistent way [39].

For the purpose of this research, only two (2) stations (Capo Verdo and Ilorin, as seen in Figure 2) were selected. The stations were selected purely based on the availability of an extensive data record. Specifically, calculation of the monthly mean of the parameters (both from AERONET and MODIS) using all-point measurements was done. A monthly mean was

considered valid only if there are more than five measurements for that month. To ensure a continuous time series, it was required that the data record should have at least 3 years of AERONET data measurements, with no less than nine monthly data points for each year during the 2000 to 2015 period.

■ Cape Verde ■ Ilorin 4E, 8N

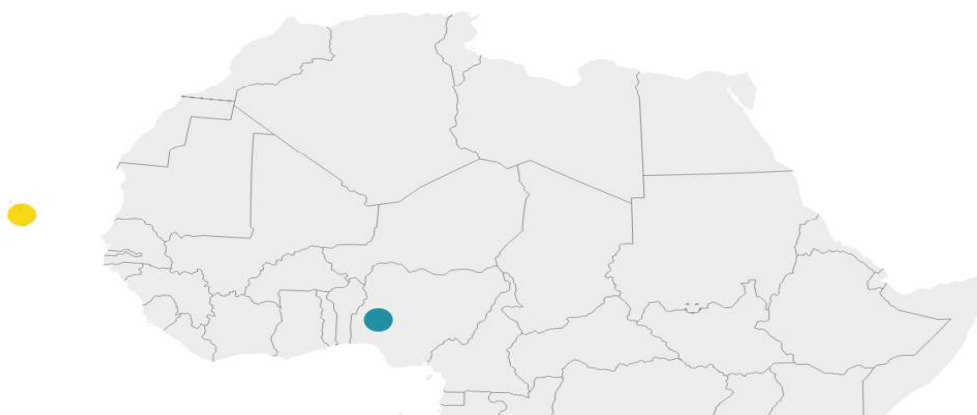


Figure 2: Map of Africa showing Cape Verde and Ilorin (<https://app.datawrapper.de/map/>)

Table 1 Details of the AERONET stations, their countries and their location (latitude and longitude)

S/No	Country	Aeronet station	Longitude	Latitude	Altitude
1	Cape Verde	Capo Verdo	22.9°W	16.7°N	60 m
2	Nigeria	Ilorin	4°E	8°N	350 m

The parameter downloaded was AOD at 470 and 660 nm. The AE was calculated using Eqn. (2). The study covers stations in Capo Verdo and Ilorin. These stations are ideally placed to study the spatio-temporal distribution of coarse (mineral dust) and fine (biomass burning) particles over the region.

Data Analysis

The large data density for the period makes it easier for monthly cycle and distribution trends of the parameters to be distinguished. The daily data were used to compute the monthly averages over the entire period of study, where seasonal averages can be deduced. An adjusted validation method is hereby proposed for this work. For each station, both MODIS τ data were validated using AERONET τ after setting the intercepts to zero. The dataset have been validated in an earlier work [41]. The entire study period for each station was also

analyzed with respect to climatology and seasonal variation of the monthly mean data of AOD and AE to reveal the temporal variability of these properties.

Statistical analysis

Statistical analysis is used to calculate average values, standard deviation, CV, and SF of the AOD data series over some AERONET stations in West Africa. The seasonal fraction of τ denotes the mean seasonal contribution (percentage) to the total annual τ and is defined as the ratio of the sum of τ in each season to the sum of τ in all seasons during a year, that is:

$$SF(\%)_{For \tau} = \frac{\tau_s}{\tau_y} \times 100\% \quad (4)$$

where τ_s is the sum of τ in a particular season and τ_y is the sum of τ in all months of a year.

Similarly, the seasonal fraction of α denotes the mean seasonal contribution (percentage) to the total annual α and is defined as the ratio of the sum of α in each season to the sum of α in all seasons during a year, that is:

$$SF(\%)_{For \alpha} = \frac{\alpha_s}{\alpha_y} \times 100\% \quad (5)$$

Coefficient of variation in (%) is used to analyze the temporal variability of τ . It is the ratio of standard deviation to the mean of the dataset and is defined as:

$$CV(\%) = \frac{\text{Standard deviation}}{\text{mean}} \times 100\% \quad (6)$$

RESULTS AND DISCUSSION

For this part of the study, we have selected six AERONET stations providing datasets meeting the requirements specified earlier. In the following sections, the trends for the stations located in SSA are discussed. The MODIS trends of τ (550 nm) and α (470 – 660 nm) at the AERONET stations are shown.

