Original Article

JOURNAL OF OCEAN AND CLIMATE

The International Journal of Ocean and Climate Systems
Volume 9: 1–13

DOI: 10.1177/1759313118820306
journals.sagepub.com/home/ocs
SAGE

Spatial and seasonal variations in atmospheric aerosols over Nigeria: Assessment of influence of intertropical discontinuity movement

Ayansina Ayanlade[1], Godwin Atai[1] and Margaret Olusolape Jegede[2]

Abstract

This study examines the influence of intertropical discontinuity movement on seasonality and distribution of atmospheric aerosols over Nigeria, using remote sensing approach. The Moderate Resolution Imaging Spectroradiometer (MODIS) Terra aerosol optical depth, wind speed and precipitation/intertropical discontinuity (ITD) dataset were used. Geospatial interpolation model was used to analyse the aerosol seasonal distribution. Correlations analysis was used to evaluate the degree of influence of wind and ITD on the monthly distribution of aerosol. The results show significant variations in monthly mean distributions of aerosol, but the variation is much more extraordinary during Harmattan season than Wet and Dry seasons, with 0.29 ⩽ aerosol optical depth ⩾ 0.46. In other ecological zones, the highest mean aerosol optical depth values were observed in the months of December, January and February with 0.30 ⩽ aerosol optical depth ⩾ 0.60, with highest value in Sahel ecological zone. Generally, the results further show a strong relationship between aerosol optical depth distribution and migration of ITD with correlation $r^2 \geqslant 0.60$ @ $p = 0.05$ mostly during Dry and Harmattan seasons but relatively low correlation $r^2 \leqslant 0.40$ @ $p = 0.05$ during Wet season. The major findings of this study are that seasonal shifts in the location of the ITD considerably affect not only rainfall distribution, resulting in the Wet and Dry seasons in the study area, but also have significant impacts on atmospheric aerosol distributions. Although not all aerosols presented in this study are dust originated from Sahara desert, since biomass-burning activities frequently occur in the study area, the study concludes that satellite-based aerosol optical depth datasets continue to be advantageous to understand atmospheric aerosols distribution in a region where there is fewer ground aerosols data.

Keywords

Aerosol optical depth, wind speed, intertropical discontinuity, remote sensing, Nigeria

Date received: 15 March 2018; accepted: 19 November 2018

Introduction

Aerosols have been studied as suspension particles in the atmosphere and exert significant impacts in the atmosphere on local, regional and global scales, giving rise to air pollution (Demott et al., 2003; Ravindra et al., 2008; Scerri et al., 2016; Zhang and Christopher, 2003) and likely adverse human health effects (Baumbach, 2012; Kim et al., 2015). The majority of these studies have revealed the Sahara as the largest source of windblown aerosols;

[1]Department of Geography, Obafemi Awolowo University, Ile-Ife, Nigeria
[2]African Institute for Science Policy and Innovation, Obafemi Awolowo University, Ile-Ife, Nigeria

Corresponding author:
Ayansina Ayanlade, Department of Geography, Obafemi Awolowo University, Ile-Ife, Nigeria.
Email: aayanlade@oauife.edu.ng; sinaayanlade@yahoo.co.uk

nonetheless, the influence of the Bodélé Depression in Chad is the largest source of most dust over Nigeria. Although major sources of desert dust include the Sahara, Middleton (2017) has further noted that dust-raising occurs all across the global drylands such as the Middle East, central and eastern Asia and long-range transport enables dust from these sources to reach other part of the world. They have a wide range of impacts on climate forcing, visibility, and human health and quality of life, and their unprecedented increase over countries of Africa in recent times is a cause for concern (Amiri-Farahani et al., 2017; Péré et al., 2018; Schepanski et al., 2017). Aerosols interact directly and indirectly also with solar radiation travelling in space and thus affect the amount of radiative energy reaching the surface and to be reflected back to space (Bran et al., 2018; Brindley et al., 2015; Péré et al., 2018; Zhang and Christopher, 2003). Other studies have reported in the literature that although aerosols are natural and anthropogenic sources, suspended in the atmosphere to the exception of all hydrometeors (Hidy and Brock, 2016), they are usually dispersed and distributed in the atmosphere by turbulence movement of air masses; but are being removed from the atmosphere by ice, dew and precipitation as well as dry sedimentation (Demott et al., 2003; Jones and Harrison, 2004).

Globally, the annual cycles are mainly related to Sahara dust and biomass burning in southern hemisphere with major aerosol sources, including biomass burning in South America and dust in West Africa (Duncan et al., 2003; Herman et al., 1997; Prospero et al., 2014; Strong et al., 2015). On local scales, domestic wood burning fires, vehicular emissions and industrial gas flaring give rise to urban air pollution (Ravindra et al., 2008) and likely adverse human health effects (Baumbach, 2012). On regional scale, aerosols diffuse from regions where emissions are high to regions of the relatively clean atmosphere (Zhang et al., 2012). They are categorized into two origins; primary particles are emitted directly in solid or liquid form into the atmosphere space. Primary aerosol particles are natural sources (Peacock, 2008) such as volcanic ash particles (Arnalds et al., 2013; Butwin et al., 2018), and deserts and oceans (Reynolds et al., 2017; Zhou et al., 2018). The deserts are usually wind-driven dust particles from the pool of soil. The ocean sources are sea salt from bursting bubbles and are released directly into the atmosphere (O'Riordan, 1989); however, diesel from machine engines and combustion processes consist of the manmade sources of primary aerosols (Bonan, 2015). But secondary aerosols on the other hand are formed from some precursor gas through gas-to-particle conversion, they are often referred to as 'new particle formation' (NPF) or nucleation (Birmili et al., 2003). These various sources, including dust, fires, fossil fuel and biofuel combustion, and agricultural practices contribute to aerosol concentrations.

In seasonal estimating, aerosol particles have so far not been treated in countless detail, and the importance of including temporal and spatial variations in the aerosol concentration is therefore not well documented. Nigeria as a developing nation, for instance, does little to protect the environment, with little enforcement of regulations in environmental laws (Bodansky, 1999; Eaton, 1997; Eneh, 2011), despite that Nigeria lies in the seasonal pathway of the Harmattan dust. Aerosols are constantly emitted into the atmosphere in large concentrations mostly in the mega-cities. However, knowledge of the identities and the concentrations of many of these atmospheric species, especially organic components, still remain vague (Kolb et al., 2010). Understanding of aerosol distributions and establishing effective control strategies of the atmospheric pollution in the study area is rather imperative, hence this study. This study, therefore, aims at examining the seasonal distribution of atmospheric aerosols in Nigeria from the period of 2001 to 2017. The study focuses on evaluating the influence of intertropical convergence zone (ITCZ) on the distribution and seasonality in atmospheric aerosol distributions over Nigeria. The ITCZ lies in the equatorial trough, a permanent low-pressure feature that marks the meteorological equator where surface trade winds, laden with heat and moisture from surface evaporation and sensible heating, converge to form a zone of increased mean convection, cloudiness and precipitation. Generally, in Nigeria, the ITCZ is frequently denoted as the intertropical discontinuity (ITD). This is because it is a zone considered to be a distinct moisture discontinuity rather than by marked convergence (Bello, 1998). This study was based on the assumption that distinctive reflectance and emission properties of objects influence the ability of sensors to measure these interactions, which allows us to use remote sensing to measure features and changes on the Earth and in our atmosphere (Dey and Tripathi, 2013; Li et al., 2016; Mhawish et al., 2018; Purkis and Klemas, 2011; Wiegner et al., 2014). Thus, satellite observations of the seasonal aerosols over Nigeria are related to the ITD movement and monsoon rainfall.

