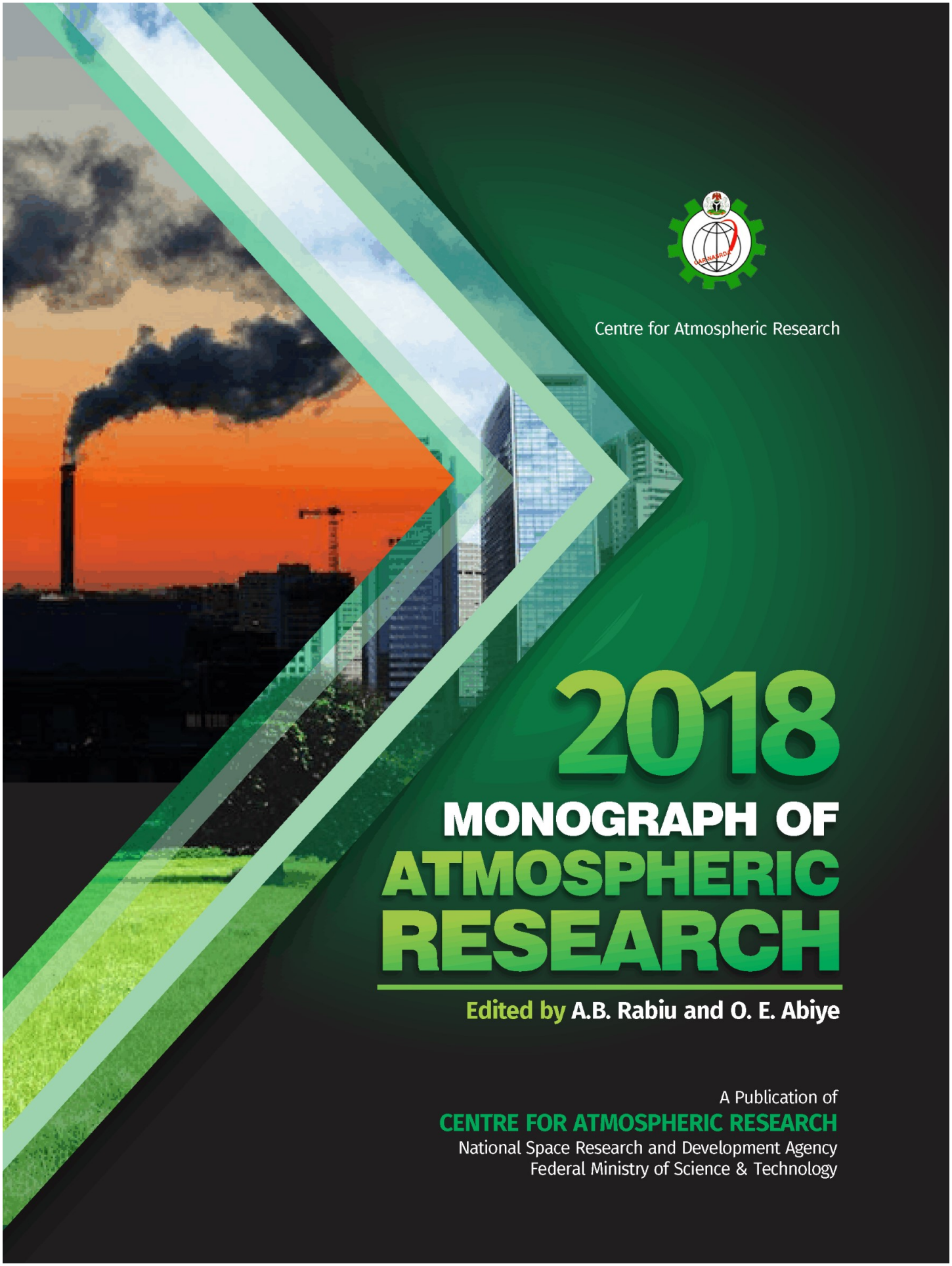

Centre for Atmospheric Research

2018 MONOGRAPH OF ATMOSPHERIC RESEARCH

Edited by A.B. Rabiu and O. E. Abiye

A Publication of
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PREFACE

The Centre for Atmospheric Research was established in January 2013 with a compelling mission to improve our understanding of the behaviour of the entire spectrum of the Earth's atmosphere; promote capacity development in relevant atmospheric sciences as a way of facilitating international competitiveness in research being conducted by atmospheric scientists; and disseminate atmospheric data/products to users towards socio-economic development of the Nation. CAR's extant core research focus includes: space weather, tropospheric studies, atmospheric research software and instrumentation development, microgravity and human space technology, and atmospheric chemistry and environmental research.

Pursuant to the above, The *Monograph of Atmospheric Research* published by the Centre for Atmospheric Research (CAR), is a collection of peer-reviewed manuscripts in Atmospheric Sciences and closely related fields. This maiden edition comprises articles presented during two separate workshops; *1st National Workshop on Microgravity and Environmental Research* (26 - 29 November, 2017) and *1st National Workshop on Air Quality* (13 - 16 March, 2018). Such workshops are integral part of CAR's capacity building program and they were primarily aimed at advancing the course of atmospheric research in Nigeria towards sustainable development. The Microgravity workshop was geared towards introducing new research opportunities in space life science by simulating microgravity conditions here at the earth's surface as a means of investigation space biological environment. The Air Quality workshop was organized in collaboration with Ministry of Environment and Nigerian Meteorological Agency (NIMET). The workshop analysed current Air Quality scenario in Nigeria, explored new opportunities for collaborative research and offered novel means of improving the present quality of life of the populace without jeopardizing the chance of the future generation. Cumulatively 196 participants participated in these two workshops and about 52 articles were eventually submitted for publication consideration in this monograph. The twenty-one articles in this very monograph are the articles that eventually made it through the rigorous peer-review process. We remain grateful to the reviewers for doing thorough work on the articles.