Aerosol Optic Depth (τ) Trends

The trend analysis of MODIS AOD, in the 550 nm band from 2000 to 2015, of the selected stations is shown in Figures 3 and 4.

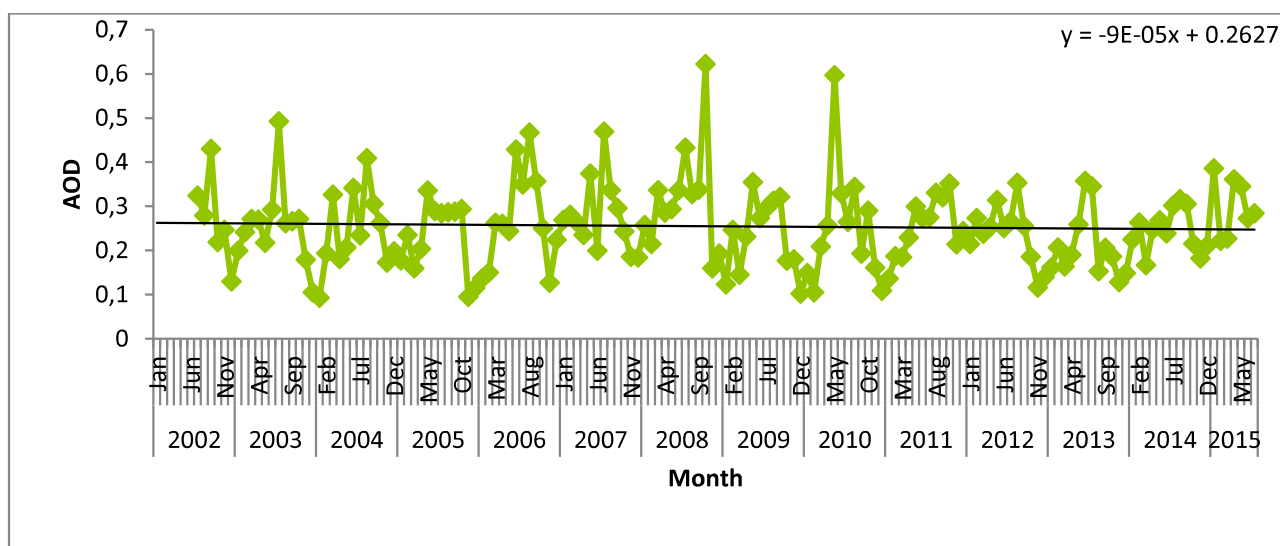
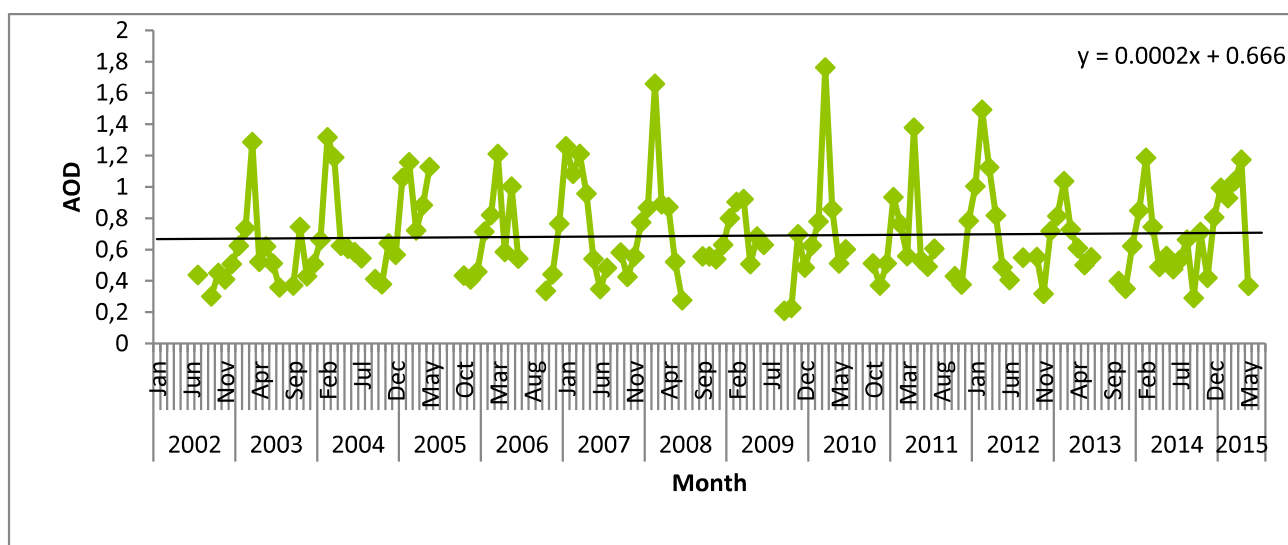