Methodology

Site description and data acquisition

The study entails the six ecological zones in Nigeria (Figure 1). The study site spread over a total area of 923,800 km^2 and situated between 4°N-14°N latitudes and 3°E-15°E longitudes (Figure 1). Nigeria is one of the largest countries in Africa covering about 14% of total West African land mass, bounded by the Niger Republic to the north, Cameroon at the East, the Republic of Benin at the West and the Gulf of Guinea in the south (Commission and Macro, 2000; Valiela et al., 2001). In this study, aerosol optical depth (AOD), wind speed and precipitation/ITD data were used (Table 1). The Moderate Resolution Imaging Spectroradiometer (MODIS) Terra satellite dataset was used, for the period January 2001 to December 2017. The MODIS AOD retrievals are at the wavelength of 550 nm, to investigate the variations in aerosol. The dataset was obtained from the National Aeronautics and Space Administration (NASA) Atmosphere Archive and Distribution System. The available MODIS data were downloaded directly from NASA Level I Atmosphere Archive, thus a multi-year mean spatial distribution of AODs over the study area was used. The Terra satellite data was used in this study because of its benefit of spatial and temporal resolutions, in that it overpasses most areas of the globe at approximately 10:30 and 22:30 local time each day (Giglio, 2007). MODIS does not only provide high spatial and temporal resolution AOD estimates over a relatively long period of record but also provide global coverage analysis (Ayanlade, 2017). The MODIS AOD is also sensitive enough to detect small values within 0.05, but the higher values indicate greater aerosol in the atmospheric column over the study area. In this study, the measurements of aerosols are based on the fact that the particles change the way the atmosphere reflects and absorbs visible and infrared light. This measurement of aerosols is generally called aerosol optical thickness in the literature, and an optical thickness <0.1 indicates clear sky while a value of 1 (reddish brown) shows very hazy conditions. This dataset was used in this study because of a limited number of aerosol ground stations in developing countries, and the available number station across Nigeria is just one (sited at Ilorin), thus the use of satellite data in this study. Besides, derivation of AOD over land has been a difficult mission, largely because of uncertainties resulting from different surfaces such as forest, bare soil and water bodies, among others (Chu et al., 2002; Gupta et al., 2018; Li et al., 2005; Mhawish et al., 2017).

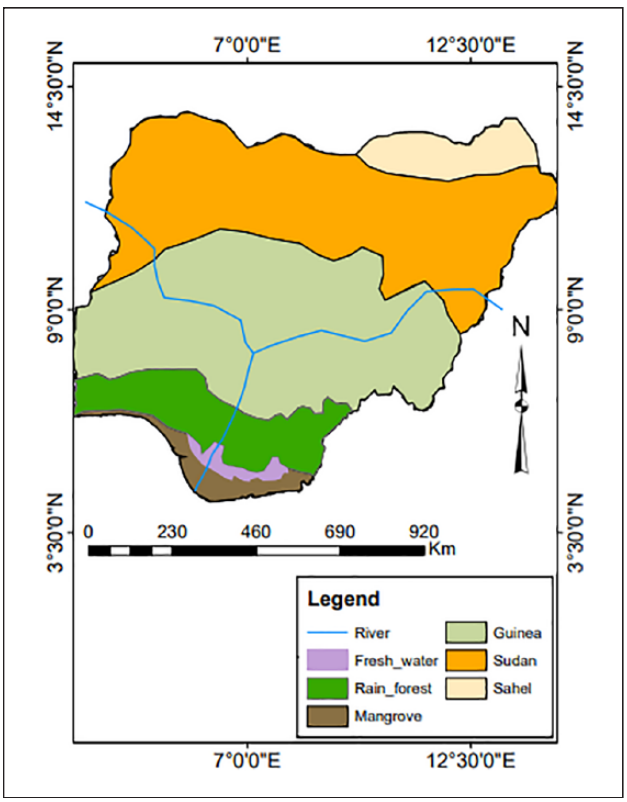

Figure 1. Ecological map of the study location, Nigeria.

Wind movement data for the study was collected from the archive of the Climate Data Assimilation System (CDAS) for the period of 2001–2017. It was developed from the joint project of National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR), with wind speed of 15×20 km. The wind data format for this study was RERL Wind Time Series Data File format, and the format was defined with the objective of accessible on different computer platforms, accessible for different software and self-contained. Precipitation/ITD data were collected from the archive of Climatic Prediction Centre Morphine Technique (CMORPH) which was generated from observations of National Oceanic and Atmospheric Administration (NOAA) polar-orbiting operational metrological satellites. The data were based on 3-hourly global CMORPH precipitation data (Beck et al., 2017; Dinku et al., 2010; Hirpa et al., 2010) aggregated to daily, with the daily averages calculated over the same accumulation period of the study. The wind, precipitation/ITD data were obtained for different points within different ecological zones in Nigeria (i.e. Sahel, Sudan, Guinea, Rainforest, Freshwater and Mangrove ecological zones).

Table 1. The summary of data type and sources.

Type	Source	Choice of data	Spatial resolution (km)	Duration
MODIS	AOD	High spatiotemporal characteristics, free availability and accessibility online, consistency, finer resolution	1	2001–2017
Wind movement	CDAS	Better spatial distribution of the nearest neighbours	15×20	2001–2017
Precipitation/ITCZ	CMORPH	Improved spatial distribution of the nearest neighbours	12×15	2001–2017

MODIS: Moderate Resolution Imaging Spectroradiometer; AOD: aerosol optical depth; CDAS: Climate Data Assimilation System; ITCZ: intertropical convergence zone; CMORPH: Climatic Prediction Centre Morphine Technique.

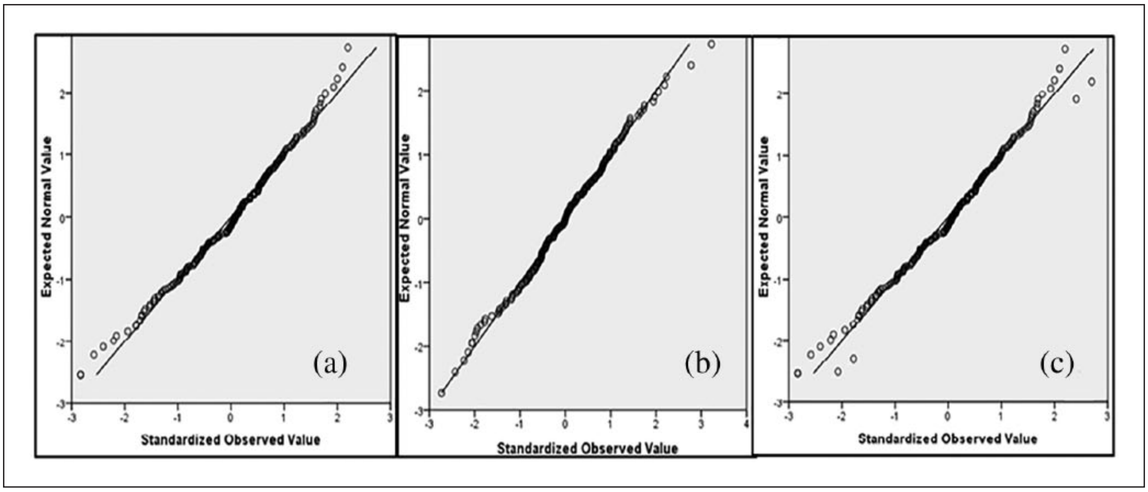

Figure 2. Q-Q plots for (a) AOD, (b) wind speed and (c) precipitation/ITD.

Data analysis

AOD data were sub-divided into monthly and seasonal distributions (Dry, Wet and Harmattan seasons) over the periods under study. The Wet season months consist of April through October, the Dry season is from the month of November till March, while Harmattan period is between December and January within the dry season. AOD monthly mean distribution was used to analyse the seasonality of aerosols. The Harmattan, though occurs within the dry season, is a period characterized by the dry and dusty northeasterly wind, typically blows from the Sahara Desert over West Africa into the Gulf of Guinea. The MODIS Dark-Target (DT) algorithm was used in this study, and it is the Collection 6 (C6) version of the DT algorithms for retrieving aerosol properties for both land and ocean. Detailed information about MODIS DT algorithm (see Levy et al. (2013) and Gupta et al. (2018)) is available at https://darktarget.gsfc.nasa.gov/atbd/overview (accessed on 16 October 2018). Geo-statistical approaches were used to examine the relationship between the monthly mean atmospheric aerosols and (a) wind movement and (b) precipitation/ITD, across Nigeria. This was done with the general aim of evaluating the influence of ITD on the monthly distribution of aerosol over the study area. This comparative interpolation analysis was done for monthly, seasonal and annual bases, using geo-statistical analytical tools. Comparisons were then made with the long-term mean seasonal variations.

The monthly, annual and seasonal maps were derived using geographic information system (GIS) spatial interpolation, for the land area over Nigeria. Kriging spatial interpolation model was used to analyse the aerosol seasonal distribution (Ayanlade, 2009; Jamaludin et al., 2016). Kriging uses a weighting mechanism that assigns more influence to the nearer data points to interpolate values at unknown locations. However, instead of using an inverse distance weighting approach, kriging uses variograms. As a measure of spatial variability, the Euclidean distance by a structural distance is specific to the attribute and the field under study (King et al., 1978). Quantum geographic information system (QGIS) alongside ArcGIS was used to interpolate the data, as in Ayanlade and Oyegbade (2016).

