

Multi-year analysis of aerosol optical properties at various timescales using AERONET data in tropical West Africa

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ABSTRACT

The optical properties of aerosols are investigated using multi-year analysis from the Ilorin AERONET site (8.320° N, 4.340° E) in Nigeria, in tropical West Africa. Characterization at five wavelengths (440, 550, 675, 870 and 1020 nm) were carried out to investigate the absorption and scattering tendencies of aerosol properties at multi-timescale. Results show large aerosol optical thickness (AOT) at 550 nm in a mixed aerosol load with 74% coarse mode dominance and 24% fine mode particles densely distributed in the dry-cold/Harmattan season (DJF) and sparsely distributed in the wet season (June–Oct). The volume size distribution (VSD) pattern shows higher variations and dominance for the coarse mode in the dry season than for the accumulation mode. The Ångström exponent (AE) α and τ_{550} show regular variations, with seasonal averaged maximum $\alpha > 1$ and τ_{550} peak at ~ 1.0 . Values of $\alpha > 1$ were observed in wet seasons; ~ 1.1 (Aug), 1.04 (Sep). Averaged single scattering albedo (SSA) is confined to values between 0.83 and 0.97, with the highest values in October and lowest values in DJF due to biomass burning (BB) emissions mixed with transported desert dust that are composed of iron oxides (hematite) absorbing mineral. Seasonal ω_0 increases with increasing wavelength and absorption was found to be the highest at 440 nm, with a total absorption of 0.16. The asymmetry parameter g shows minor interannual variations. The highest value of > 0.70 was found at the shortest wavelength (440 nm), and was found to decrease as wavelengths increased. The real part of the refractive index (RR) ranges between 1.17 and 1.44 depending on seasons, and the imaginary part of the refractive index (RI) shows higher absorption for dry season (0.009).

1. Introduction

Radiative forcing of aerosols plays a significant role in the assessment of global climate. The impact of aerosol particles on air quality and climate is complicated, and this unique environment has not been fully investigated.

Aerosol optical properties, single scattering albedo (SSA), asymmetry parameter g , Ångström exponent (AE) α , volume size distribution (VSD), refractive index (R) and aerosol compositions are key factors in aerosols climate forcings. Aerosols directly impact the radiative balance by absorption and scattering of solar radiation, and indirectly by their ability to alter the radiative properties of

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clouds (Brasseur, Orlando, & Tyndall, 1999). Changes in the climate system cannot be fully evaluated without understanding the impact of radiative forcing of aerosols on climate (Charlson et al., 1992). Understanding the impact of different aerosols species on the environment and human health is also of great importance.

The aerosol load in the atmosphere over Nigeria exhibits a complex mixture stemming from different emission sources (Eck et al., 2010; Giles et al., 2012). These include large amounts of volatile organic compound (VOC) emissions from oil and gas exploration, nitrogen oxide emissions from cities, dust emissions from the arid north, and biogenic emissions from forests. Fossil fuel combustion, biomass burning, sea spray, volcanic ash, dust and particles from automobile brake and tire wear are examples of direct aerosol emissions that impact climate and air quality in Nigeria. Anthropogenic emissions of both primary particles and precursor gases contribute appreciably to the total aerosol load (Andreae & Rosenfeld, 2008). The complexity of the aerosol-mix in Nigeria is further compounded by the ubiquitous use of mobile, small-scale and large-scale power backup generators (BUGs) used for providing electricity, due to the inadequacy of supply from the national grid. These generators are powered by fossil fuels and emit black carbon and other VOCs (Ikeme & Ebohon, 2005).

The impact of these pollutants on air quality and climate is complicated, and this unique environment has not been fully investigated to characterize and identify the percentage contribution of each aerosol mode. The country is plagued with uncontrolled emissions as there are no properly established monitoring protocols nor emission inventory baselines for natural and anthropogenic combustion, thus, emissions are uncertain (Lioussse, Assamoi, Criqui, Granier, & Rosset, 2014).

The absence of comprehensive information of aerosol optical properties, especially in this region, results in aerosols being one of the leading sources of uncertainties in climate forcing included in model assessments (Charlson et al., 1992; Hansen, Sato, & Ruedy, 1997; Heintzenberg et al., 1997; Houghton et al., 1996; Tegen & Lacis, 1996). Presently, there is only one station of atmospheric aerosol measurements in Nigeria. Therefore, very limited data exists.

In this paper, aerosol optical thickness (AOT) at a wavelength 550 nm, as well as τ_{550} and Ångström exponent (AE) α at similar wavelength, from natural and anthropogenic sources were analyzed. The single scattering albedo (SSA) and asymmetry parameter g at five wavelengths were analyzed to identify the ability of various particles to interact with incoming radiation via scattering and absorption. Furthermore, volume size distribution and refractive index were analyzed. These analyses were carried out using ground-based remote sensing measurements from the AERONET network station Ilorin, that in previous literature has been categorized as a West African station (Eck et al., 2010; Giles et al., 2012; Lee et al., 2010; Pinker, Liu, Osborne, & Akoshile, 2010). AERONET data has previously been used to characterize aerosol radiative forcings, single scattering albedo, volume size distribution as well as compositions of different aerosol loading for different regions around the world (Eck et al., 2010; Giles et al., 2012; Kim et al., 2011; Milinevsky et al., 2014; Russell et al., 2010; Sato et al., 2003; Takemura, Nakajima, Dubovik, Holben, & Kinne, 2002).