Thus, we are very pleased to present the *2018 Monograph of Atmospheric Research* which contains twenty-one articles, including some review papers, to readers in all spheres of interest across Nigeria and beyond. It is our hope that this effort will continue and will serve as a reference to atmospheric researchers in Nigeria.

Prof. A. B. Rabiu and Dr. O. E. Abiye,
Editors

Centre for Atmospheric Research

Monitoring and estimation of aerosols and air pollutants relations using multi-sensor satellite and ground remote sensing over Ilorin a sub-sahel

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ABSTRACT

The increased aerosol concentrations in regional and global scale are largely due to formation of secondary particles that may be from both natural and anthropogenic origin. Its effects on the earth atmosphere can be investigated through study of its properties such as aerosol optical depth (AOD), angstrom exponent (α) and atmospheric turbidity ($^{\beta}$) under different atmospheric conditions. In this study, AOD, α and $^{\beta}$ measurements made from Cimel Sun-photometer along with gaseous pollutants (NO_2, CO, SO_2, O_3) measurements from Satellites sensors and the concurrent prevailing meteorological conditions data obtained from Nigeria Meteorological Agency (NiMET) over Ilorin are reported for eleven year period 2005 to 2015. Comparison of MODIS (Terra + Aqua) AOD data with sun-photometer AOD for the Sub-Sahel region seasonal variations gave R value of 0.77 showing good linear agreement between the two sources. Lowest value of turbidity coefficient (0.09) occur during the peak of the rainy season with highest clarity when dust aerosol is minimal hence dust is major contributor to atmospheric turbidity in the region with highest value (0.89) in the dry season. When one to one Pearson correlation was done on the variables, the parameters showed good correlation except with ozone concentration. The role of five meteorological parameters (Temperature (T), Relative humidity (RH), Rainfall (RF), Wind speed (Ws) and Solar radiation (SR)) on the relationships gave enhanced correlation between aerosol properties and Ozone concentration. Reductions in correlations were observed with other pollutants except NO_2 in the warm dry season. Regression model was employed using AOD as the dependent variable and other variables as independent so as to be able to predict correctly the AOD over the region. The result show a good model prediction ($r^2 = 0.97$). Seasonal sensitivity was also tested on the aerosol properties and pollutants correlations. It shows good correlations in moderate RH condition with the exception of aerosol properties-CO relations which are poor.