Figure 3 shows a decreasing trend of AOD, with a value of 0.00009, was noticed in Capo Verdo for the overall duration. This indicates that the atmospheric pollution in this station has been on the decrease.



An increasing trend of AOD, with a value of 0.0002, was observed in Ilorin for the entire period covered in this work. This shows that atmospheric pollution has been on the increase in this station.

Angstrom Exponent (α) Trends

The trend analysis of AE in the 470 – 660 nm bands from 2000 to 2015 of the stations shown in Table 1 are shown in Figures 5 and 6.

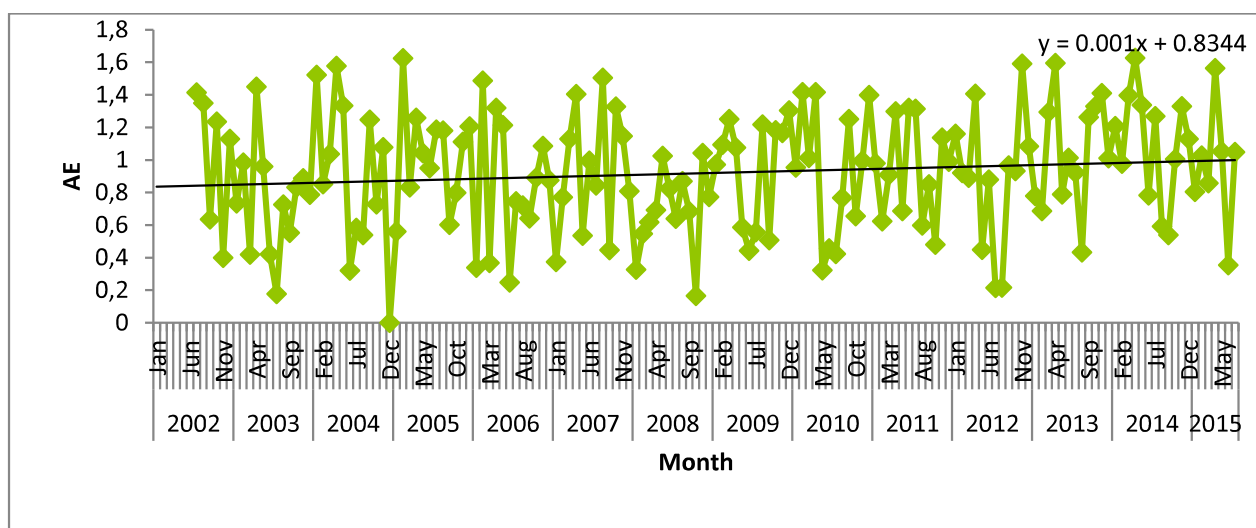


Figure 5: Monthly cycle of mean monthly value of AE in Capo Verdo (2002 – 2015)

Figure 5 shows an increase in trend of AE, with a value of 0.001, was observed in Capo Verdo for the entire period. The implication here is that more fine mode aerosols has been injected into the atmosphere in this station