Characterization of these particles was based on $\alpha \leq 1$ for coarse mode and $\alpha > 1$ for fine particles mode, and values ranging from 0 for absorbing particles to 1 for non-absorbing (scattering) particles.

Previous work on aerosols from global perspectives, for example Eck et al. (2010) and Giles et al. (2012) have shown an important radiative relevance of the aerosols properties from this station. Fawole, Cai, Levine, Pinker, and Mackenzie (2016) recently worked with measurements from the AERONET Ilorin site and detected gas flaring in the mixed-aerosol loading. Some work on visibility was carried out on the relationship between aerosol loading and variability in meteorological parameters by Oyem and Igbafe (2010). A general review on dust aerosol was given by Said (2012). Moreover, the influence of relative humidity on aerosols and hygroscopicity was carried out by Tijjani, Fatima, and Aliyu (2014).

Improved understanding of the aerosol optical properties and characterization over Nigeria requires an aerosol measurement network to be established. There is however only one functional aerosol measurement station in the country at the time of this study. Using currently available data, this study investigated and analyzed the complex nature of the composition and the scattering and absorption ratios (SSA and g) of different aerosol particles influencing climate in Nigeria. Results from this research are expected to provide useful information on the variability of τ_{550} , aerosol optical parameters and contribute to their representation in aerosol models. Other applications are to contribute to air quality legislation, as well as to validation of satellite remote sensing measurements in the region.

This paper is organized in the following order. A summary of the data source and methods are presented in Section 2. In Section 3, a theoretical background of aerosol optical properties including the general AE relations are presented. Section 4 contains results and discussion. Multi-year description and evaluation of annual averaged τ_{550} and α , as well as seasonal averaged values are presented in Subsections 4.1 and 4.2. Subsection 4.3 presents variation of SSA at various wavelengths, and seasonal variation of SSA and g are presented in Subsection 4.3.1. In Subsection 4.3.2 interannual variability of g is presented. Also, seasonal volume size distribution and refractive index are discussed in Subsections 4.4 and 4.5. Finally, the conclusion is given in Section 5.

2. Data sources and methodology

AERONET is a network of ground-based sun/sky photometers taking real-time ground-based remote sensing measurements of aerosols optical properties. This network was established by the National Aeronautics and Space Administration NASA and LOA-PHOTONS (CNRS) and has been expanded by collaborators at different levels (Holben et al., 1998). It is a well established data archive with over 400 stations worldwide (Chubarova, Poliukhov, & Gorlova, 2016) providing a database of aerosol optical, micro-physical and radiative properties for the purpose of aerosols research and characterization. The data is validated against other data archives and the network is known for its standardization of instruments, calibration, processing and distribution (Holben et al., 1998; Smirnov, Eck, Dubovik, & Slutsker, 2000). In addition to aerosols optical depth, AERONET provides other data such as inversion products, precipitation, single scattering albedo, asymmetry factor, refractive index and volume size distribution (Dubovik & King,



Fig. 1. © Google Earth map showing Ilorin location of the AERONET site in Nigeria.

2000) etc. Aerosol optical depth data are computed at three different data quality levels: Level 1.0 (unscreened), Level 1.5 (cloud-screened), and Level 2.0 (cloud screened and quality-assured).

In this paper, Version 2 Level 2.0 quality-assured and cloud screened data with a minimal uncertainty was utilized. Level 2.0 almucantar retrievals were ideal for this research and were provided at a daily timescale scale interval, these retrievals were manually checked and filtered to confirm authenticity. AERONET is a unique network because of inversion techniques that allow a steady retrieval of the optical properties of aerosol in locations with varying emission sources and conditions. One of the stations in the network is sited at Ilorin, Nigeria. The sun/sky photometer CE-318 CIMEL makes two basic measurements, either direct sun or sky, both within several programmed sequences. The direct sun measurements are made in nine spectral bands requiring approximately 10 s each. Nine interference filters at wavelengths of 340 nm, 380 nm, 440 nm, 500 nm, 670 nm, 675 nm, 870 nm, 940 nm and 1020 nm are located in a filter wheel which is rotated by a direct drive stepping motor. The accuracy and precision in the measurement is scientifically validated and data retrieval and data quality control are reasonable (Dubovik et al., 2000, 2002). AERONET data can be accessed https://aeronet.gsfc.nasa.gov/new_web/data.html.

Here, was AOT calculated at wavelength 550 nm (a precise visible band) from the primary AERONET sun/sky photometer retrievals at 440 nm and 675 nm using Eq. (2). Furthermore, the Ångström exponent (α) particle size was calculated using Eq. (3), and was subsequently applied in Eq. (2) to calculate τ_{550} . Both τ_{550} and α values were presented independently using time series at daily resolution, due to the fact that the short residence times of aerosol particles in the atmosphere ranges from days to weeks. Additionally, a site such as Ilorin is predisposed to the influence of both dry air from the North and humid air from South, therefore diurnal changes in meteorological variables can affect aerosol parameters and makes it necessary to initially study aerosol distributions at a daily scale (Eck et al., 2010; Fawole et al., 2016), followed by considering multi-year averaged τ_{550} and α . The daily calculated values of τ_{550} and α , were also averaged to monthly mean and then to seasonal averaged values and were presented using time series, to establish and deduce important points and visualize the relation between τ_{550} and α .