Keywords: Aerosol Optical Depth, Air pollutant, Meteorological Parameters, Turbidity, Satellite Sensor

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INTRODUCTION

Climate change and increasing level of atmospheric pollutants have made the studies of the atmosphere, atmospheric dispersion of air pollution and its interaction with atmospheric radiation becoming increasingly important (Marje, 2008). Interaction of atmospheric constituents with solar radition during their stay in the atmosphere causes atmospheric turbidity. Concentrations of carbon dioxide, methane, carbon monoxide and nitrous oxide have been on increase as a result of fossil fuels combustion, biogenic emissions associated with a rising human population and other human activities (IPCC, 2013). Particulate scattering is the most important solar radiation attenuation process in polluted air, followed by particulate absorption, gas absorption and gas scattering in descending order. Particle absorption is important only if elemental carbon is present and gas absorption only when nitrogen dioxide concentrations are high. The greenhouse gases are transparent to solar radiation but absorb in the Infrared spectrum. The radiative properties of gases can depend on temperature and pressure, which can cause the widening of absorption lines (*Jackobson, 1999*). Also, ozone at ground level can, at elevated concentrations, lead to respiratory effects in humans and vegetation damage (Seinfeld and Pandis, 1998).

The link between respiratory ailments and pollutant concentrations is the major reason for detailed studies of aerosol particles and trace gases (*Binaku et al., 2013*). Tropospheric aerosols may contain sulphate, ammonium, nitrate, sodium chloride, trace metals, carbonaceous material, crustal elements, and water. The carbonaceous fraction of aerosols consists of both elemental and organic carbon with the former been the strongest particulate absorber. There are many other effects of aerosol and pollutants to human, environment and atmosphere such as fine particulate matter ($PM_{2.5}$) ability to penetrate deeper into the lungs and cause health damages such as lung cancer and cardiopulmonary mortality (Dockery and Pope, 1994).

So, it is necessary to fully describe the relations between concentration of aerosol particles, simultaneously measured concentrations of gaseous pollutants and meteorological parameters over a localized region since variations in aerosol constituents and local meteorological conditions have significant impacts on determining the magnitudes of such relations. The limited number of air quality measuring equipment and studies of such on the atmospheric optical properties of aerosols in Nigeria leaves a gap that is worth investigating. Though, some studies had investigated the variation and spread of aerosols and pollutants in some Nigeria cities using satellite data. Onyeuwaoma et al., (2015) used MODIS (AOD) and AIRS (CO) data to study the loading pattern of aerosols across some selected Nigeria cities. Also, the radiative properties of dust and

biomass burning based aerosols had been investigated over sub-sahel Africa by Pinker et al. (2010) and the effects of aerosol loading on visibility in Ilorin had been study by *Adimula, et al. (2008)*.

The mineralogy characteristics of hamattan dust in Ilorin and Ife had been investigated and major mineral composition had been analysed by *Falaiye, et al. (2013)* . Using satellite observation data of aerosols and pollutants in Africa is an efficient way to determine and distinguish their spread, impacts and relation over a long period as it provides more complete coverage over longer time scales and space in place of in situ measurements that is not available. Ground-based and satellite sensing of air pollutants may show different, but complementary characteristics; however, both are important in different situations, as well as for cross validation of the pollution origin (*Park et al., 2015*).

The main purpose of the present work is to study the effects and relationship between concurrently measured meteorological parameters (T, RH, RF, Ws and SR) and aerosol properties (AOD, α and $^{\beta}$) along with air pollutants concentrations (NO_2, CO, SO_2, O_3) to be able to identify the sources and impact of pollutant in the region. Multivariate statistical techniques are applied to the atmospheric data to reduce data dimensions as well as aid in determining natural and anthropogenic sources of air pollutants.