Influence of ITD on the monthly distribution of aerosol were assessed. Correlation analysis was used to evaluate the degree of influence of ITD on the monthly distribution of aerosol over Nigeria (Pinker et al., 1994). The correlation analysis started by testing the normality of each variable (AOD, wind speed and precipitation/ITD data) used in the analysis, using Quantile-Quantile (Q-Q) plots as presented in Figure 2. It is clear from the Q-Q plots that all variables used fall in a straight diagonal line with a positive slope, which indicates that the variables follow approximately a normal distribution, thus Pearson product–moment correlation coefficient (r^2) was used to calculate the relationship between observed AOD, wind speed and precipitation/ITD

$$r = \frac{\sum (x-\bar{X})(y-\bar{Y})}{\sqrt{\left[\sum (x-\bar{X})^2\right]\left[\sum (y-\bar{Y})^2\right]}} \tag{1}$$

where $-1 \le r \le 1$ and X represents AOD while Y denotes values for wind or precipitation/ITD. The main aim of correlation analysis is to evaluate the relationship between ITD and distribution of aerosol. Thus, the logarithm values for AOD, wind speed and precipitation/ITD were correlated for each ecological zones, in order to determine zones of high low correlations, and so as to evaluate the degree of influence of ITD on the monthly distribution of aerosol over Nigeria (Tegen et al., 1997).

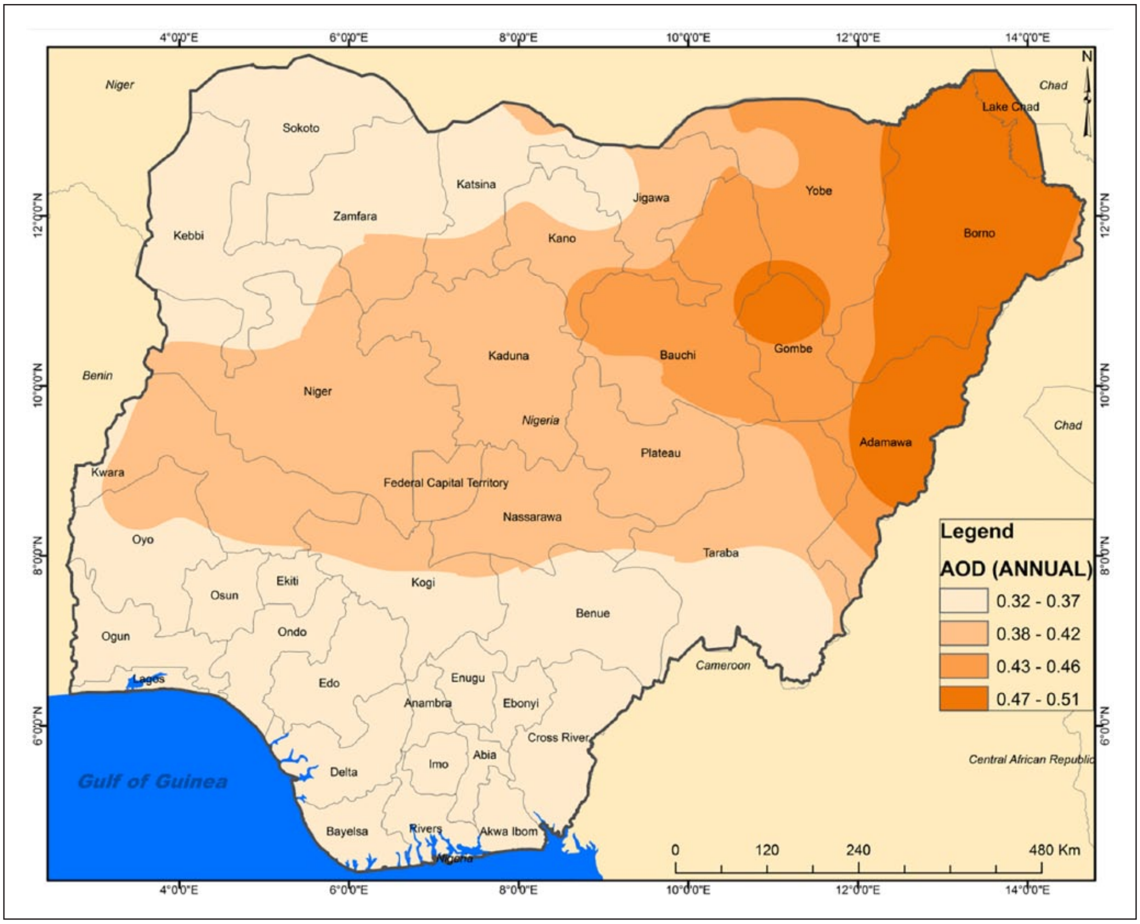

Figure 3. Annual distributions of atmospheric aerosol 2001–2017.

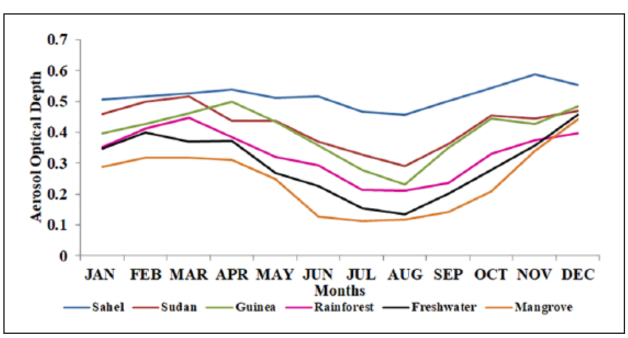

Figure 4. Monthly mean variations in aerosols over Nigeria, 2001–2017.

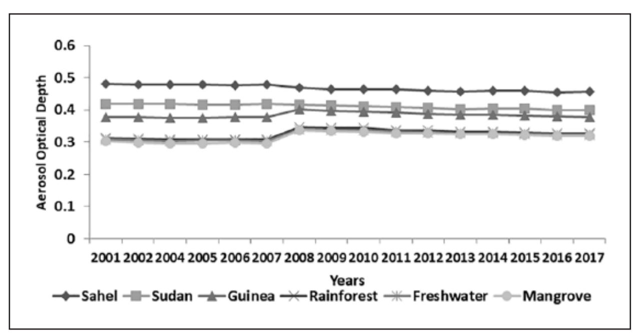

Figure 5. Annual mean variations in aerosols 2001–2017.

Results

Variations in the AOD distribution over different ecological zones

The results of annual distributions of atmospheric aerosol in the study area are indicated in Figure 3. From Figure 3, annual aerosol is generally towards the Northern part of the study area with 0.43 ≤ AOD ≥ 0.51, mostly in the Northeast of the area. However, results revealed that AOD increases from north to south, predominantly during Dry and Harmattan seasons.

The results further show both monthly and seasonal (Figures 4 and 5) variation in the AOD over different ecological zones. Figure 4 shows the monthly mean variations in the atmospheric aerosols across all the ecological zones, with Sahel ecological zone having the highest concentration of atmospheric dust while Mangrove ecological zone recorded the lowest. In the Sahel ecological zone, AOD in the months of January was 0.51 but increased to 0.56 in