AERONET also provides optical parameters: SSA describes the ratio of scattering to the extinction coefficient and the asymmetry factor, g , which describes the angular distribution of scattered radiation and determines whether the particle scatter radiation is in either the forward or backward direction. The four wavelengths 440, 675, 870 and 1020 nm were retrieved directly at daily scale. At 550 nm, SSA was obtained by interpolation between 440 and 675 nm. A similar approach was applied to calculate g . Multi-year average seasonal variability of SSA and g at these wavelengths was computed. Dataset availability for τ_{550} , SSA, g , and VSD is 2005–2009 and 2012 (6 years) and for refractive index 1998–2015 (13 years, with exception of 2002–2005, where retrievals are not available).

The geolocation of Ilorin is latitude 8.320° N and longitude 4.340° E and elevation of 350 m above sea level (see Fig. 1). The Ilorin site is in the tropical savanna climate zone, Köppen classification Aw (Markus, Grieser, Christoph, Bruno, & Franz, 2006). The average precipitation rate in Ilorin is 1217 mm with the variation of 222 mm between peak and light wet months. Ilorin is sited in north central Nigeria at the point of convergence (Intertropical Convergence Zone, ITCZ) between the monsoon from the South Atlantic Ocean (Gulf of Guinea), and the tropical continental airmass from the northern Sahara deserts. This system facilitates transport of dust from the Sahel region and pollution from biomass burning of the savanna primarily in the Sahel and Sudanese zones towards Nigeria during the dry-cold/Harmattan and dry-warm seasons (November to April) in addition to terrestrial emissions of natural and anthropogenic

sources. These are the key sources of aerosol particles in this region (Eck et al., 2010).

3. Theoretical background

Aerosol optical thickness was measured in discrete spectral intervals with Sun photometers installed at the surface, but gas and water vapor absorption prevents τ measurement at all wavelengths (Schuster, 2005). The general Ångström exponent AE relationship is presented in Eq. (1). We used Eq. (2) to derive AOT at 550 nm τ_{550} and Eq. (3) to derived AE also at 550 nm using primary AERONET 440 nm and 675 nm retrievals (Ångström, 1964):

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

where τ is aerosol optical thickness AOT, β is Ångström's turbidity coefficient, λ is wavelength and α is the Ångstrom exponent AE.

$$\tau_{550} = \tau_{675} \left(\frac{550}{675} \right)^{-\alpha} \quad (2)$$

where α is the Ångstrom exponent defined as equation (3)

$$\alpha = - \frac{\ln \left(\frac{\tau_{440}}{\tau_{675}} \right)}{\ln \left(\frac{675}{440} \right)} \quad (3)$$

The α depends mostly on the aerosol size distribution: small values of α correspond to large particles such as seasalt, whereas values between 1 and 2 correspond to polluted air masses containing sub-micron-sized particles such as sulfates, nitrates and carbonaceous aerosol (Lioussé et al., 1996).

The resulting standard error of 0.02 maximum absolute uncertainty value is normally obtained from a direct measurement of the AOT, independent of the aerosol load. The relative uncertainty on α is a function of the optical thickness. The standard error for τ_{550} is given in Eq. (4) (Hamonou et al., 1999; Hodzic et al., 2004).

$$\frac{\Delta \tau_{550}}{\tau_{550}} = \left(1 + \frac{\ln \left(\frac{550}{440} \right)}{\ln \left(\frac{675}{440} \right)} \right) \frac{\Delta \tau_{440}}{\tau_{440}} + \left(\ln \left(\frac{550}{675} \right) / \ln \left(\frac{675}{440} \right) \right) \frac{\Delta \tau_{675}}{\tau_{675}} \quad (4)$$

Also, ϖ_0 is defined as the ratio of scattering (Q_{scat}) to the extinction coefficient ($Q_{scat} + Q_{abs}$). The ϖ_0 data at wavelengths 440, 550, 675, 870 and 1020 nm were also evaluated.

$$\varpi_0 = \frac{Q_{scat}(\lambda)}{Q_{scat}(\lambda) + Q_{abs}(\lambda)} \quad (5)$$

Another important optical property of atmospheric particles used in radiative transfer and climate model is g which describes the angular distribution of scattered radiation. Mathematically, g is define by;

$$g = \frac{\omega_1}{3} = \frac{1}{2} \int_{-1}^1 P(\cos \theta) \cos \theta d\cos \theta \quad (6)$$

where P is the phase function, it is define for aerosols, molecules and cloud particles. P represents the angular distribution of scattered angle θ . P can be expressed using the Legendre polynomials (ω_1), and ω_1 in Eq. (6) stands for $l = 1$, (Korras-Carraca, Hatzianastassiou, Matsoukas, Gkikas, & Papadimas, 2015; Liou, 2002).

An additional important parameter from AERONET retrievals is the volume size distribution that can be represented in a lognormal form as;

$$\frac{dV(r)}{d \ln r} = \sum_{i=1}^n \frac{C_i}{\sqrt{2\pi}\sigma_i} \exp \left[-\frac{(\ln r - \ln R_i)^2}{2\sigma_i^2} \right] \quad (7)$$

where C_i is the particle volume concentration, R_i is the median or geometric mean radius, σ_i is the variance width of each mode, r is the particle radius, and n is the number of lognormal aerosol modes.