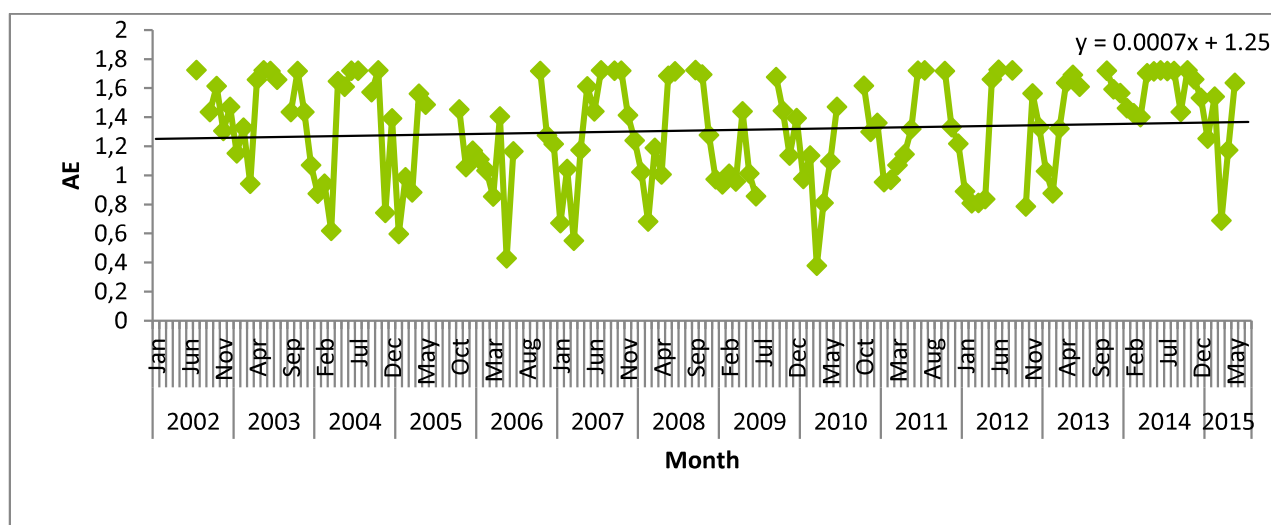


Figure 6: Monthly cycle of mean monthly value of AE in Ilorin (2002 – 2015)

Figure 6 shows an increasing trend of AE, with a value of 0.0007, was noticed in Ilorin for the overall period. The value of the trend here shows a weaker influence than what was obtained in Capo Verdo. The implication is that there has been a steady, but insignificant increase in fine mode aerosols in this station over the years.

Table 3 shows the results of the overall mean of AOD and AE in both stations, as well as the results of calculated CV using Eqn. (6).

Table 3 Overall mean of AOD and AE and their coefficient of variation (CV) in the selected AERONET stations in West Africa

Description	Mean	CV(%)	Mean	
CV(%)				
Capo Verdo				Ilorin
AOD	0.2548	35.49	0.6870	43.56
AE	0.9198	39.68	1.3115	26.93

Table 3 shows the means and CV of AOD and AE in the stations under consideration.

For the Capo Verdo station, the mean AOD and CV for overall period are summarized. The mean AOD value for the station is 0.2548. This shows that the station is polluted. The overall data has a low variance (35.29%).

For the Ilorin station, the mean AOD overall has a value of 0.6870. This shows that Ilorin has a more polluted atmosphere than Capo Verdo. The overall data also has a low variance (43.56%).

The first significance of Table 3 is that, though insignificant, the AOD values in Ilorin are on the increase during the period under consideration. This observation may be as a result of the movement of the North-East trade wind and local activities in the area. On the other hand, the AOD values in Capo Verdo during the same period are reducing. This observation could be linked to the movement of the South-West trade wind and local activities in the area. The result of the trend analysis is also supported by the observation deduced from Figures (3 and 4).

Table 3 also shows the results of the CV of AOD in the listed stations. The results show that the CV is generally a low variance regime, i.e., less than 100 %.

Table 3 also contains the result of the trend analysis and CV of AE in the stations under consideration.

For the Cape Verdo station, the mean AE value is 0.9198. The overall data has a variance of 39.67%. This shows that there are increasing episodes of fine mode aerosols in the station.

For the Ilorin station, the overall period has 1.3115 the mean value of AE. The overall data has a variance of 46.58 %.

There is insignificant, but general increment in the values of AE across the stations. This may indicate the increasing influence of fine mode aerosols across the stations. The results of the CV of AE in the listed stations also show a generally low variance regime.

Table 4 shows the results of the seasonal mean of AOD and AE in both stations, trend analysis, as well as the results of calculated seasonal CV using Eqn. (6).