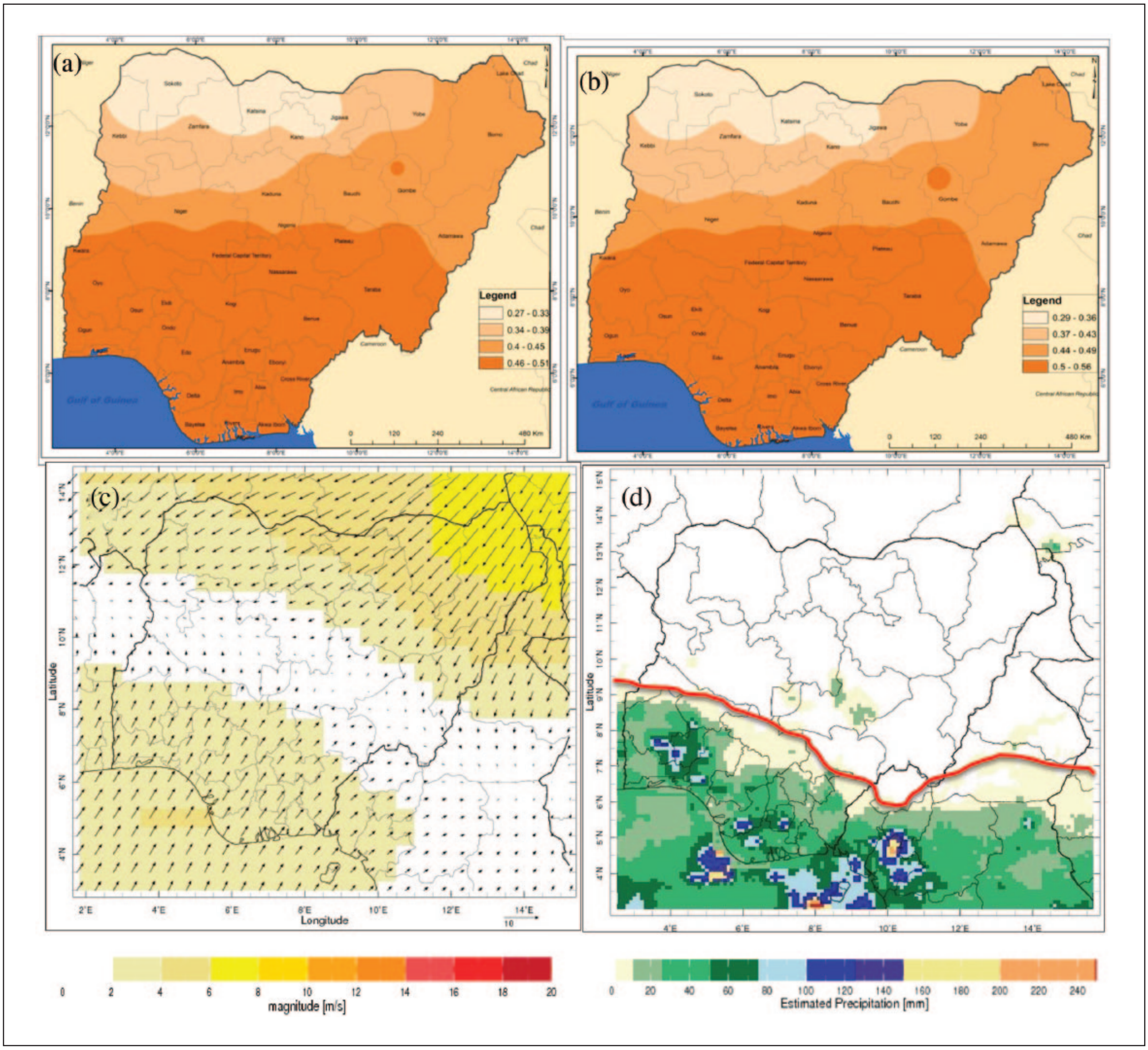

Figure 6. Variations in atmospheric aerosol distributions during the Dry season: (a) the mean AOD distribution during the Dry season, (b) mean AOD distribution in the month of March, (c) the magnitude and direction of the wind during the Dry season and (d) the mean precipitation/ITD during the months of March.

December (Figure 4). The annual analysis shows the same scenario with the highest atmospheric aerosols distribution in Sahel ecological zone, though seasonality of atmospheric aerosols was not shown much using annual values (Figure 5). Over the years of study, the results show the lowest atmospheric aerosol values in Mangrove ecological zone but highest in a very small portion of the Sahel ecological zone (Figure 5). In other ecological zones, the maximum AOD values were observed in the months of December, January and February with $0.30 \leqslant \text{AOD} \geqslant 0.4$ (Figure 4). Nevertheless, the lower AOD was recorded in the months of April through October: $0.18 \leqslant \text{AOD} \geqslant 0.29$, within the least values in the month of August ($\text{AOD} \leqslant 0.29$), in other ecological zones besides the Sahel. In Rainforest ecological zone, for instance, highest AOD was 0.47 in months of January, and 0.47 in December; maximum AOD was 0.51 in March, but least AOD of 0.14 in August (Figure 4). Mangrove ecological zone recorded slightly similar temporal variation in aerosol as that of Rainforest zone, only that for Mangrove ecological zone, AOD was 0.45 in months of January but decreased to 0.44 in December, maximum AOD was 0.50 in March, but minimum AOD of 0.14 in August.

The monthly analysis is a reflection of the seasonality of aerosols, such that the distribution of atmospheric aerosols also vary during three major seasons in the study area.

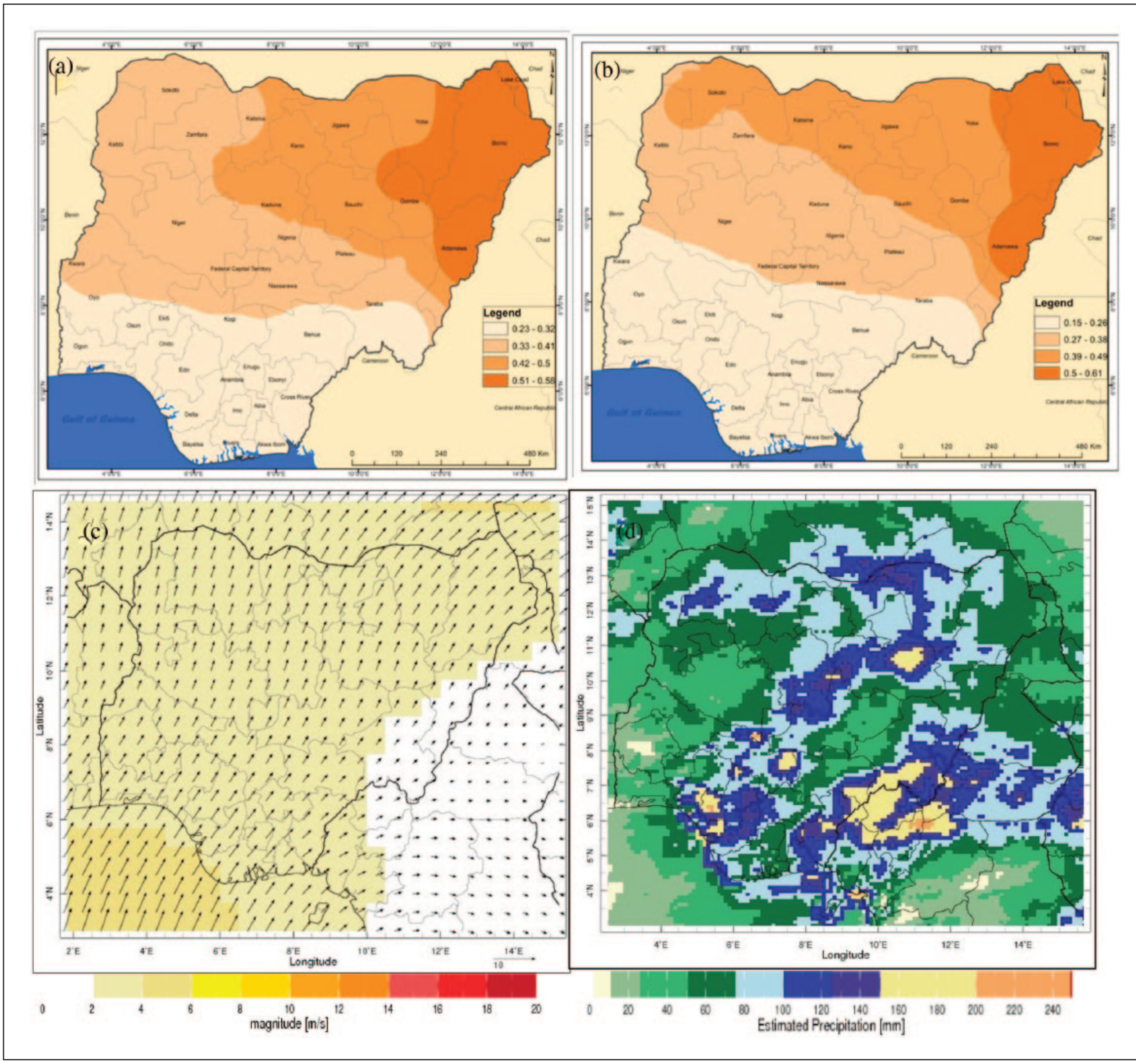

Figure 7. Variations in atmospheric aerosol dispersion during the Wet season: (a) the mean AOD during the Wet season, (b) mean AOD distribution in the month of July, (c) the magnitude and direction of the wind during the Wet season and (d) the mean precipitation/ITD during the months of July.