MATERIALS AND METHODOLOGY

Study Area

Ilorin (4.3°E 8.3°N) is a north central city of Nigeria with roughly 1 million residents and Kwara state as a whole comprises of about 4 million residents (*NPC, 2015*). Many interstate highways link the city area to other states in the region, one mega highway linking south to north of Nigeria and a mid-international Airport. Major point sources of aerosol in Ilorin include metal processing, paints, pharmaceuticals, matrass and flour mills factories. Emissions from mobile sources and mentioned points contribute to the atmospheric pollution signature of the region in addition to the other sources such as biomass burning, firewood burning, charcoal processing and dust invasion. The primary composition of particulate matter in this sub-Sahel region is dust and organic carbon species (*Pinker et al., 2010*). Regional transport of pollutants from both north and south also contributes to the local atmospheric aerosol loading of Ilorin as it has been investigated by *Haywood et al. (2008)*.

Measurement Techniques

Aerosol Robotics Network (AERONET)

The AERONET is a network of ground-based Sun-Sky Radiometers that measure sky radiances (Almucantar and Principal plane scan) and aerosol optical depth at multiple wavelengths (340 – 1640 nm) (Holben et al., 1998). Both AOD and almucantar measurements in four selected spectral bands are considered as basic set of ground-based observations. The accuracy of the AERONET aerosol optical depth measurements is + 0.01 to ± 0.02 for the wavelength ⩾ 0.44μm and the uncertainty in measured sky radiances due to calibration error is + 5% (Eck et al., 1999) which is the slope of the logarithm of aerosol optical depth (u03c4a). The details about AERONET could be find elsewhere (*Smirnov et al., 2000*).

Moderate Resolution Imaging Spectro-Radiometer (MODIS)

MODIS observes the globe over Ocean and Land at 2330 km wide swath giving global coverage (*Kaufman et al., 1997; Tanré et al., 1997*). The combination of MODIS on Terra and Aqua at around 10:30 am and 1:30 pm LT equator overpass, respectively, provides complete daily coverage with adequate overlaps (*El-Askary et al., 2015*). The MODIS AOD uncertainty is ±0.05 (±0.15 × AOD) over land and ±0.03 (±0.05 × AOD) over the ocean. The algorithm for aerosol retrieval from MODIS over land is of two types: Dark Target (near infrared spectrum) over dark surfaces (thick vegetated land) with global expected uncertainty of ±(0.05 + 0.15) (*Remer et al., 2005*) and Deep blue algorithm which is applicable to brighter surface (Desert and Arid land) (*Hsu et al., 2004*).

Aura Ozone Monitoring Instruments (OMI)

OMI was launched in July 2004 on NASA's EOS-Aura satellite and is a nadir-viewing spectrometer. It is orbiting at 705 km and crossing the equator in an ascending orbit at around 1:45 pm local time representing day time observation (*Levelt et al., 2006*). OMI's outputs are accurate in arid environment, complement, enhance and elongate the heritage of Total Ozone Mapping Spectrometer (TOMS) data, and contribute to dust source mapping and emission/transport studies (Torres et al., 2007).

Aqua Atmospheric Infrared Sounder (AIRS)

AIRS has been operational since 2002 on NASA's Aqua satellite. It has 2378 channels, covering the spectral range 649–1136, 1217–1613, 2181–2665 cm^{-1}. Each cross track swath consists of 90 pixels, with a footprint of 15 km at nadir (Aumann et al., 2003). AIRS estimates CO using radiative transmittance in the 4.50 to 4.58 μm band from the daytime ascending measurements, crossing an equator at around 1:30 pm from Southern Hemisphere to Northern Hemisphere (*Olsen, 2007*).

Data Acquisition and Method

Eleven year (2005-2015) of aerosol properties and air pollutant data and six year (2005-2010) of meteorology data were used for this study including: level 2.0 AOD from AERONET and MODIS (Terra and Aqua) of MOD08 collection 6 Q3, Angstrom exponent (440-870 nm), derived turbidity from AERONET data, Nitrogen dioxide (NO_2) and Sulphur dioxide (SO_2) column concentration from OMI, Carbon monoxide (CO) and Ozone (O_3), column concentrations from AIRS all of NASA satellite sensors with the meteorological measurements from archives of NiMET. The algorithm adopted for the retrieval of MODIS AOD was combined dark target and deep blue (Land) since Ilorin is neither totally brighter nor fully vegetated covered surface and not surrounded by sea or ocean (*Levy et al., 2013*).