The VSD usually gives the mixture of different types of aerosols present and can help identify transported aerosols through advection circulation into a location that is influenced by scavenging processes and meteorological impacts (Adesina et al., 2019).

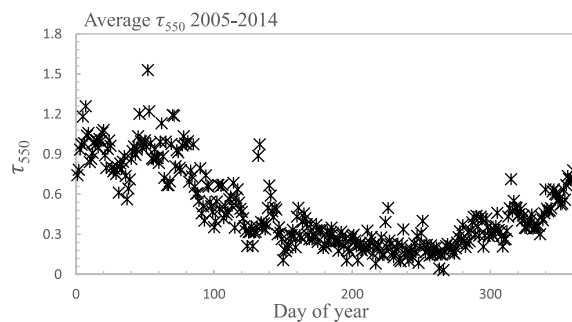


Fig. 2. Averaged aerosol optical thickness AOT at 550 nm 2005–2014 over AERONET Ilorin site.

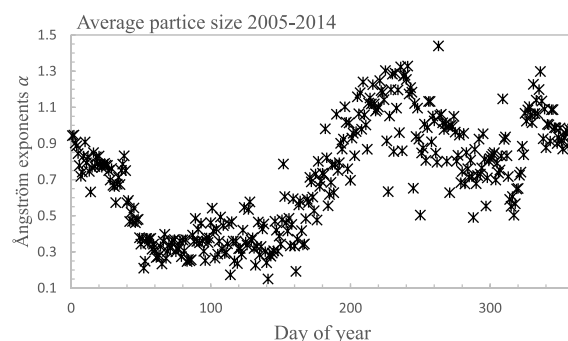


Fig. 3. Averaged Ångström exponent α at 550 nm 2005–2014 at AERONET Ilorin site.

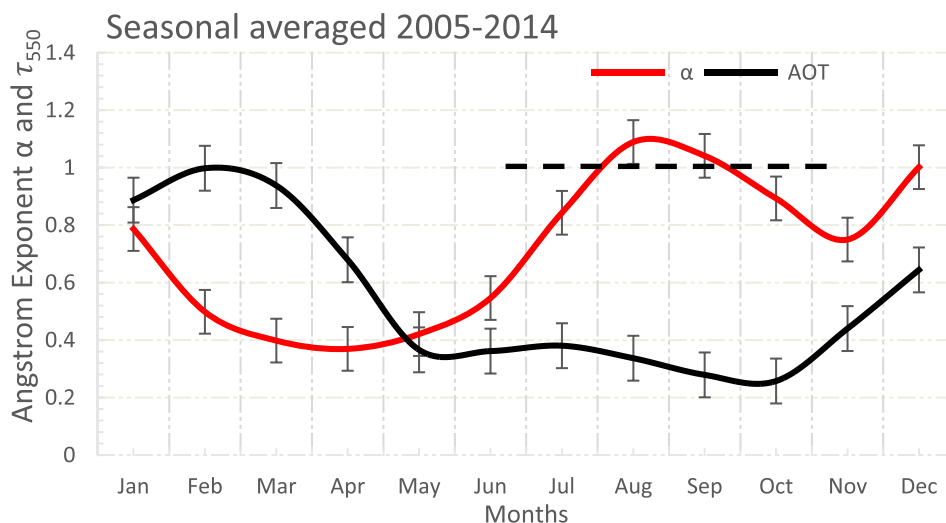


Fig. 4. Seasonal averaged distribution of Ångström exponent AE and aerosol optical thickness AOT at 550 nm (dash line displayed values of $(\alpha > 1)$). The uncertainty of the AERONET τ_{550} and α retrieval is presented as error bars.

4. Results and discussion

4.1. Multi-year description of and evaluation of Ångström exponent (AE)

In this subsection, averaged τ_{550} and α at the Ilorin AERONET site are shown in Figs. 2 and 3.

A day-to-day variability was observed throughout the period, with recurrent high $\tau_{550} > 1.0$ mainly occurring at the beginning of the year (Fig. 2). The maximum τ_{550} was pronounced in the dry-cold month of February, with τ_{550} elevated values due to transported desert dust particles by trade winds from the Sahara and Sahel zones of North Africa, combined with aerosols from local sources such as

Table 1Summary of ARONET-Ilorin-Nigeria τ data points and different mode occurrences.

Serial Number	Year	Data points	Aerosol Modes	Occurrence of different Aerosol modes per year	% of Occurrence of different Aerosol modes per year
1	2005	266	Coarse ($\alpha \leq 1$)	210	78.9
			Fine Particles ($\alpha > 1$)	56	21.1
2	2006	270	Coarse	212	78.5
			Fine Particles	58	21.5
3	2007	300	Coarse	249	83.0
			Fine Particles	51	17.0
4	2008	216	Coarse	178	82.4
			Fine Particles	38	17.6
5	2009	178	Coarse	152	85.4
			Fine Particles	26	14.6
6	2012	249	Coarse	186	74.7
			Fine Particles	63	25.3

anthropogenic pollution and biomass burning from agricultural activities in Nigeria (Cooke, Koffi, & Gregoire, 1996; Dwyer, Pinnock, Gregoire, & Pereire, 2000). The minimum τ_{550} was observed during the peak wet months (June–October). These low values of $\tau_{550} < 0.3$ are due to precipitation that wet-deposits the aerosol particles, removing them from the atmosphere and leaving behind a less dusty sky with high solar intensity reaching the Earth's surface. The seasonal cycle of varied aerosol load coincides with the dry-cold/Harmattan (December–February), dry-warm (March–May) and wet months (June–October) in this region.