During the Harmattan and Dry seasons (Figures 6 and 8), aerosol distribution increases towards the south ($AOD > 0.39$) around Guinea, Rainforest, Freshwater and Mangrove ecological zones, but much more during Harmattan, with $0.39 \leqslant AOD \geqslant 0.46$, than Dry seasons (Figures 6(a) and 8(a)). Throughout the Wet season (Figure 7) on the other hand, the aerosol appears mainly in the northern part of the study area, around Sahel and Sudan ecological zones with $AOD \geqslant 0.51$, but very low in the southern part with $AOD < 0.29$, very low around Guinea, Rainforest, Freshwater and Mangrove ecological zones (Figure 7(a)). This is obvious during the peak of the rainy season, the month of July (Figure 7(b)).

The reasons for these scenarios are obvious. During the Harmattan months, the dusty atmosphere in many parts of Nigeria, with less precipitation (Figure 8(b)) is due to ITD movement towards the coastal part (Figure 8(d)) of the country (Ologunorisa and Tamuno, 2003; Omotosho and Abiodun, 2007). This is most common in January. Also, this could be a result of the prevalent flow of the tropical continental (cT) air mass from the Sahara desert to the Atlantic Ocean over the inward flow of the tropical maritime (mT) air mass from the ocean leading to the hazy atmosphere observed in the southern part (Figures 6(c) and 8(c)). Besides, December and January are the peaks of Harmattan season, with very strong north-western wind

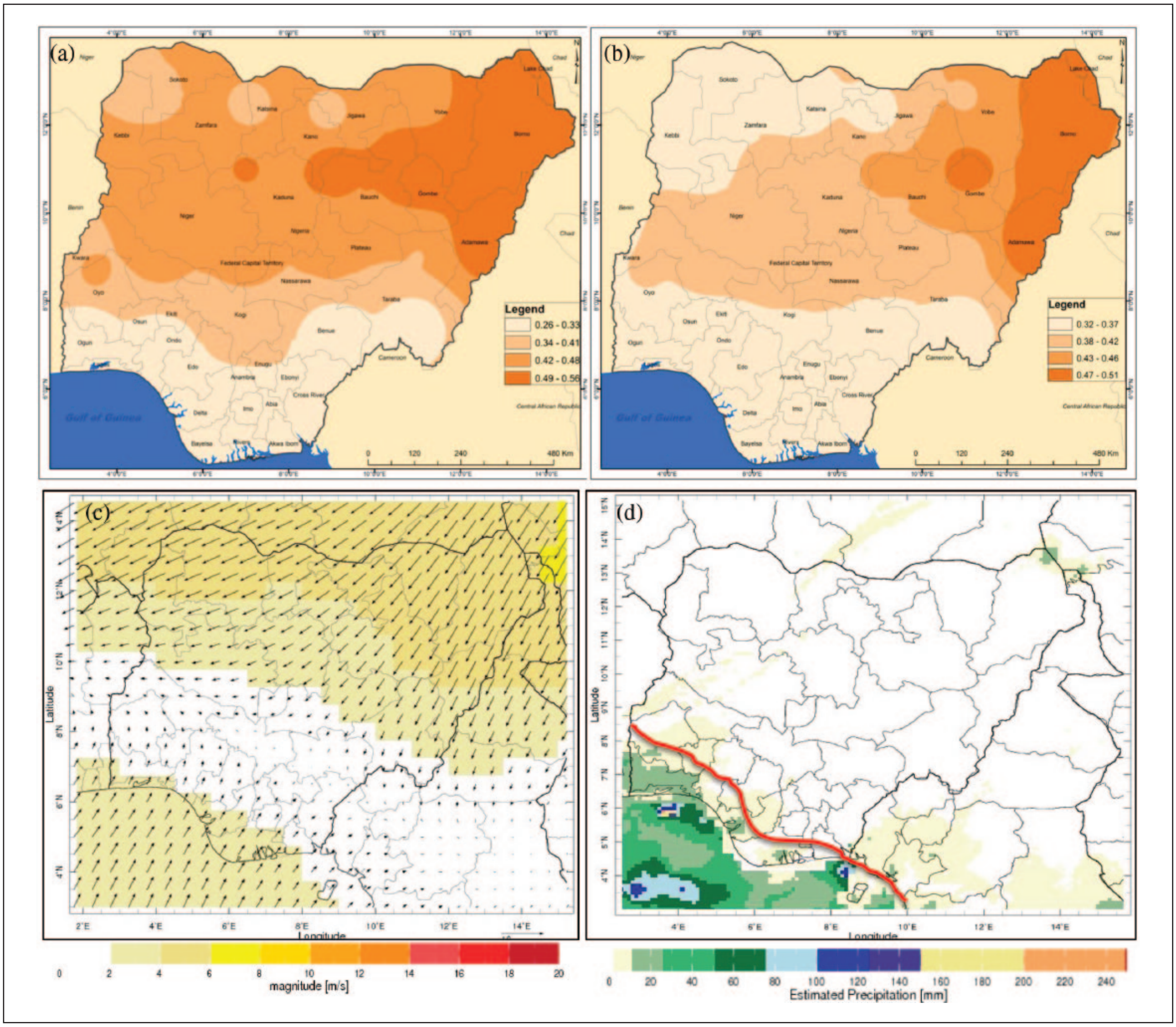

Figure 8. Variations in atmospheric aerosol distributions during Harmattan season: (a)the mean AOD during the Harmattan season, (b) mean AOD distribution in the month of December, (c) the magnitude and direction of the wind during Harmattan season and (d) the mean precipitation/ITD during the months of December.

magnitude (Figure 8). During these months, much of atmospheric dusts are results of windblown dust from the Sahara desert that covers the entire country. The scenarios during the Wet season (Figure 7) are as a result of the prevalent flow of the mT air mass from the Atlantic Ocean over the movement of the cT air mass (Ogunjobi et al., 2008).

ITD movement effects on the AOD distribution

Table 2 shows the relationship between atmospheric aerosol distribution, wind and precipitation/ITD over different ecological zones in the study area. In general, the results show significant positive correlation in all ecological zones, with the highest correlation value $r^2=0.71@$ $p=0.05$ observed during the Harmattan season around the Guinea ecological zone. However, lowest correlation value $r^2=0.21@$ $p=0.05$ (Table 2) was observed during Wet seasons around the Freshwater ecological zone and this could imply that the zone is characterized by high wash out of dust deposition by precipitation, and the prevalent southwesterly trade wind over the northeasterly trade wind. These values reveal the influence of ITD on atmospheric aerosol distribution, as the prevalent northeasterly trade wind blows dust from the Sahara desert to the coastal areas (Table 2).

In Sahel ecological zone, the result shows significant moderate correlation $r^2=0.53@$ $p=0.05$ during Dry seasons; this could imply that the zone is characterized by the absence of precipitation, and the presence of prevalent northeasterly trade wind, blowing Saharan dust to the

Table 2. Correlation summary for AOD, wind and precipitation/ITD data of Nigeria.

Ecological zone	Wet season	Dry season	Harmattan season
Sahel	0.40**	0.53**	0.49**
Sudan	0.31	0.62**	0.62**
Guinea	0.34	0.62**	0.71**
Rainforest	0.31	0.42**	0.61**
Freshwater	0.21	0.31	0.68**
Mangrove	0.31	0.22	0.52**

AOD: aerosol optical depth; ITD: intertropical discontinuity.
**Significant at $p < 0.05$.

coastal areas. In Sudan ecological zone as well, the relationship is a relatively strong one with correlation $r^2=0.62$ @ $p=0.05$ mostly during Dry and Harmattan seasons, but relatively low correlation $r^2=0.31$@ $p=0.05$ during Wet season. The reason for this low correlation results is not really clear. This might be a result of relatively low precipitation in this zone compared to southern region, and a significantly huge amount of atmospheric dust blown by the prevalent northeasterly trade wind from the Sahara desert while the Wet season could be characterized by high pressure of southwesterly trade wind (ocean wind) blowing polluted air accumulated from factories.