Table 4 Seasonal mean of AOD and AE, their trends and their coefficient of variation (CV) in the selected AERONET stations in West Africa

Dry season			Rainy season			
Description	mean	trend (month ⁻¹)	CV(%)	mean	trend	(month ⁻¹)
CV(%)						
<u>CAP</u>						
AOD	0.1932	0.0002	32.02	0.2984	-0.0003	27.43
AE	0.9630	0.0051	34.55	0.8893	0.0002	43.30
<u>ILO</u>						
AOD	0.8081	0.0008	39.68	0.5659	0.0004	38.69
AE	1.1139	0.0043	25.86	1.5091	-0.0004	19.77

Table 4 shows the seasonal mean of AOD and AE, their trends and their CV in the AERONET stations in West Africa.

The trend variation of AOD in the dry season at Capo Verde is 0.0002 month⁻¹ while it is -0.0003 month⁻¹ during the rainy season. The averaged AOD during the dry season is 0.1932 while it is 0.2984 during rainy season. The dry season data has the highest variance (32.12%) followed by rainy season (27.52%). This shows that there are more aerosols loading during the rainy season in this station.

The trend variation of AOD during the dry season at Ilorin is 0.0008 month⁻¹ while it is 0.0004 month⁻¹ during the rainy season. This shows a gradual increase in aerosol loading during both seasons, but more pronounced during the dry season as expected. These observations may be as a result of early rain and, or the introduction of more anthropogenic aerosols into the atmosphere. The averaged AOD during the dry season is 0.8081 while it is 0.5659 during rainy season. The dry season data has the highest variance (39.68%) followed by the rainy.

The trend variation of AE in the dry season at Capo Verde is 0.00513 month⁻¹ while it is 0.000202 month⁻¹ during the rainy season. The averaged AE during the dry season is 0.963 while it is 0.889 during rainy season. The rainy season has the highest variance (43.31%) followed by the overall data (39.67%) and then dry season (34.58%). This shows that there is an increase in fine mode aerosol loading during the dry season.

The trend of AE in dry season at Ilorin is 0.00429 month⁻¹ while it is -0.000582 month⁻¹ during the rainy season. The averaged AE during the dry season is 0.747 while it is 1.085 during rainy season. The trend here shows that there has been a consistent increase in coarse mode aerosols during the rainy seasons over the years. The rainy season has the highest variance (51.25%) and dry season (39.22%).

The seasonal mean of AOD in these stations show that the stations are highly polluted, irrespective of the season. It is only in Ilorin station that there is a significant difference between the mean values of AOD during the two seasons. This observation may not be unconnected with the movement of the ITCZ.

The results of the calculated seasonal fraction of AOD and AE in both stations are shown in Table 5 below.

Table 5 Seasonal fractions (SF) of AOD and AE in the selected AERONET stations in West Africa

AOD		AE	
Dry season SF (%)	Rainy season SF(%)	Dry season SF (%)	Rainy season SF(%)
CAP			
31.39	68.61	43.35	56.65
ILO			
58.81	41.19	42.47	57.53

From Table 5, 68.61% of the aerosol loading was observed during the rainy season in Capo Verdo while Ilorin has its largest (58.81%) aerosol loading in the dry season. These results indicate that aerosol loading is more at Capo Verdo during rainy season while same is observed in dry season at Ilorin.

Similarly, more than 50% of AE contribution in both stations occurred during the rainy season. This shows that fine mode aerosols are dominant in both stations during rainy season.

CONCLUSION

The trend analysis of AOD and AE in Ilorin and Capo Verdo, West Africa has been presented. The data used was for a period from 2002 to 2015. The trend analysis results shows that for the Ilorin station, there is an increase in aerosol loading during both dry and rainy seasons. The averaged AOD during both seasons show that the station is polluted. For the Capo Verdo station, the average AOD during both seasons shows a decrease during rainy season and an increase during dry season. Nonetheless, the station is also polluted all year round.

For the Ilorin station, the trend of AE in dry season is increasing while it is decreasing during the rainy season. The averaged AE in both seasons show an increase in the episode of fine mode aerosols. For the Capo Verde station, the average AE trend values for both seasons show an increment. This shows that there are increasing fine mode aerosols loading overall.

RECOMMENDATION

A crucial challenge, in the study area, to improve the knowledge aerosol loading and type trend is the need for more AERONET stations in West Africa.

Future field campaign experiments should provide further insight into the processes that led to the results of the trend analysis in this study. A tailored approach to the analysis of aerosols' diurnal cycle is needed to make the role of local circulation of aerosols in this region more apparent.

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