Ångström exponents $\alpha \leq 1$ and $\alpha \geq 1$ quantify the contribution of coarse and fine mode particles to the total extinction (Eck et al., 1999; Holben et al., 2001). Here, we present the characterization of aerosol particle sizes over Nigeria based on this classification.

The distribution of Ångström exponent α over the site is presented in Fig. 3. Day-to-day variations of particle size were observed with high particle sizes $\alpha > 1$ found common in the second half of the year. The observed maximum α is greater than 1.4 and the minimum α is 0.1. This range of values indicates the presence of both coarse and fine particle mode aerosols at the site.

The optical thickness is higher in the dry-cold/Harmattan season, DJF, compared to other seasons (Fig. 2). On a global perspective, AERONET detects the contrast in optical thickness values between dry and wet seasons over Nigeria, similar to that which was observed over Southern Africa and South America by Takemura et al. (2002). When compared with other AERONET sites, for instance Eck et al. (2010), Nigeria is one of the regions with highest concentration of complex mixed-aerosols in the world.

4.2. Seasonal averaged τ_{550} and Ångström exponent

In this subsection, results for the seasonal averaged τ_{550} and α are presented. Seasonal averaged τ_{550} has a wide range, with minimum values from ~ 0.25 to 0.36 , decreasing over the wet season (May through October). Maximum τ_{550} , from ~ 0.88 to ~ 1.0 , reflects the peak period of aerosol mixture (coarse and fine particles mode) resulting from a combination of dust, biomass burning and anthropogenic activities in the region (Fig. 4).

The corresponding α seasonal average has minimum values from ~ 0.36 to 0.39 , coinciding with the maximum τ_{550} . The maximum α ranges from ~ 1.04 to 1.08 and coincides with minimum τ_{550} . Values of $\alpha > 1$ were observed in the wet season, for example ~ 1.1 in August or ~ 1.04 in September (Fig. 4). Values of $\alpha > 1$ that represents fine particle (FP) aerosols in the wet season are likely due to emissions sources other than the biomass burning that dominates the dry season. Other important sources include anthropogenic emissions in Nigeria that affect both climate and the quality of air.

Additional anthropogenic emission sources in Nigeria are: fossil fuel emissions from vehicles, industry/energy emissions, and two-stroke engines. Additional emission contributions are from using residential firewood for domestic cooking, roasting and street frying spots, as well as local charcoal making that have previously received less attention. These sources produce year-round emissions. This results in a complex and unique mixture of aerosols over Nigeria. Summarily, the Ångström exponent is large over Nigeria, even in the wet season.

Furthermore, we calculated the seasonal (2005–2014) annual mean percentage of different particles in the aerosol regime over Nigeria based on different aerosol modes in order to establish the percentage contribution of aerosols loading over this site in Nigeria (see Table 1). We found the coarse aerosol mode as dominant (76%) followed by fine mode particles (24%) at Ilorin. Also, the decadal mean occurrences of τ_{550} is 155.8 for coarse mode particles and 49.4 for fine mode particles.

4.3. Averaged single scattering albedo SSA relationship to wavelength

The single scattering albedo ω_0 relates the ratio of scattering to the extinction coefficient and is a significant parameter in determining the aerosol radiative effect. It depends on the aerosol refractive index (particle composition) and the volume size distribution (Dubovik & King, 2000). Single scattering albedo values ranging from 0 (absolute absorption) to 1 (absolute scattering) determine the contribution of aerosol particles to absorption or scattering of incoming solar radiation in the atmosphere. This paper presents multi-year averaged ω_0 at different wavelengths using AERONET data at the Ilorin site.

The transported North African desert dust is the main source of aerosol particles that strongly impact West Africa during Harmattan

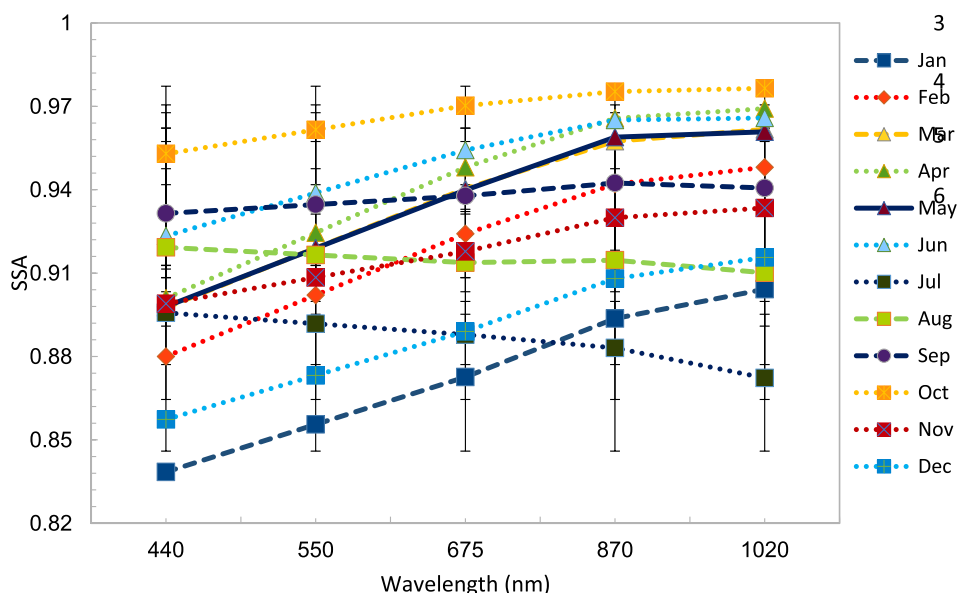


Fig. 5. Multi-year average distributions of single scattering albedo τ_0 at multiple-wavelength AERONET Ilorin site. The uncertainty of the AERONET τ_0 retrieval is presented as standard deviation.