For Guinea ecological zone, the correlation results show a significantly strong correlation both in Dry season $r^2=0.62$ @ $p=0.05$ and Harmattan seasons $r^2=0.71$ @ $p=0.05$, but very significantly low during the Wet season ($r^2=0.34$). In all, low correlation values are obvious for Freshwater and Mangrove zones in Dry and Wet seasons with $0.21 \leqslant r^2 \geqslant 0.31$. This might be due to the result of the convection transfer of southwesterly trade wind (ocean wind) against the northeasterly trade wind (land wind) rising huge amount of dust and the excessive factories gases into the atmosphere from the zone, while in the Wet season, it might be due to the fact that there was high precipitation (wash out) recorded in the zone. In the Harmattan season, most of the aerosols originate from the Sahara and reaching the coastal part of the study area during December and January.

Discussion

Generally, three major findings are obvious from this study. First, there appears to be a significant monthly variation in the distribution of AOD over Nigeria, but the intensity appears considerably more during Harmattan season than Wet and Dry seasons. The results also show that the relationship between AOD and ITD vary over different ecological zones but much more so in Sahel ecological zone. Largely, over the study area, the atmospheric aerosol was highest in the months of Harmattan and Dry seasons, but lowest during the months of Wet seasons. These results imply that Harmattan blows most of the dust from the Sahara, during a period when subtropical ridge of high pressure stays over the central Sahara desert and the low-pressure ITCZ stays over the Gulf of Guinea. Thus, Harmattan covers entire Nigeria, with fine dust and sand particles composition picked as it moves over the Sahara. Other reasons for these scenarios might be because of the diagonal movement of Northeasterly and Southwesterly air masses, resulting from the earth's angular inclination and the Bodélé Depression in Chad (Washington et al., 2006). This is considerably obvious in that, as the Northeasterly air mass travels from the Sahara desert through the Northeastern direction, Southwesterly comes interchangeably from the Atlantic Ocean through the coastal region into Nigeria, and the implication is that both have notable effects on the seasonality of aerosol. Globally, aerosols are spread all over the world; it has nonetheless a strong regional imbalance which generally results in modification of climate through their direct and indirect effects on radiative forces and condensation particles (Akimoto, 2003). Accordingly, the geographical location of Nigeria in the sub-Saharan West Africa makes aerosol pollution a familiar phenomenon which its concentrations exhibit strong seasonal variability, mainly driven by seasonally changed air mass patterns during Harmattan, Dry (November–March) and wet (April–October) seasons.

An increase in the correlation values during the Harmattan season, as observed in this study, could thus be related to low precipitation during this period (Anuforom et al., 2007; Balarabe et al., 2015; Middleton and Goudie, 2001; Pinker et al., 1994). Earlier studies have reported Sahara-Sahel region as one of the major dust sources to the countries neighbouring the Gulf of Guinea (Kim et al., 2017; Moreno et al., 2006; Mulitza et al., 2010). On the other hand, the larger amount of aerosol in Nigeria is not only influenced by the Bodélé Depression area (Anuforom et al., 2007; Washington et al., 2006) but also influenced by the Harmattan wind, as it raises much of the aerosols while ITD determines their seasonality. The study by Kim et al. (2017) further noted the role of surface wind and vegetation cover in multi-decadal variations of dust emission in the Sahara and Sahel and their findings suggest Saharan-Sahelian winds system as the main driver of inter-annual variation of dust emission. However, the influence of the ITD on Harmattan dust deposition has been observed by Lyngsie et al. (2013) in Ghana and their result revealed various effects of ITD on dust deposition during the Harmattan period. The major difference between their findings and that of this study is that Lyngsie et al. (2013) only examined the dust deposition during the Harmattan without considering the variation in the AOD over different seasons of the year, which is the major contribution of this study. However, the results from this study revealed the influence of ITD on seasonality of

AOD, on a continuous basis. Previous studies have shown that aerosols are being dispersed and distributed in the atmosphere by turbulence movement of air masses, but are being removed from the atmosphere by ice, dew and precipitation as well as dry sedimentation (Jones and Harrison, 2004).

The findings from this study further suggest that the satellite-based observations of atmospheric aerosols have merits for a better understanding of aerosols concentration both on local and regional scales (Chew et al., 2016; Ten Hoeve and Augustine, 2016). Aerosols have been seen as environmental pollution issues in many developed countries of the world for a very long time. However, until now, Nigeria has not devoted the required attention to this issue, only on a local scale, as local municipal sanitation matters. The lack of environmental pollution awareness in Nigeria for so long could be ascribed principally to ignorance on the part of policymakers as well as the general citizenry in whose perceptions pollution was thought to arise from manufacturing industries alone (Eti et al., 2006). In the last few decades, however, environmental protection is now being enforced by the various national and state environmental protection agencies (Oforibika et al., 2018).

Studies have shown that aerosol has impacts on visibility. Looking at the recent rapid growth of urbanization and industrialization in different parts of the world including Nigeria, visibility degradation has become an important urban atmospheric environmental problem. The reduction in visibility has been caused by the scattering and absorption of solar radiation of particles and gaseous pollutants released into the atmosphere (Cohen, 2006). Despite that aerosols are very imperative in atmospheric radiation transmission, their mass is less than 1 billion of the total atmospheric mass. In local scale levels, urban aerosol not only has impact on extinction of solar radiation but also has an effect on atmospheric long-wave radiation, which is a key driver of the local energy balance of a place (Han et al., 2012). Consequently, there are considerable relation between visibility, solar radiation, wind speed and dust deposition, which were considerably stated in McTainsh (1980). Aerosol has impact not only on visibility and physical environment, but it has many impacts also on human health. A study by Kim et al. (2015) reviewed evidence of the impacts of airborne particulate matter on the human health. The major finding from this study revealed that particulate matter in the atmospheric aerosol can cause noticeable illnesses and lead to reduction of human life in the long term since many of this particulate matter can be suspended and travel distances over a long time in the atmosphere. There is a need, therefore, for effective control and appropriate policy for more stringent strategies in order to reduce air pollution effects on human health (Kim et al., 2015; Mateos et al., 2018; Valavanidis et al., 2008; Wu et al., 2017). Although not all of these aerosols are originated from Sahara desert, biomass-burning activities frequently occur in the study area which usually produces smoke that is also transported westward into the Atlantic region of the study area (Christopher and Jones, 2010; Mulitza et al., 2010). The findings by Mulitza et al. (2010) have further suggested that, for about 200 years, human-induced dust emissions from the Sahel region have contributed to the atmospheric dust load. Again, this present study has contributed to the research knowledge, on the seasonality in atmospheric aerosol distributions over Nigeria, as well as the nature of spatial patterns of aerosols. The findings from this study provide further evidence to enhance the understanding of the influence of wind and precipitation/ITD on the seasonal variations in AOD.

Conclusion

The study aimed at examining the seasonal distribution of atmospheric aerosols over Nigeria over the period of 2001–2017, using Dark Target MODIS AOD data. Both geospatial and correlation analyses were performed to show spatial and temporal variations in atmospheric aerosols and the influences of ITD over the period of study. For this study, AOD of less than 0.1 indicates a crystal clear sky with maximum visibility, whereas the higher AOD induces significant visibility reduction. The major finding of this study is that the atmospheric aerosol distributions vary over time and space, but there appears to be significance in monthly variations. In terms of the seasonality of atmospheric aerosols, the seasonal variation is much higher during Harmattan season than Wet and Dry seasons, though, highly concentrated in the northern part of the study area, which is the source region. Furthermore, one of the major findings is that the relationship between AOD and ITD varies over different ecological zones but appears much more significant in Sahel ecological zone compared to other ecological zones. What is obvious from this study is that ITD plays a significant role in seasonality of AOD and that the migration of ITD is fundamental to the understanding of atmospheric aerosols distribution.

Seasonal shifts in the location of the ITD considerably affect not only rainfall distribution, resulting in the Wet and Dry seasons in the study area, but also have significant impacts on atmospheric aerosols distribution. ITD typically reaches its maximum northward extent of the study area during the months of July and August and its maximum southward extends in the months of December and January every year. The major findings from this study are that the least AOD values in the southern part of the study area during the months of July and August might be the results of the fact that ITD reaches its maximum northward extend during this period, with very low atmospheric aerosols in the southern part. At the peak of Harmattan season, in December and January, the mean position of ITD is genially far south of the study area reflecting the southern movement of wind and pressure, and atmospheric aerosols cover the whole country at this time of the year. The results from this study imply that the Sahara is certainly the largest source of windblown dust aerosols, but the influence of ITD is apparent as the Bodélé Depression in Chad is the largest source of dust in the region and source of most dust over Nigeria.