To cover for more time of sampling in the day and gaps in-between swaths of terra ship in the tropical region, terra and aqua pixels retrieved AOD were combined for comparison with AERONET measured AOD. The AERONET AOD at 440 nm was interpolated to 550 nm using Angstrom relation to be able to compare with MODIS AOD that was retrieved at 550 nm. This

is because 550 nm is close to the peak of the solar spectrum and previously used for MODIS validation. The turbidity coefficient possessed the potential information about atmospheric turbidity over the period of study and was calculated according to the Angstrom formula using AOD_{440}, and α at 440-870 nm as shown in equation (1) (*Angstrom, 1964*).

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

where β is the turbidity coefficient, α is the Angstrom exponent and λ is the wavelength. Hence it may also be derived from the intercept of the linear fit of ln AOD against ln λ by introducing natural logarithm to equation (1) above:

$$\ln AOD = \ln\beta - \alpha \ln\lambda \quad (2)$$

The concentration of air pollutant as well as MODIS AOD pixels were retrieved over the study location from the aforementioned satellites' sensors through Goddard Earth Sciences Data and Information Services Centre Interactive Online Visualization ANd ANalysis Infrastructure., (GIOVANNI) from 2005 to 2015. It utilizes a variety of software packages (such as IDL, Panoply, and Python) and analytical functions authored by the GES DISC software development and engineering staff (NASA, 2015).

The measurement of solar radiation was done in millilitres (ml) using gunn bellani radiometer which was converted to MJm^{-2} then to Wm^{-2} with others remained as they were measured. Some of the parameters were averaged into monthly values while others are in monthly amount because meteorological variables are in monthly values. They were co-located both in space and time, gathered in a database for analysis. Comparison of AERONET and MODIS AOD over Ilorin is done to estimate the accuracy of the retrieval method adopted. Seasonal partitioning of the data is done into three: Wet (May – October), Cool Dry (November – January), and Warm Dry (February – April) for seasonal analysis. Furthermore, the role of considered meteorological parameters and RH seasonal sensitivity on the correlation of AOD and above listed air pollutants were analysed by keeping the meteorological parameters as control variables in the correlation analysis. Regression model was adopted using SPSS version 15.0 to predict the AOD in the region using other parameters as input variables.

RESULTS AND DISCUSSION

Comparison of MODIS and AERONET AOD

Figure 1 shows the comparison of AOD at Ilorin between the ground-based (AERONET) and satellite (MODIS) remote sensing techniques. There are 106 monthly samples over the 11 year period. The result shows the coefficient of determination R^2 is 0.60 with R value of 0.77 indicating good linear agreement between the combined MODIS and AERONET AOD. This combined dark target and deep blue retrieval algorithm with terra and aqua MODIS inclusive shows better agreement with AERONET over Ilorin when compared with previous validation study using MOD04 deep blue algorithm alone which gives R value of 0.65. So it is worth validating using the retrieval algorithm adopted in this study.

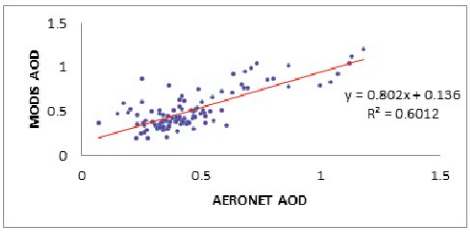


Figure 1: Comparison between monthly MODIS AOD and AERONET AOD over 2005-2015

The seasonal variation of AOD from both measurement techniques follows the same trend rising from January till March before dropping through May to the minimum in July. Except for June and December, MODIS AOD is very close or slightly smaller than AERONET AOD as it is shown in Figure 2 with their standard deviations drawn as error bars. The mean standard deviation is 0.14 for both AODs revealing the closeness of their distribution. The overall slight underestimation of AOD by the retrieval method of MODIS adopted here is consistent with the result by Sani et al. (2017) only in the dry season, which is the peak of aerosol loading of different size distribution thereby causing much hindrances to the surface reflected radiation getting to the satellite sensor.