(DJF) season. The value of approximately 0.95 was obtained using AERONET retrievals over northern Africa where soil dust is the dominant aerosol type (Takemura et al., 2002). Earlier Sokolik and Toon (1999) calculated τ_0 of hematite (absorbing mineral) as 0.65 at wavelengths from 0.2 to 0.6 μm in the same region.

In contrast, the value of τ_0 of 0.86 at 0.53 μm using the refractive index was determined from several measurements over same region by Carlson and Benjamin (1980). Overall, there is uncertainty in the value of τ_0 for the northern Africa desert region and this calls for further research into the optical properties of soil dust. In comparison to northern Africa, where the dominant aerosol is soil dust, Nigeria experiences similar dominant coarse mode (soil dust, 76%), and the value over Nigeria ranges between 0.83 and 0.97 (Fig. 5).

Fig. 5 shows averaged seasonal variability of τ_0 at five (5) wavelengths (440, 550, 675, 870 and 1020) nm. Averaged τ_0 over the Ilorin AERONET site was found to be confined to values between 0.83 and 0.97 with the highest values observed in October during the wet season due to high humidity, when hygroscopicity tends to increase the value of τ_0 depending on the wavelength, and lowest value were observed in DJF (dry-cold/Harmattan season). The τ_0 decreases with increasing particle size for desert dust aerosols at short wavelengths <600 nm, and depending on the percentage composition of iron oxides (Di Biagio et al., 2019). The lowest values observed during the dry-cold/Harmattan (DJF) season is due to a combination of desert-originated aerosols with biomass burning aerosols that are absorbing particles and resulted in high absorption.

Despite the decrease in τ_0 values during the DJF dry-cold/Harmattan season, the season experiences a drop in temperature (Harmattan), probably the amount of absorbing particles are less than non-absorbing particles (in desert dust). However, the drop in temperature in the season is inconsistent in recent times in Nigeria.

The total absorption found at this site across different wavelengths as deduced from τ_0 values is 0.16. Overall, when $\tau_0 > 0.94$, this represents sulfate aerosols that are scattering particles. Changes of τ_0 from 0.95 to 0.85 would change the radiative forcing of desert dust from significant cooling to significant warming because absorption of as little as 0.1 can cause an increase in the temperature of the local environment (Hansen et al., 1997). In addition, values of $\tau_0 > 0.85$ generally describes aerosols that cool the planet and values of $\tau_0 < 0.85$ relate to aerosol absorption that warms the planet (Hansen et al., 1981).

The values of τ_0 retrieved from AERONET can include some biases and errors (Dubovik et al., 2000; Smirnov et al., 2000). The uncertainty is within 0.03 for high aerosol loading, with an optical thickness at 0.44 μm or higher than 0.5, while uncertainty increases to 0.05–0.07 for lower AOT (Dubovik et al., 2000). The uncertainty of the AERONET retrieval is presented as standard deviation bars in Fig. 5.

Single scattering albedo τ_0 , generally increases with increasing wavelength. This indicates a high absorption by aerosols at the UV range of the spectrum that is a feature of aerosols such as iron oxides from desert dust (Adesina et al., 2019). However, a peculiar trend in τ_0 was noticed in the months of July and August, where a decrease occurred in τ_0 from 870 to 1020 nm, representing higher absorption at longer wavelengths. This decrease is mostly characteristic of fine particle aerosols that absorb at longer wavelengths (Fig. 5). Such small size particles are associated with black carbon from biomass burning or urban/industrial aerosol (Dubovik et al., 2002).

It is deduced from averaged τ_0 that absorption is highest at lowest wavelengths of 440 nm, thus, τ_0 increases with increasing wavelength, except in a few instances, in mixed-aerosol atmospheric conditions over Nigeria.