Acknowledgements

The authors thank NOAA Climate Diagnostics Center and NASA Langley Research Center for providing satellite data used in this study. Thanks to the International Research Institute for Climate and Society (IRI), New York, USA, for providing the initial training on satellite data acquisition and climate data analysis.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Ayansina Ayanlade https://orcid.org/0000-0001-5419-5980

References

Akimoto H (2003) Global air quality and pollution. *Science* 302: 1716–1719.

Amiri-Farahani A, Allen RJ, Neubauer D, et al. (2017) Impact of Saharan dust on North Atlantic marine stratocumulus clouds: Importance of the semidirect effect. *Atmospheric Chemistry and Physics* 17: 6305–6322.

Anuforom A, Akeh L, Okeke P, et al. (2007) Inter-annual variability and long-term trend of UV-absorbing aerosols during Harmattan season in sub-Saharan West Africa. *Atmospheric Environment* 41: 1550–1559.

Arnalds O, Thorarinsdottir EF, Thorsson J, et al. (2013) An extreme wind erosion event of the fresh Eyjafjallajökull 2010 volcanic ash. *Scientific Reports* 3: 1257.

Ayanlade A (2009) Seasonal rainfall variability in Guinea Savanna part of Nigeria: A GIS approach. *International Journal of Climate Change Strategies and Management* 1: 282–296.

Ayanlade A (2017) Variations in urban surface temperature: An assessment of land use change impacts over Lagos metropolis. *Weather* 72: 315–319.

Ayanlade A and Oyegbade EF (2016) Influences of wind speed and direction on atmospheric particle concentrations and industrially induced noise. *Springerplus* 5: 1898.

Balarabe M, Abdullah K and Nawawi M (2015) Seasonal variations of aerosol optical properties and identification of different aerosol types based on AERONET data over sub-Sahara West-Africa. *Atmospheric and Climate Sciences* 6: 13–28.

Baumbach G (2012) *Air Quality Control: Formation and Sources, Dispersion, Characteristics and Impact of Air Pollutants – Measuring Methods, Techniques for Reduction of Emissions and Regulations for Air Quality Control*. Berlin: Springer Science & Business Media.

Beck HE, Van Dijk AI, Levizzani V, et al. (2017) MSWEP: 3-hourly 0.25 global gridded precipitation (1979-2015) by merging gauge, satellite, and reanalysis data. *Hydrology and Earth System Sciences* 21: 589–615.

Bello N (1998) Evidence of climate change based on rainfall records in Nigeria. *Weather* 53: 412–418.

Birmili W, Berresheim H, Plass-Dülmer C, et al. (2003) The Hohenpeissenberg aerosol formation experiment (HAFEX): A long-term study including size-resolved aerosol, H_2SO_4, OH, and monoterpenes measurements. *Atmospheric Chemistry and Physics* 3: 361–376.

Bodansky D (1999) The legitimacy of international governance: A coming challenge for international environmental law? *American Journal of International Law* 93: 596–624.

Bonan G (2015) *Ecological Climatology: Concepts and Applications*. Cambridge: Cambridge University Press.

Bran SH, Jose S and Srivastava R (2018) Investigation of optical and radiative properties of aerosols during an intense dust storm: A regional climate modeling approach. *Journal of Atmospheric and Solar-Terrestrial Physics* 168: 21–31.

Brindley H, Osipov S, Bantges R, et al. (2015) An assessment of the quality of aerosol retrievals over the Red Sea and evaluation of the climatological cloud-free dust direct radiative effect in the region. *Journal of Geophysical Research: Atmospheres* 120: 10862–10878.

Butwin M, Pfeffer M, Von Löwis S, et al. (2018) Frequency and characteristics of volcanic ash and dust suspension events in Iceland. In: *Proceedings of the EGU general assembly conference abstracts*, Vienna, Austria, 8–13 April, pp. 18300. Boston, MA: AMS.

Chew BN, Campbell J, Hyer EJ, et al. (2016) Relationship between aerosol optical depth and particulate matter over Singapore: Effects of aerosol vertical distributions. *Aerosol and Air Quality Research* 16: 2818–2830.

Christopher SA and Jones TA (2010) Satellite and surface-based remote sensing of Saharan dust aerosols. *Remote Sensing of Environment* 114: 1002–1007.

Chu D, Kaufman Y, Ichoku C, et al. (2002) Validation of MODIS aerosol optical depth retrieval over land. *Geophysical Research Letters* 29: MOD2–1–MOD2–4.

Cohen B (2006) Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability. *Technology in Society* 28: 63–80.

Commission NNP and Macro O (2000) *Nigeria Demographic and Health Survey, 1999*. Abuja, Nigeria: National Population Commission

Demott PJ, Sassen K, Poellot MR, et al. (2003) African dust aerosols as atmospheric ice nuclei. *Geophysical Research Letters*. Epub ahead of print 17 July. DOI: 10.1029/2003GL017410.

Dey S and Tripathi SN (2013) Remote sensing of atmospheric aerosols. In: Colbeck I and Lazaridis L (eds) *Aerosol Science: Technology and Applications*. New York: Wiley, pp. 119–151.

Dinku T, Connor SJ and Ceccato P (2010) Comparison of CMORPH and TRMM-3B42 over mountainous regions of Africa and South America. In: Gebremichael M and Hossain F (eds) *Satellite Rainfall Applications for Surface Hydrology*. New York: Springer, pp. 193–204.

Duncan BN, Martin RV, Staudt AC, et al. (2003) Interannual and seasonal variability of biomass burning emissions constrained by satellite observations. *Journal of Geophysical Research: Atmospheres* 108: ACH 1–1–ACH 1–22.

Eaton JP (1997) The Nigerian tragedy, environmental regulation of transnational corporations, and the human right to a healthy environment. *Boston University International Law Journal* 15: 261–571.

Eneh OC (2011) Managing Nigeria's environment: The unresolved issues. *Journal of Environmental Science & Technology* 4: 250–263.

Eti MC, Ogaji S and Probert S (2006) Strategic maintenance-management in Nigerian industries. *Applied Energy* 83: 211–227.

Giglio L (2007) Characterization of the tropical diurnal fire cycle using VIRS and MODIS observations. *Remote Sensing of Environment* 108: 407–421.

Gupta P, Remer LA, Levy RC, et al. (2018) Validation of MODIS 3 km land aerosol optical depth from NASA's EOS Terra and Aqua missions. *Atmospheric Measurement Techniques* 11: 3145–3159.

Han S, Bian H, Zhang Y, et al. (2012) Effect of aerosols on visibility and radiation in spring 2009 in Tianjin, China. *Aerosol and Air Quality Research* 12: 211–217.

Herman J, Bhartia P, Torres O, et al. (1997) Global distribution of UV-absorbing aerosols from Nimbus 7/TOMS data. *Journal of Geophysical Research: Atmospheres* 102: 16911–16922.

Hidy GM and Brock JR (2016) *The Dynamics of Aerocolloidal Systems: International Reviews in Aerosol Physics and Chemistry*. Amsterdam: Elsevier.

Hirpa FA, Gebremichael M and Hopson T (2010) Evaluation of high-resolution satellite precipitation products over very complex terrain in Ethiopia. *Journal of Applied Meteorology and Climatology* 49: 1044–1051.

Jamaludin AR, Yusof F, Kane IL, et al. (2016) A comparative study between conventional ARMA and Fourier ARMA in modeling and forecasting wind speed data. In: *Proceedings of the AIP conference*, 21 June 2016, pp. 060022. Melville, NY: AIP Publishing.

Jones AM and Harrison RM (2004) The effects of meteorological factors on atmospheric bioaerosol concentrations – A review. *Science of the Total Environment* 326: 151–180.

Kim D, Chin M, Remer LA, et al. (2017) Role of surface wind and vegetation cover in multi-decadal variations of dust emission in the Sahara and Sahel. *Atmospheric Environment* 148: 282–296.

Kim K-H, Kabir E and Kabir S (2015) A review on the human health impact of airborne particulate matter. *Environment International* 74: 136–143.

King MD, Byrne DM, Herman BM, et al. (1978) Aerosol size distributions obtained by inversions of spectral optical depth measurements. *Journal of the Atmospheric Sciences* 35: 2153–2167.

Kolb C, Cox R, Abbatt J, et al. (2010) An overview of current issues in the uptake of atmospheric trace gases by aerosols and clouds. *Atmospheric Chemistry and Physics* 10: 10561–10605.

