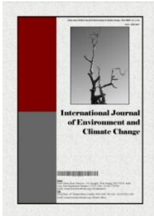

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Aerosol Optical Depths during Two Harmattan Seasons in Ile-Ife, Nigeria

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Aim: To quantify the atmospheric aerosol loading in order to predict the severity and accompanying consequences of aerosols at a tropical location in Ile-Ife, southwest Nigeria.
Place and Duration of Study: Department of Physics and Engineering Physics, Obafemi Awolowo University, Ile-Ife, Nigeria, between November 2017 and March 2019.
Methodology: Daily measurements of Aerosol Optical Depth (AOD) at about the local noon (12:30 pm–1:30 pm) for two consecutive Harmattan seasons (November 2017–March 2018; and November 2018 – March 2019) were carried out at three different wavelengths, 465 nm, 540 nm and 619 nm using a manually operated hand-held sun photometer (model Calitoo).
Results: The mean values of AOD were 0.98, 0.87 and 0.83 in the 465 nm, 540 nm and 619 nm wavelengths respectively for November 2017 – March 2018; and 0.94, 0.83 and 0.78 in the 465 nm, 540 nm and 619 nm wavelengths respectively for November 2018 – March 2019. The values assume high levels of haziness at the study location. Intense Harmattan dust storm was experienced on some typical days with AOD values > 2. The resulting elevated level of atmospheric haziness led to visibility deterioration and visibility values greatly reduced to 1 km on such days. December, January and February months were the peak of the Harmattan. The distribution of the particle size indicated that the dominated aerosol is the coarse mode Harmattan dust during the period of study.
Conclusion: The study location experiences a polluted atmosphere during the Harmattan season.

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Keywords: Aerosols; haziness; aerosol optical depth; harmattan.

1. INTRODUCTION

Atmospheric aerosols are small (between the range of 10^{-4} μm and 10^{2} μm) solid or liquid particles suspended in the atmosphere [1,2]. Their wide variety of sources (both natural and anthropogenic) and properties (such as size, optical thickness and chemical composition) are heterogeneous and vary both temporally and spatially [3]. They are dispersed in the atmosphere through turbulence, diffusion and movement of air masses. Aerosols are removed from the atmosphere through precipitation such as rainfall, ice, dew, etc. They can also be removed through sedimentation in which the particles fall under gravity [2]. Aerosols' microphysical properties (e.g. particle size distribution and refractive index) and optical properties (e.g. extinction, phase function and single-scattering albedo) are important in the determination of the effect of atmospheric aerosols on climate and in air quality control [4,5].

Aerosols are responsible for many physical processes occurring in the atmosphere which include attenuation of incoming solar radiation, reduction in visibility that affects airport operations, attenuation of radio signals and some health challenges [6,7]. They attenuate incoming solar radiation by scattering and absorption which lead to either cooling or warming of the atmosphere [8,9].

The ability of aerosols to warm or cool the atmosphere depends on factors such as chemical composition, relative contribution of various chemical species, and surface albedo [10]. Scattering of solar radiation by aerosols increases the surface albedo by reducing the amount of energy which the earth absorbs and hence, cool the earth surface [11]. Absorption of solar radiation by atmospheric aerosols causes a reduction in cloudiness which in turn leads to changes in the atmospheric stability and reduction of surface fluxes [12,13].

The amount of aerosol loading in the atmosphere is usually quantified by an optical measure called Aerosol Optical Depth (AOD). AOD is a measure of extinction (scattering and absorption) of solar radiation that reaches the Earth's surface through a vertical column of atmosphere as a result of aerosols [14]. It is also a measure of atmospheric haziness which is an indicator of the transparency of the atmosphere containing aerosols. The higher the AOD at a particular wavelength, the less the solar radiation of that wavelength that reaches the Earth's surface. AOD is a dimensionless quantity and wavelength-dependent. Increase in AOD values is indicative of large amount of aerosols in the atmosphere and consequently results in lower visibility [15,16]. Effects of AOD can be quantified by its magnitude: the sky is crystal clear if AOD < 0.1, and AOD = 1 indicates very hazy sky of poor visibility [17]. The relationship between AOD and horizontal visibility V_H can be derived using the empirical formula proposed by Aranuvachapun [18]:

$$V_H = -4.3[\frac{In\ (0.4615)}{AOD}] \tag{1}$$

AOD varies seasonally as it values are observed to be higher in the summer than in the winter in the temperate region as recorded in many studies [19-23].