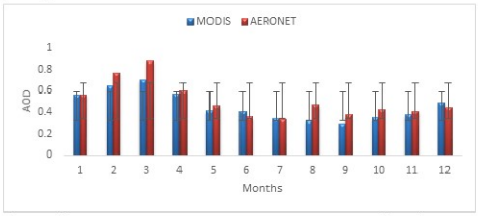


Figure 2: Monthly average values between MODIS (Terra and Aqua) and AERONET AOD

Seasonal Behaviour of Aerosols and Air pollutants over the region

The overall statistical analysis of all the parameters is summarized in Table 1. The AOD_{550}, α and $^{\beta}$ used in this section is that of AERONET. For the period considered, the maximum monthly average AOD is 1.20 which occurred in the warm dry season with the mean value of 0.5 and standard deviation of 0.2.

The maximum alpha value (1.26) recorded during cool dry season shows that the condition of atmosphere is relatively below the mean atmospheric condition (α = 1.3) which provides information on the aerosol number distribution (*Khoshsima et al., 2014*). Dust particle is found to be the major cause of atmospheric turbidity in the region due to the lowest value of turbidity coefficient (0.09) experienced in the wet season while the warm dry season which normally witness dust aerosol invasion at high altitude experienced maximum turbidity (0.89). Also, an exponential dependence of Angstrom Exponent (α) on AOD (R^2=0.51, y = -0.446ln(x) + 0.4627) in the warm dry period support the claim of dust influenced turbidity during the warm dry season as shown in Figure 3 with poor trend in the other two seasons.

Table 1: Statistical Summary of the DaTa

	N	Minimum	Maximum	Mean	Std. eDeviation	SSkewness	Kurtosis
AOD_{550}	106	.18	1.20	.504	.224	1.146	.606
$Alpha_{(440\text{-}870\ nm)}$	106	.25	1.26	.706	.288	.141	-1.072
Beta	106	.09	.89	.306	.191	1.321	.876
NO_2 ($molcm^{-2}$)	132	2.46 $x10^{15}$	4.80 $x10^{15}$	3.14$x10^{15}$	4.61 $x10^{14}$	1.322	2.088
CO ($molcm^{-2}$)	132	1.84 $x10^{18}$	3.34 $x10^{18}$	2.28 $x10^{18}$	3.40 $x10^{17}$	.759	-.653
SO_2 (DU)	132	0	.64	.010	.085	4.814	32.387
O_3 (DU)	132	255.45	331.56	294.727	12.492	-.035	.508
T_{max} (°c)	72	27.60	37.00	32.421	2.488	-.032	-1.090
RH (%)	72	42.00	88.00	75.569	10.540	-1.225	1.087
RF (mmh^{-1})	71	.00	318.60	112.358	97.840	.350	-1.147
Ws (ms^{-1})	72	1.30	7.00	4.727	1.418	-.291	-.991
SR (wm^{-2})	72	157.06	296.84	239.887	33.252	-.702	-.247

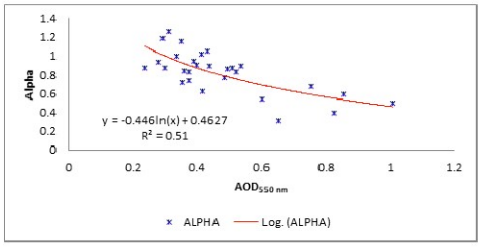
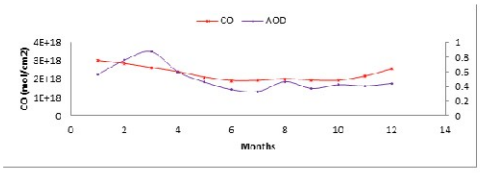