Levy R, Mattoo S, Munchak L, et al. (2013) The collection 6 MODIS aerosol products over land and ocean. *Atmospheric Measurement Techniques* 6: 2989–3034.

Li C, Lau A-H, Mao J, et al. (2005) Retrieval, validation, and application of the 1-km aerosol optical depth from MODIS measurements over Hong Kong. *IEEE Transactions on Geoscience and Remote Sensing* 43: 2650–2658.

Li Z, Zhang Y, Shao J, et al. (2016) Remote sensing of atmospheric particulate mass of dry PM2. 5 near the ground: Method validation using ground-based measurements. *Remote Sensing of Environment* 173: 59–68.

Lyngsie G, Olsen JL, Awadzi T, et al. (2013) Influence of the inter tropical discontinuity on Harmattan dust deposition in Ghana. *Geochemistry, Geophysics, Geosystems* 14: 3425–3435.

Mctainsh G (1980) Harmattan dust deposition in northern Nigeria. *Nature* 286: 587–588.

Mateos A, Amarillo A, Carreras H, et al. (2018) Land use and air quality in urban environments: Human health risk assessment due to inhalation of airborne particles. *Environmental Research* 161: 370–380.

Mhawish A, Banerjee T, Broday DM, et al. (2017) Evaluation of MODIS Collection 6 aerosol retrieval algorithms over Indo-Gangetic Plain: Implications of aerosols types and mass loading. *Remote Sensing of Environment* 201: 297–313.

Mhawish A, Kumar M, Mishra AK, et al. (2018) Remote sensing of aerosols from space: Retrieval of properties and applications. In: Islam T, Hu Y, Kokhanovsky AA, et al. (eds) *Remote Sensing of Aerosols, Clouds, and Precipitation*. Amsterdam: Elsevier, pp. 45–83.

Middleton N (2017) Desert dust hazards: A global review. *Aeolian Research* 24: 53–63.

Middleton N and Goudie A (2001) Saharan dust: Sources and trajectories. *Transactions of the Institute of British Geographers* 26: 165–181.

Moreno T, Querol X, Castillo S, et al. (2006) Geochemical variations in aeolian mineral particles from the Sahara–Sahel Dust Corridor. *Chemosphere* 65: 261–270.

Mulitza S, Heslop D, Pittauerova D, et al. (2010) Increase in African dust flux at the onset of commercial agriculture in the Sahel region. *Nature* 466: 226–228.

Oforibika AG, Alalibo IK and Solomon L (2018) Environmental pollution and reportage in Nigeria. *World Rural Observation* 10: 75–77.

Ogunjobi K, He Z and Simmer C (2008) Spectral aerosol optical properties from AERONET sun-photometric measurements over West Africa. *Atmospheric Research* 88: 89–107.

Ologunorisa T and Tamuno T (2003) Spatial and seasonal variations of sandstorms over Nigeria. *Theoretical and Applied Climatology* 75: 55–63.

Omotosho JB and Abiodun BJ (2007) A numerical study of moisture build-up and rainfall over West Africa. *Meteorological Applications* 14: 209–225.

O'Riordan T (1989) The challenge for environmentalism. *New Models in Geography* 1: 77–102.

Peacock KW (2008) *Natural Resources and Sustainable Development*. New York: Infobase Publishing.

Péré J-C, Rivellini L, Crumeyrolle S, et al. (2018) Simulation of African dust properties and radiative effects during the 2015 SHADOW campaign in Senegal. *Atmospheric Research* 199: 14–28.

Pinker RT, Idemudia G and Aro TO (1994) Characteristic aerosol optical depths during the Harmattan Season on sub-Sahara Africa. *Geophysical Research Letters* 21: 685–688.

Prospero JM, Collard FX, Molinié J, et al. (2014) Characterizing the annual cycle of African dust transport to the Caribbean Basin and South America and its impact on the environment and air quality. *Global Biogeochemical Cycles* 28: 757–773.

Purkis SJ and Klemas VV (2011) *Remote Sensing and Global Environmental Change*. Hoboken, NJ: John Wiley & Sons

Ravindra K, Sokhi R and Van Grieken R (2008) Atmospheric polycyclic aromatic hydrocarbons: Source attribution, emission factors and regulation. *Atmospheric Environment* 42: 2895–2921.

Reynolds RL, Urban F, Goldstein HL, et al. (2017) Measuring dust emission from the Mojave desert (USA) by daily remote-camera observations and wind-erosion measurements: Bearing on 'Unseen' sources and global dust abundance. In: *Proceedings of the AGU fall meeting abstracts*, Washington, DC, 10–14 December.

Scerri MM, Kandler K and Weinbruch S (2016) Disentangling the contribution of Saharan dust and marine aerosol to PM10 levels in the Central Mediterranean. *Atmospheric Environment* 147: 395–408.

Schepanski K, Heinold B and Tegen I (2017) Harmattan, Saharan heat low, and West African monsoon circulation: Modulations on the Saharan dust outflow towards the North Atlantic. *Atmospheric Chemistry and Physics* 17: 10223–10243.

Strong JD, Vecchi GA and Ginoux P (2015) The response of the tropical Atlantic and West African climate to Saharan dust in a fully coupled GCM. *Journal of Climate* 28: 7071–7092.

Tegen I, Hollrig P, Chin M, et al. (1997) Contribution of different aerosol species to the global aerosol extinction optical thickness: Estimates from model results. *Journal of Geophysical Research: Atmospheres* 102: 23895–23915.

Ten Hoeve JE and Augustine JA (2016) Aerosol effects on cloud cover as evidenced by ground-based and space-based observations at five rural sites in the United States. *Geophysical Research Letters* 43: 793–801.

Valavanidis A, Fiotakis K and Vlachogianni T (2008) Airborne particulate matter and human health: Toxicological assessment and importance of size and composition of particles for oxidative damage and carcinogenic mechanisms. *Journal of Environmental Science and Health, Part C* 26: 339–362.

Valiela I, Bowen JL and York JK (2001) Mangrove forests: One of the World's threatened major tropical environments: At least 35% of the area of mangrove forests has been lost in the past two decades, losses that exceed those for tropical rain forests and coral reefs, two other well-known threatened environments. *Bioscience* 51: 807–815.

Washington R, Todd MC, Engelstaedter S, et al. (2006) Dust and the low-level circulation over the bodélé depression, Chad: Observations from BoDEx 2005. *Journal of Geophysical Research: Atmospheres* 111: D03201.

Wiegner M, Madonna F, Binietoglou I, et al. (2014) What is the benefit of ceilometers for aerosol remote sensing? An answer from EARLINET. *Atmospheric Measurement Techniques* 7: 1979–1997.

Wu C-F, Woodward A, Li Y-R, et al. (2017) Regulation of fine particulate matter (PM2. 5) in the Pacific Rim: Perspectives from the APRU global health program. *Air Quality, Atmosphere & Health* 10: 1039–1049.

Zhang J and Christopher SA (2003) Longwave radiative forcing of Saharan dust aerosols estimated from MODIS, MISR, and CERES observations on Terra. *Geophysical Research Letters* 30: 1–3.

Zhang X, Wang Y, Niu T, et al. (2012) Atmospheric aerosol compositions in China: Spatial/temporal variability, chemical signature, regional haze distribution and comparisons with global aerosols. *Atmospheric Chemistry and Physics* 12: 779–799.

Zhou Q, Li J, Xu J, et al. (2018) First long-term detection of paleo-oceanic signature of dust aerosol at the southern marginal area of the Taklimakan Desert. *Scientific Reports* 8: 6779.

Author biographies

Ayansina Ayanlade is a researcher and lecturer in the Department of Geography, Obafemi Awolowo University, Ile-Ife, Nigeria. He earned his PhD from King's College London, University of London, UK. His research areas of interest are Applied Climatology with specific interest in land-climate processes, climate change studies, and application of remote sensing and GIS to land-atmospheric interactions.

Godwin Atai is a graduate student in the Department of Geography, Obafemi Awolowo University, Ile-Ife, Nigeria. His work mainly involves application of remote sensing (RS) and GIS in atmospheric studies, supervised by Dr Ayanlade.

Margaret Olusolape Jegede is a researcher and lecturer in the African Institute for Science Policy and Innovation (AISPI), Obafemi Awolowo University, Ile-Ife, Nigeria. Her research interests are Environmental Science Policy and Innovation.