In sub-Sahara Africa, particularly in West Africa, the concentrations and distributions of atmospheric aerosols exhibit strong seasonality caused by change in air mass (northeasterly trade wind and southwesterly trade wind) patterns during the dry (Harmattan) season (November-March) and the rainy (wet) season (April-October) [24]. During the wet season, there are usually heavy and continuous rainfall of different magnitude which reduce the concentrations of aerosol loading in the atmosphere. Conversely, the Harmattan season is characterised by desert dust particles transported from the Sahara desert and local emissions such as biomass burning and land clearing in preparation for farm activities. The Harmattan is a prevailing north-easterly wind regime that dominates the West African region [25] and peaks between November and February. The dry wind transports and deposits the Saharan dust over the entire region and extends as far as to the Gulf of Guinea. The dust plumes mainly originate from the Bodele Depression which is located in the North-East of Lake Chad [26]. Other sources of the dust plume includes north-central Sahel between Bilma to part of the Faya Largeau area and the Chad Basin [27,28]. The behaviour of the sub-tropical anticyclone over the desert region has been observed to trigger the raising of dust in the source region [29].

During a Harmattan dust spell, there is a sharp increase in the values of AOD when compared to the average for the season [30]. These can result in some environmental challenges such as visibility deterioration, cancellation of air flights, attenuation of radio signals, etc. It was recorded that the most critical aviation accident in Nigeria occurred during the Harmattan of November 1973 as a result of thick dust haze which obstructed the Kano airport [31,29]. Hence, it is essential to determine the concentration of atmospheric haziness of a particular location with the aim of assessing the degree of air pollution of the atmosphere.

The Angstrom wavelength exponent (α) is a parameter that is generally used to illustrate the wavelength dependence of AOD and to distinguish and characterize different aerosol types and sizes [32,33,34]. When $\alpha<1$, it indicates that the aerosol size distribution is dominated by coarse-mode aerosols of effective radius usually greater than 0.5μm. These aerosols are mainly dust outflows or sea-spray. Conversely, $\alpha\geq1$ indicates a size distribution of fine-mode aerosols of effective radius smaller than 0.5μm, associated with biomass burning and urban pollution [32]. Therefore, examining AOD values and aerosol size evaluation is imperative in the interpretation of aerosol types, sources and their climatic effects [35]. Angstrom [36] defined aerosol size as a measure of the differences of Aerosol Optical Depth (AOD) at two wavelengths, λ_1 and λ_2:

$$\alpha = \frac{\text{In}\,\frac{\text{AOD}\,(\lambda_1)}{\text{AOD}\,(\lambda_2)}}{\text{In}\,\frac{\lambda_2}{\lambda_1}} \tag{2}$$

where α is the aerosol particle size known as the Angstrom exponent.

Globally, several studies have been conducted on AOD based on ground and satellite observations. The AOD at a tropical site along the coastal belt of the Arabian Sea at Kannur (11.86 ^{0}N, 75.35 ^{0}E) was investigated from January to December, 2010 by Praseed et al. [37]. The one-year data analysed revealed the significant seasonal variation of AOD with relatively higher values recorded in the summer than in the winter. The summer enhancement in AOD was attributed mainly to the wind driven aerosols in the context of pre-monsoon season at the location. Fouquart et al. [38] measured AOD over Niger during December, 1980. The AOD at 550 nm varied from 0.2 on clear days to 1.5 on very dry haze days. Increased AOD on the hazy days was associated with small Angstrom exponent (α = 0.2), while for the clear days α reached its standard continental value (α = 1.3). The variation was interpreted as an indication of changes in the size distribution of particles with a shift towards larger particles for the haziest days. The effects of aerosols on reduction of visibility in Ilorin, Nigeria from 1990 - 1999 was conducted by Adimula et al. [39]. Aerosol loading in Ilorin was found to be high with concentrations reaching 4.0 in certain cases. The monthly AOD value at 500 nm indicated that aerosol loading exhibited variability from about 0.5 to > 2.0 during the Harmattan months. There was an increase in the aerosol loading from September which reached maximum in January for the years considered.