Figure 3: Variation of Alpha as function of AOD for warm dry season

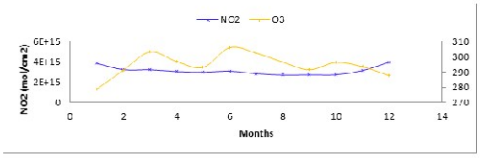
On daily basis, the columnar NO_2 and CO concentrations behaved in sinusoidal pattern, that is, some days of high emission and the others with low emission into the atmosphere. Human activities leading to the emissions occur both on working days and weekends which shows that emission sources are not only from industries and mobile emissions. Also, it has been established that carbon monoxide (CO) is a good tracer for biomass burning as it had a relative long chemical lifetime of a month or more (*Huang et al., 2013*). So, most peak in the daily observation fall in December-January-February (DJF) which happens to be the period of intense biomass burning in the region (see Figure 4A). The highest contributor to CO concentration in the region is bush burning for animal hunting and agricultural activities. In a seasonal behaviour, both parameters follow the pattern of AOD over the year with the maximum in the beginning of the year dropping to the minimum in the peak of rainy and later in the year rise toward December (see Figure 4A & B). This reveals their contribution to the aerosol loading in the region. In the case of SO_2, which is predominant anthropogenic sulphur-containing air pollutant, has majority of its daily measurement as background measurement (< 0.1 DU) in the region (*Fioletov et al., 2011*). Since the major point source of the pollutant is power plant, that is emission from fuel combustion and there is none in the area. But other minor sources such as emission from industrial diesel generating plants and trucks exist in the region which forms both the background and high episode measurement. The majority of the peaks in the daily analysis are below 0.5 DU with little peaks just above it and one abnormal isolated peak of value 10.0 DU which occurred on the 4th of December, 2006 and its emission source is worth investigating. It was observed that there is no daily and seasonal regular patterns behaviour of the pollutant.

Ground level ozone (O_3) being a secondary air pollutant which is a major constituent of atmospheric smog shows the maxima values in March and June while the minima in January throughout the years considered. The March maxima may be as a result of abundant solar radiation during longer day of been experienced which promotes the photochemical reactions among the precursors. The June maxima may be as a result of large population of trees and plants generating more volatile organic compound (VOCs), also anaerobic biological processes and lighting during the rains produce Nitrogen oxides (NO_x) in addition to vehicular emissions which are precursors to ground level Ozone (*Godish, 1991*). The minima in December-January may be as a result of reduction in the production of ozone precursor from natural sources and high scattering of incoming solar radiation by heavy harmmattan dust present in the atmosphere (Figure 4B).

(4A)



(4B)



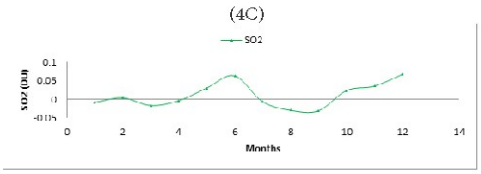


Figure 4(A-C): Seasonal behaviour of AOD and Air pollutants over Ilorin (2005-2015)

Relationship between the variables

The essence of investigating the relationship is to consider effect of mixing and dependency within the parameters. The correlation matrix of the variables as shown in Table 2 unveiled co-linearity, low to moderate Pearson correlations within aerosol properties, air pollutant and meteorological parameters. In the overall correlation, turbidity coefficient (β), carbon monoxide, and temperature are positively correlated with AOD, 0.94, 0.52, and 0.55, respectively.

This suggests that increase in AOD can be as a result of contributions from coarse mode particles, major emitter of CO which is biomass burning and at the period of maximum air temperature in the region. Angstrom exponent (α), and relative humidity show equal anti correlation with AOD, (-0.50) showing misbehaviour of aerosol at higher humidity (*Altaratz et al., 2013*). Among the air pollutants in the overall correlation, only NO_2 and CO correlated (0.68) showing the linear relationship between the two which may be as a result of some common sources of the pollutants. The meteorological parameters considered correlated either positively or negatively with some aerosol properties and air pollutants in the analysis as shown in Table 2 revealing the favourable and non-favourable conditions for the parameters.