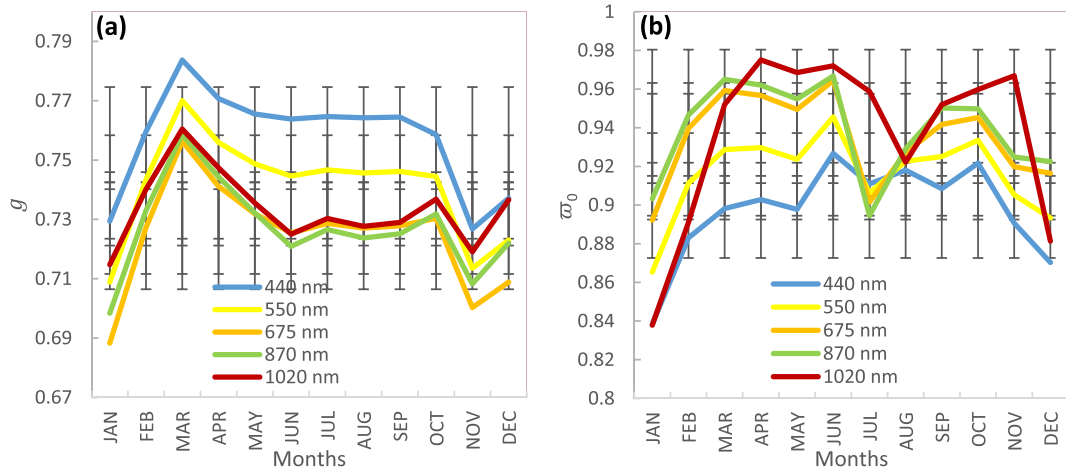


Fig. 6. Seasonal variability of (a) asymmetry parameter g , and (b) single scattering albedo (SSA) ϖ_0 (1998–2015).

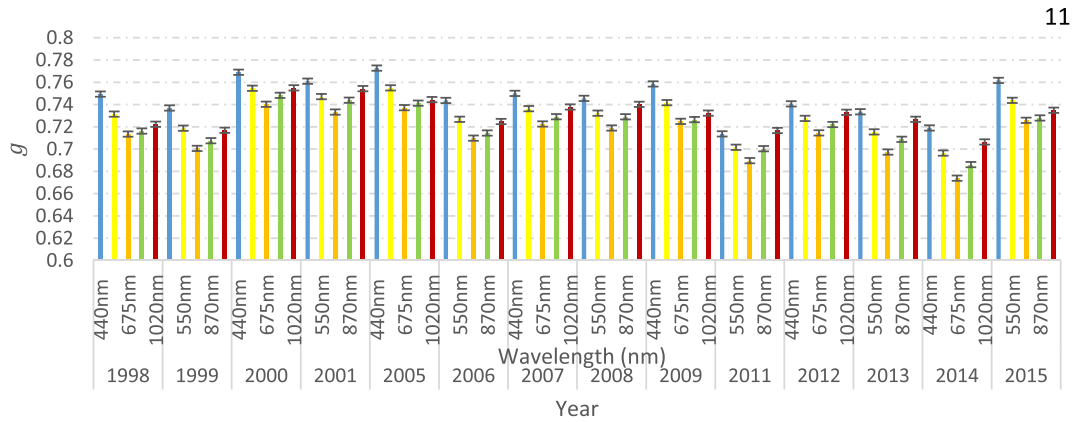


Fig. 7. Interannual variability of asymmetry parameter at different wavelength.

4.3.1. Seasonal variations of asymmetry parameter (g) and single scattering albedo (ϖ_0)

Asymmetry parameter g determines the backward and forward scattering of aerosol particles. This is in addition to ϖ_0 , an important parameter in analyzing optical properties of aerosols.

Seasonal variations are observed in both g and ϖ_0 , with increasing values in DJF coinciding to the peak dry-cold/Harmattan season (Fig. 6a), a season characterized by coarse mode aerosols. A drop in the g values was observed from April to November followed by an increase in December to mark the commencement of the dry season. The drop is attributed to the precipitation scavenging that clears the sky in the wet season (Fig. 6a). The highest value of $g = 0.78$ was observed at the shortest wavelengths of 440 nm. A similar pattern was observed between wavelengths of 675, 870 and 1020 nm, where g showed almost equal values, except for minor differences at the beginning of the year. In general, the values of g observed over Nigeria shows forward scattering.

On the other hand, the highest value of $\varpi_0 = 0.97$ was observed at the longest wavelength of 1020 nm and lowest value $\varpi_0 = 0.83$ at the shortest wavelength of 440 nm. The plot shows an irregular pattern across all wavelengths considered throughout the season. This is likely caused by the mixture of different aerosol types (both coarse and fine particulate) in a mixed-aerosol complicated Nigeria's atmosphere.

4.3.2. Interannual variability

Interannual variability of g shows minor variations between different wavelengths, with the highest values of $g \sim 0.78$ observed at 440 nm and the lowest value $g \sim 0.67$ at 675 nm. The maximum variation value of 0.09 was found across all wavelengths of study. Overall, the five wavelengths studied on average show the highest value of $g > 0.7$ (Fig. 7) at the Ilorin AERONET site. The asymmetry parameter shows a decrease with increasing wavelength between 440 and 675 nm, and an increase with increasing wavelength between 870 and 1020 nm. The seasonal averages are limited to providing a generalized estimate of aerosol parameters for Ilorin-Nigeria. The high values of g over Nigeria are likely due to dominant coarse mode aerosol particles and depend on their composition.

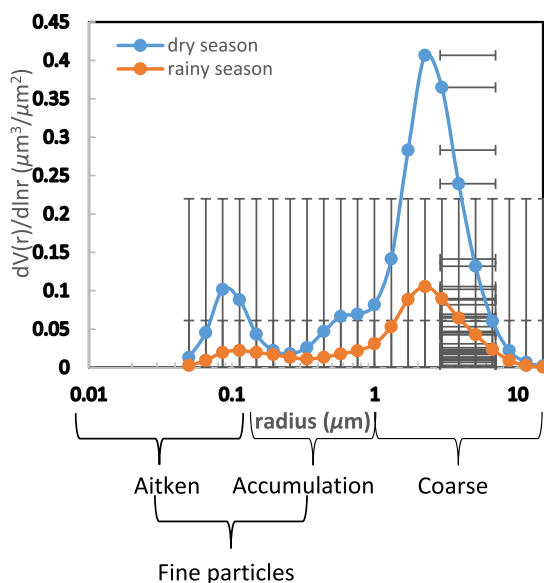


Fig. 8. Mean volume size distribution in different seasons with standard deviation.