Most of the studies that have been conducted on aerosols in Nigeria were focused on mega cities such as Ilorin, Lagos, Port-Harcourt. But it is important to understand the properties and dynamics of aerosols from rural to urban areas. Ile-Ife, Nigeria where this study was conducted is a semi-urban town that has no major industrial establishment unlike the aforementioned larger cities. There is no availability of Aerosol Robotic Network (AERONET) data for this region, hence the use of a manually operated instrument for the measurement of AOD. Therefore, the main objective of this study is to determine quantitatively the atmospheric aerosol loading as indicated by the Aerosol Optical Depth during two Harmattan seasons with a focus on Ile-Ife, Nigeria.

2. MATERIALS AND METHODS

2.1 The Study Site

The study site is located at the Obafemi Awolowo University (OAU), Ile-Ife, Nigeria (7.52 ^{0}N and 4.52 ^{0}E) (Fig. 1) within the tropical zone of West Africa. OAU campus is a sub-urban environment where there are no major industrial activities but presence of particulate matters due to heavy dust loading is prevalent during the dry season. The road network is tarred and distant areas are natural bushes and forests. A highway is located at about 2 km from the main campus. The area experiences two main alternating seasons: dry (Harmattan) season and rainy (wet) season. The Harmattan is a period of high atmospheric loading of wind-blown dust usually between November and March. Alternatively, the wet season is a period of high atmospheric moisture content beginning from April, peaks in July and ends in late October [40].

Fig. 1. Map of Nigeria indicating the position of the study site

2.2 Measurement of Aerosol Optical Depth

Measurement of Aerosol Optical Depth (AOD) was carried out on the roof-top of the Department of Physics and Engineering Physics building, Obafemi Awolowo University (OAU), Ile-Ife, Nigeria The AOD data used in this study was acquired manually using a portable sun photometer (model Calitoo). Calitoo is a hand-held sun photometer that has optical filters transmitting radiation at three different wavelengths i.e. 465 nm, 540 nm and 619 nm of the visible part of the electromagnetic spectrum (https://www.calitoo.fr/index.php?page=en). Each channel is fitted with a photodiode suitable for the particular wavelength range. Calitoo has a small aperture of < 2 mm which makes the light intensity measured by the instrument not to be influenced by atmospheric scattering. The small aperture is laser-aligned to ensure accurate orientation with the optical channels. The radiometer uses 4 AA batteries of 1.5 V. Its dimensions of 210 mm x 100 mm x 35 mm and weight of 400 g (with batteries) make the photometer to be portable for use. It operates at a temperature of about -20 °C to 55 °C. It has a built-in GPS, a pressure sensor and a temperature sensor that makes the position and time of measurements to be recorded. The measurement of AOD was achieved by pointing the Calitoo sun photometer directly at the sun and search for the intensity of the sun. The tracking of the sun is done manually. Calitoo automatically measures the total transmittance of the atmosphere and then calculates AOD values instantaneously using a variant of the Beer-Lambert law as shown in eq. (3):

$$I(\lambda) = I_o(\lambda)\exp[-m\,(\tau_a + \tau_g + \tau_{NO_2} + \tau_w + \tau O3 + \tau r)] \quad (3)$$

where I_o is the sunlight intensity outside the atmosphere, I is the light received on the ground, λ is the wavelength of light, τ_a is the aerosol transparency coefficient, τ_g is the gas (CO_2 and O_2) transparency coefficient, τ_{NO_2} is the nitrogen dioxide transparency coefficient, τ_w is water vapor transparency coefficient, τ_{O_3} is the ozone transparency coefficient, τ_r is the Rayleigh scattering coefficient and m is air mass coefficient (optical path) = $1/_{\sin\theta}$, where θ is the zenith angle of the Sun. AOD measurements (about 100 values) were taken on a daily basis, only on clear sky days between 12:30 pm and 1:30 pm (GMT) when the sun was vertically overhead for two consecutive Harmattan seasons (November 2017 – March 2018 and November 2018 – March 2019).

3. RESULTS AND DISCUSSION

3.1 Daily Variations of Aerosol Optical Depth

The measured daily average variations of Aerosol Optical Depth (AOD) at three wavelengths (465 nm, 540 nm and 619 nm) on cloud-free days for two consecutive Harmattan seasons (Season I: November 2017 – March 2018 and Season II: November 2018 – March 2019) are presented in Fig. 2. The missing gaps show days when measurements were not available. The results showed there were significant day-to-day fluctuations in the measurements of AOD. The variations are attributed to frequent occurrences of surging episodes of Harmattan dust storms over the study location. In Season I, observed values of AOD ranged between 0.29 and 2.75; 0.25 and 2.63; 0.24 and 2.60 in the 465 nm, 540 nm and 619 nm wavelengths respectively. Similarly, in Season II, AOD values varied between 0.29 and 2.31; 0.22 and 2.12; 0.21 and 1.95 in the 465 nm, 540 nm and 619 nm wavelengths respectively.

In season I, the study area experienced a very high episode of Harmattan dust surge on December 9, 10, 11 and 12 in the year 2017. Due to the high intensity of the Harmattan dust storm, the Calitoo photometer could not capture the values of AOD especially on the two days (December 9 and 10) when the surges were very critical. These episodes led to disruption in the aviation industries in Nigeria and flights were cancelled as a result of visibility deterioration as reported by local news. Due to the intense dust spell, there was a sharp increase in the values of AOD on December 11 (2.7, 2.6 2.5 in the respective wavelengths) and December 12 (2.5, 2.4, 2.3 in the respective wavelengths), 2017. On January 2, 2018, there was another scenario of intense Harmattan dust spell at the study location which caused a sudden rise in AOD values (2.7, 2.6 and 2.5 in the respective wavelengths). On the aforementioned three days, AOD reached its peak values in season I and visibility was greatly reduced to 1 km as shown in Fig. 3. Likewise, in season II, the study location experienced some surges of Harmattan dust storms on January 26, February 2, 8, 13, 18 and 27 in the year 2019. On all these days, the values of AOD were greater than 1.9, 1.7 and 1.6 in the respective wavelengths and visibility was between 1.2 and 1.4 km. The visibility values obtained for both seasons as presented in Fig. 3 ranged between 1 and 12 km. At the onset of the dry season when the Harmattan has not fully commenced, and at the end of the dry season when the Harmattan is no more intense, most of the visibility values obtained were > 4 km. On the contrary, when the Harmattan was severe, visibility values were low (≤ 4 km).

Fig. 4 shows that out of all the days considered in this study (257 days), 65 % had visibility values ≤ 4 km while 35 % of all the days had visibility values > 4 km. This denotes that visibility deterioration is a major consequence of atmospheric turbidity.

Fig. 5 shows the correlation between AOD and visibility. At high values of visibility, there were corresponding low values of AOD and vice versa. High visibility values signify a clean atmosphere while low visibility values are indicative of the presence of Harmattan haze.

Table 1 shows the monthly mean values of AOD for the observed seasons. In season I, the mean AOD values recorded in November were 0.55, 0.48 and 0.46 in the respective wavelengths. These values were lower than the values obtained in the subsequent months, thus, implying the presence of little amount of aerosol particles in the atmosphere at this period. In December, the mean AOD values increased gradually to 1.10, 1.00 and 0.96 in the respective wavelengths, and reached maximum of 1.38, 1.22 and 1.11 in the respective wavelengths in January, signifying the peak of the Harmattan. As the Harmattan gradually concludes, AOD values dropped to 1.09, 0.99 and 0.94 in the respective wavelengths in February; and 0.73, 0.66 and 0.65 in the respective wavelengths in March due to washouts of aerosols by occasional rain showers.

Similarly, in season II, the lowest mean values of AOD were obtained in November 0.51, 0.44 and 0.42 in the 465 nm, 540 nm and 619 nm wavelengths respectively. The values increased to 0.74, 0.65, 0.61 and 1.22, 1.07, 0.96 in