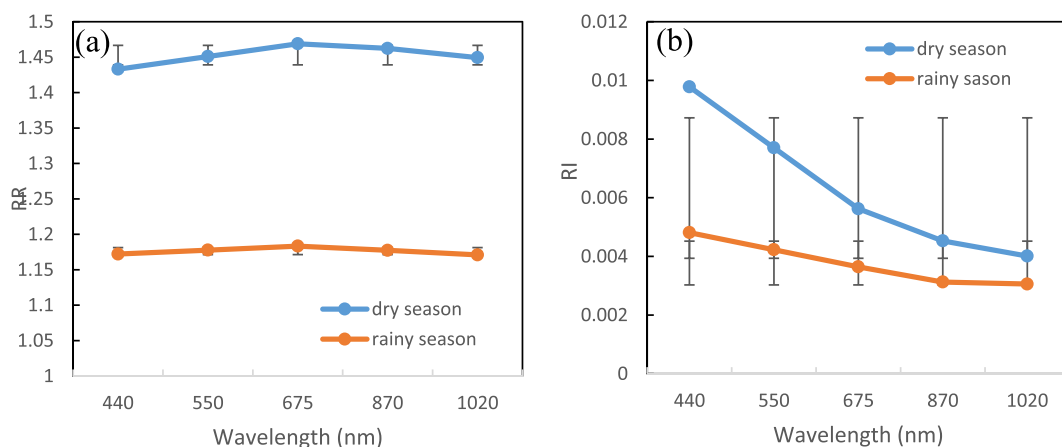


Fig. 9. Seasonal AERONET data Ilorin mean refractive index (a) real and (b) imaginary at five different wavelengths with standard deviation.

4.4. Seasonal variability of the volume size distribution

The volume size distribution VSD shows the ratio of the volume of the coarse and the accumulation mode particles present in the two seasons (Fig. 8). Significant changes were observed in the size of the accumulation and the coarse modes between the two seasons. The volume size distribution shows higher values in the coarse mode for both seasons than in the accumulation mode. The mean volume of the coarse particles had a noticeable variation with a radius ranging from 2 to 7 μm . The accumulation mode particle distribution was lowest in the wet season compared to the dry season, and increased to a maximum of $0.1 \mu\text{m}^3/\mu\text{m}^2$ at radius 0.1 μm during the dry season. Overall, the volume size distribution value in the dry season was higher than in the wet season throughout the two modes, and the coarse mode aerosol dominated the size distribution. This coarse mode corresponds with the dominant aerosol obtained using the Ångström exponent. Thus, the VSD and AE both show the dominance of coarse mode aerosols in the atmosphere over Ilorin, Nigeria.

4.5. Seasonal variability of refractive index

The refractive index R consist of two parts: the real (RR) and the imaginary (RI) parts. Refractive index reveals the tendency of aerosol particles to scatter and absorb incoming radiation. The complex refractive index for aerosol particles depends on the chemical composition of a particle. High values of the RR indicate scattering while high values of the RI indicate absorption. In Fig. 9a and b, the

seasonal RR and RI for the AERONET Ilorin site are presented. Comparing the RR and the RI, it can be observed that the RR exhibits larger dependence on seasons than the RI. The RR averages around 1.17 for the wet season and around 1.44 for the dry season. Although the dry season aerosols have higher scattering, the RI also shows higher absorption for the dry season (0.009). The high absorption during dry season may be attributed to the impact of desert dust (iron oxides) coupled with biomass burning from domestic firewood use and agricultural activities.

5. Conclusion

The aerosol optical properties and composition in the atmosphere over Nigeria are still uncertain due to very limited observations. We investigated observations of τ_{550} and optical properties from the AERONET Ilorin station in Nigeria. We have found from particle size and volume size distribution that coarse mode aerosols are dominant at 76% occurrence, and fine mode particles are secondary at 24% occurrence. Although the mixture of coarse and fine particle modes is higher in the DJF season, the signatures of fine modes particles ($\alpha > 1$) were seen throughout the year. We presented the characterization of aerosol optical properties and identified the compositions with coarse mode aerosol as dominant mode. SSA, ω_0 , and asymmetry parameter, g , at five wavelengths were evaluated, with the highest absorption found at the shortest wavelengths, which indicates absorption by large particles. The observed absorption across all wavelengths was found to be approximately 0.16 over the AERONET Ilorin site, which can impact changes in surface temperature. Absorption of as little as 0.1 can cause an increase in temperature of the local environment (Hansen et al., 1997). Changes of (for example, from 0.95 to 0.85) would alter the radiative forcing of desert dust from significant cooling to significant warming (Hansen et al., 1997). The volume size distribution showed higher concentrations in the dry season. The RR ranges between 1.17 and 1.43 in the shortest wavelength depending on the seasons, and the RI show higher absorption for dry season (0.009). Results shed light on the complex mixture of aerosols for a tropical region as well as determine the magnitude of absorption of these particles. Potential impacts on global climate based on present and future aerosols loading over Nigeria requires a better understanding of emissions of different aerosol precursors and better observational contains that are lacking over this region.

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