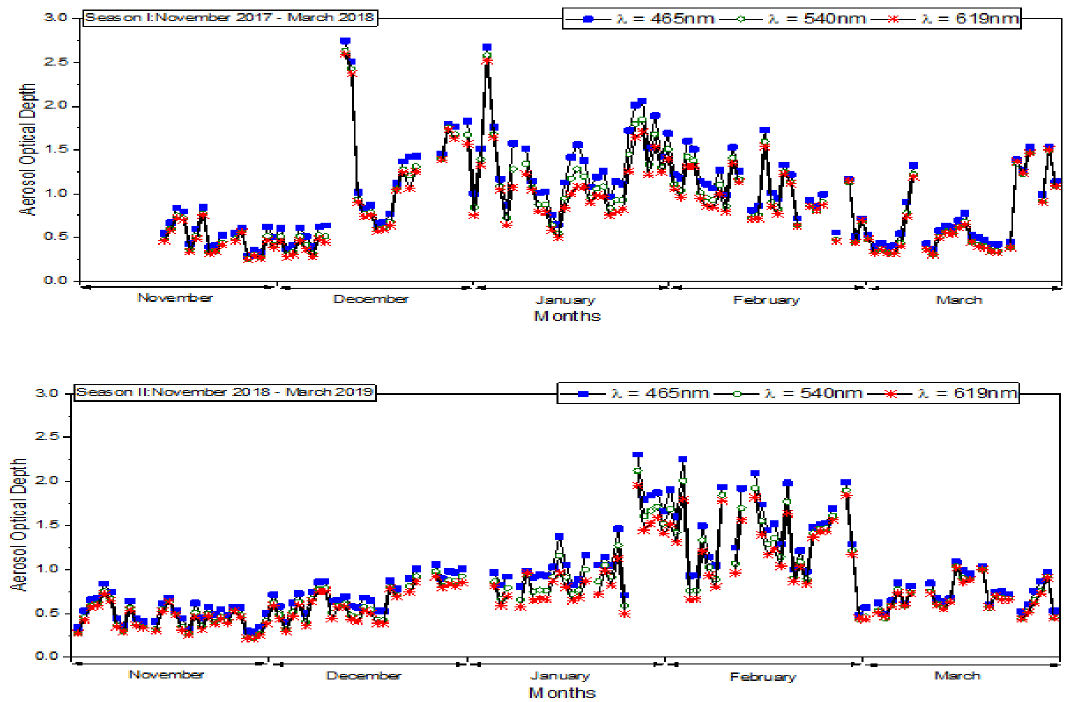

Fig. 2. Daily variations of aerosol optical depth during two Harmattan seasons

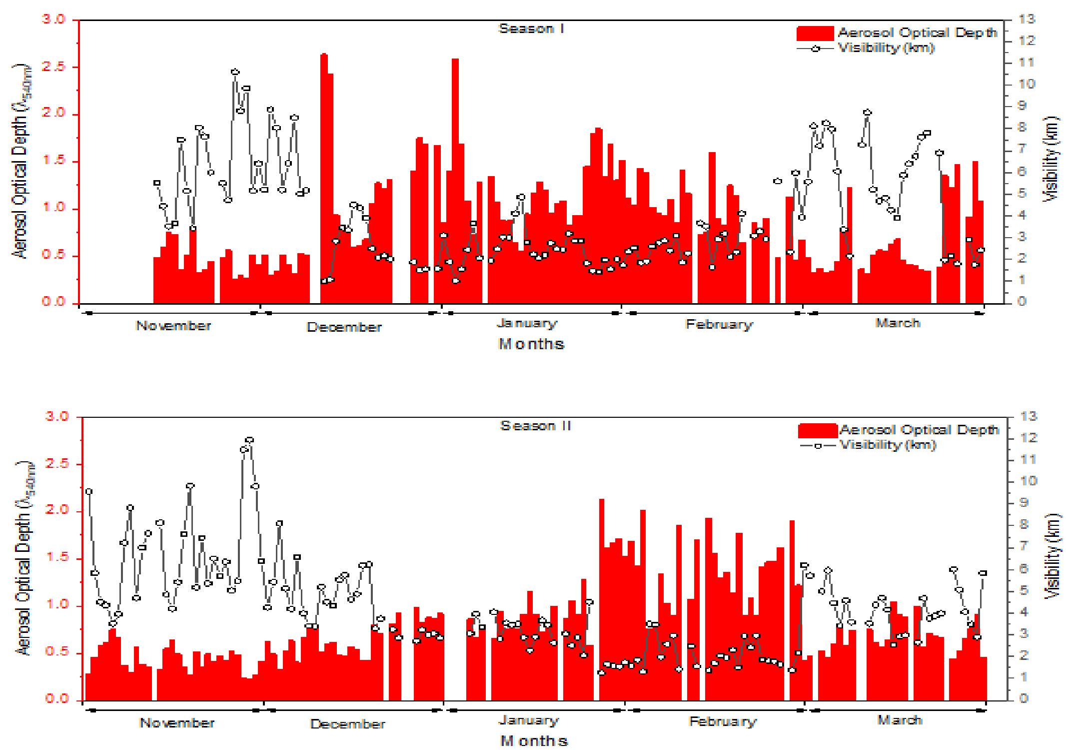

Fig. 3. Daily variations of aerosol optical depth (red columns) and visibility (circles) during two Harmattan seasons

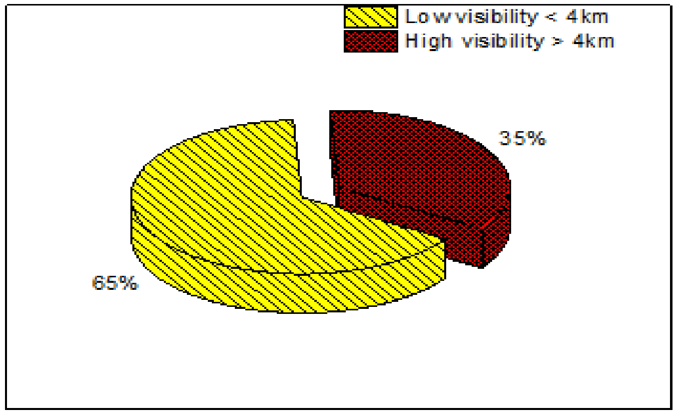

Fig. 4. Distribution of visibility values during two Harmattan seasons at Ile-Ife

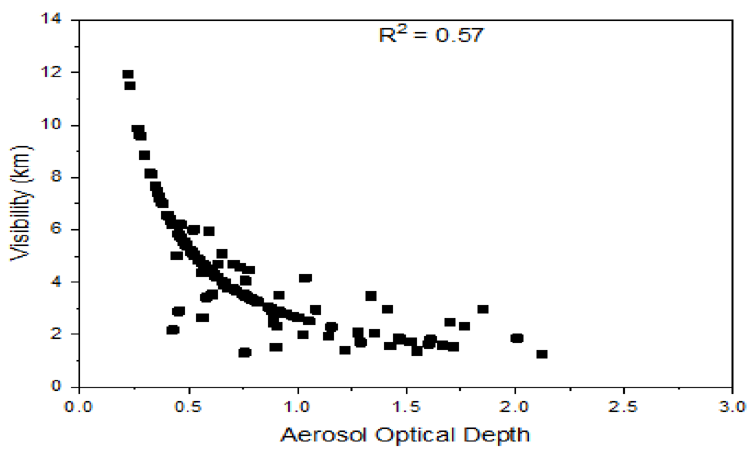

Fig. 5. Correlation between visibility and aerosol optical depth

Table 1. Monthly mean values of aerosol optical depth (AOD)

MONTHS	Season I (November 2017 – March 2018)			Season II (November 2018 – March 2019)		
	λ_1 (465 nm)	λ_2 (540 nm)	λ_3 (619 nm)	λ_1 (465 nm)	λ_2 (540 nm)	λ_3 (619 nm)
November	0.55	0.48	0.46	0.51	0.44	0.42
December	1.10	1.00	0.96	0.74	0.65	0.61
January	1.38	1.22	1.11	1.22	1.07	0.96
February	1.09	0.99	0.94	1.49	1.35	1.26
March	0.73	0.66	0.65	0.73	0.67	0.65
Mean	0.97	0.87	0.82	0.94	0.84	0.78

December and January respectively. The peak values of AOD were obtained in February (1.49, 1.35 and 1.26 in the respective wavelengths). These values indicate the climax of the Harmattan in season II. The observed values dropped to 0.73, 0.67 and 0.65 in March.

Fig. 6 shows that the mean values of AOD (λ = 540 nm) in season I peaked earlier than in season II which implies that the study location experienced a late Harmattan in season II. The maxima obtained in the two seasons represent the peak of the surging episodes of Harmattan dust spell at the location.

3.2 Aerosol Size Evaluation

The aerosol particle size estimated in this study was deduced using the Angstrom exponent (α) for the AOD values at two wavelengths, 465 nm and 540 nm. The Angstrom exponent exhibited variability from 0.2 to 1.8 as presented in Fig. 7. The AOD-α plot describes quantitatively the concentration and size of aerosols. The plot shows an inverse relationship between AOD values and Angstrom exponent. That is, at high values of AOD, low values (α < 1) of Angstrom exponent were obtained suggesting coarse particles. In contrast, at low values of AOD, high values (α ≥ 1) of Angstrom exponent were observed indicating fine particles.

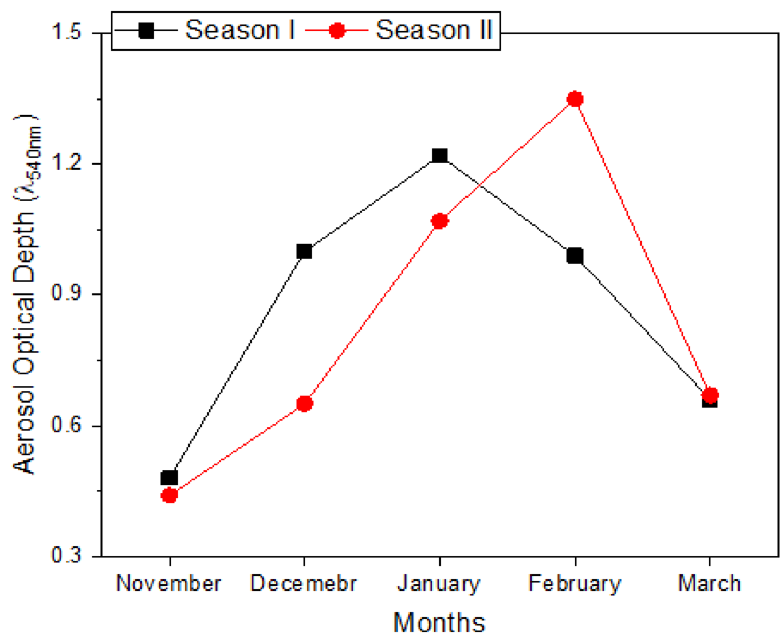

Fig. 6. AOD (540nm) monthly mean values comparison in two Harmattan seasons

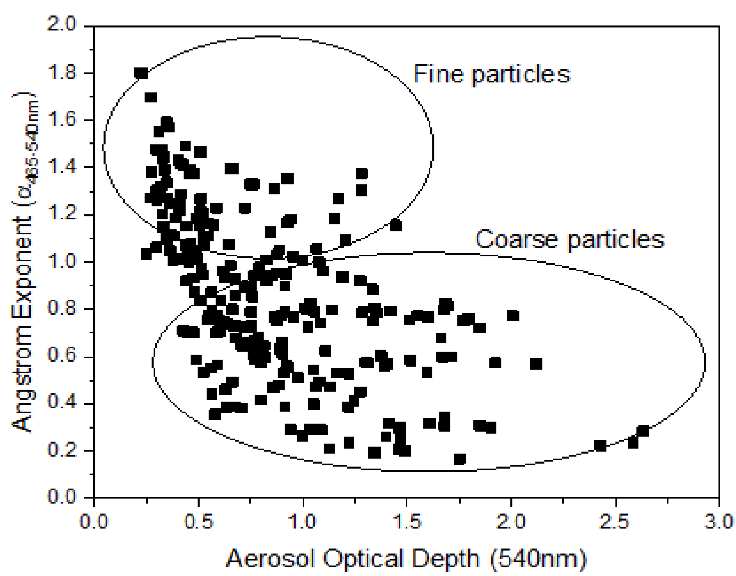

Fig. 7. Scatterogram of angstrom exponent Vs aerosol optical depth

Fig. 8a & b shows the concentration of Angstrom Exponent in season I and season II respectively. The variations show the presence of both coarse Harmattan dust (α < 1) and fine particles (α ≥ 1), probably smoke at the location.

In season I, there was an increase in the concentration of the particle size, α < 1 from 47% in November to 60% in December. The amount of the particle size was constant in December and January and increased to 92% in February. The concentration of the particle size α < 1 decreased to 54% in March signifying an increase in fine particles. In season II, in November, the concentration of the particle size, α < 1 was much lesser than the particle size α ≥ 1 signifying dominance of fine particles at this period. In December, α < 1 increased steadily to 56% and also increased to 84% in February. This suggests that as the Harmattan approaches, there was a significant increase in the concentration of coarse Harmattan dust. There was only 1% increment in the concentration of the particle size, α < 1 in March.

From the particle size distribution obtained for the two seasons, it was observed that, at the peak of the Harmattan (December and January in season I; February and March in season II), there was no significant change in the distribution of the particle size. Also, for the two seasons, the particle size, α < 1 dominated the study location during the Harmattan seasons.

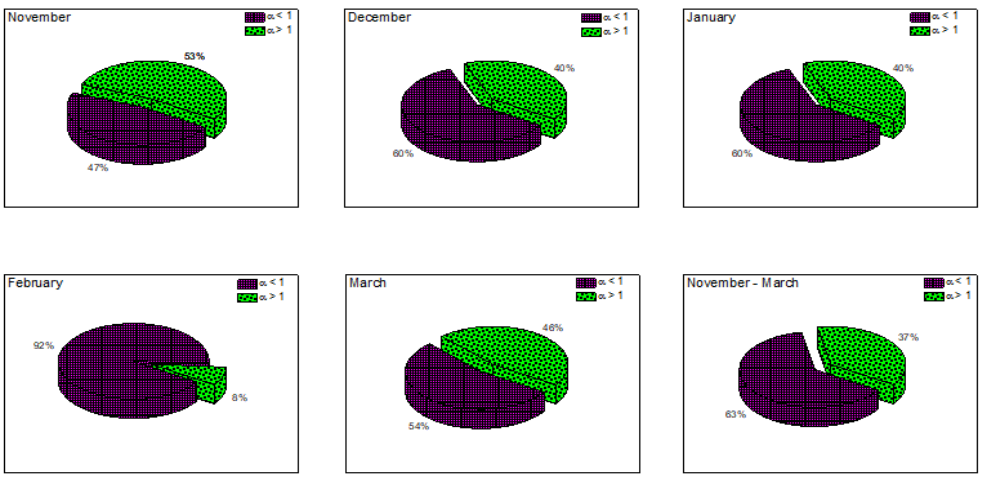

Fig. 8a. Concentration of Angstrom exponent (α) in season I

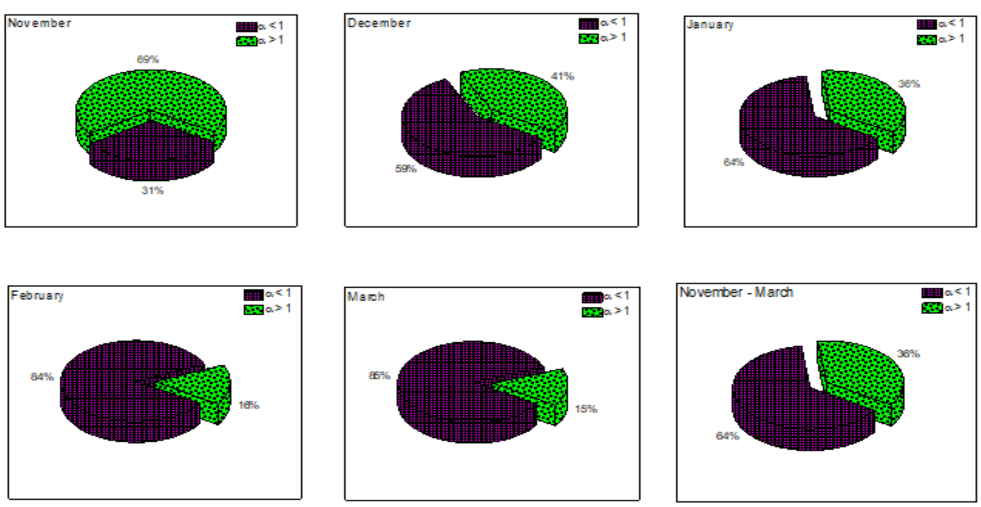

Fig. 8b. Concentration of Angstrom exponent (α) in season II

4. SUMMARY AND CONCLUSION

The study measured the Aerosol Optical Depth (AOD) at three different wavelengths, 465 nm, 540 nm and 619 nm respectively using a manually operated hand-held sun photometer (Calitoo) at a tropical location, Ile-Ife, southwest Nigeria (4.31^{o}N, 7.31^{o}E). The study was carried out for two consecutive Harmattan seasons (season I: November 2017 – March 2018 and season II: November 2018 – March 2019).

The measured values of AOD indicated that the study location is relatively hazy during the Harmattan season with a mean value of 0.97, 0.87 and 0.82 in the 465 nm, 540 nm and 619 nm wavelengths band respectively in season I and 0.94, 0.84 and 0.78 in the 465 nm, 540 nm and 619 nm wavelengths band respectively in season II. Intense Harmattan dust storm was experienced on some typical days and AOD values were > 2. The resulting elevated level of atmospheric haziness led to visibility deterioration and visibility values greatly reduced to 1 km on such days. The months of December, January and February were observed to be the peak of the Harmattan. The distribution of the particle size indicated that the study location was dominated with coarse Harmattan dust during the period of study.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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