In the seasonal correlation analysis, improvements are observed in some relations and reductions in others. Improvements are observed in the relations of AOD-alpha and AOD-beta during the cool dry season compared to the overall, this drops in the case of AOD and α but consistent for AOD and β in the warm dry season. In the wet season, the relations within the three aerosol properties are not significant and these may be due to the amount and composition of the aerosol particle and likewise the atmospheric conditions. It means that different aerosol types, including fine mode (urban pollution & biomass burning) and coarse mode (dust) aerosols, can be found in the region during the wet season. NO_2-CO relation that was established is found to occur in cool dry season with a bit reduced correlation (0.60), this period is the peak of movement of people and goods likewise biomass burning. Relationships are established between ozone concentration and aerosol properties only in the warm dry season with positive correlation between AOD and O_3 (0.61) and β and O_3 (0.68) while negative correlation exit between α and O_3 (- 0.77). This improvement may be due to increment in ozone formation due to the peak period of temperature in the year and the types of aerosol present in the atmosphere. The season may be otherwise referred to as ozone season (Duncan et al., 2014).

During the season good visibility is observed on the ground surface with dust reside at a very high altitude (>3000m) above ground level. This suggests that aerosol particles at the period are transported and mainly dust coated or ageing dust particles of highest volume size distribution (dV(r)/dlnr) ~ 0.4 (μm3/μm2) compare to other seasons and reduced optical behaviour compared to pure dust particles (Akoshile et al., 2016). SO_2 correlated with temperature (0.51) only in the wet season. This may be as a result of lower concentration of SO_2 in the atmosphere coinciding with low temperature during the season and it is basically being used to study the emission control of the power plants over a long period of time.

The Influence of the Meteorological Parameters on pollutants relations

The effects of weather parameters on the aerosol properties and air pollutants relation are summarized in Table 3.

The maximum temperature and solar radiation measurement of the day were used for the investigation because it is the period when there is strong boundary layer mixing and intense surface heat flux. It is generally observed that AOD-α, AOD-CO, and NO_2-CO relations are greatly reduced below significant level while AOD-β and α-β relations are relatively reduced but still in significant level. The reduction may be due to changing nature of some variables such as RH and RF.

In the warm dry season, temperature and solar radiation are intense with moderate relative humidity values (50-60%) and scattered rainfall in the region. Improvements are noticed in all the already established relations in the season and new relations evolved such as AOD-NO_2 (0.70), α-NO_2 (-0.81), and β-NO_2 (-0.72). These suggest that vehicular emissions which are the main sources of NO_2 contributed to coarse mode particles which are the major cause of atmospheric turbidity in the region. Moreover, SO_2 that has not been found to have good correlation with any of the air pollutants or aerosol properties in the previous analysis shows improvements with AOD and Beta in negative direction (-0.59 and -0.58 respectively). Also, NO_2-O_3 relation is found to be correlated (0.78) meaning more photochemical reactions of precursor gases occurred during the season. Low humidity value (20-40%) with no rainfall and average temperature dominate in the cool dry season. Like in the previous season, new relations evolved such as NO_2-SO_2 (0.66) and SO_2-O_3 (-0.50) apart from relations within the aerosol properties. This shows that some percentages of NO_2 are been emitted from same source of SO_2 which is power generating stations. Almost all the established relations in the dry seasons performed woefully in the wet season of high humidity (70-85%), intense rainfall, moderate temperature and improve wind speed, except AOD-β (0.81) with little reduction while β-CO (0.51) has improved relation in the season. This may be as a result of washout of most aerosol particles in the atmosphere and reductions in optical properties of the present ones. The result of the simulation of AOD using all other variables as input in regression model shows very good result with R-Square and Adjusted R-Square value of 0.965 and 0.95, respectively as shown in Table 4. This suggests that AOD can be accurately predicted with all the variables considered in place.

Table 2: Correlation matrices of variables in Ilorin during the period of study and over the seasons Overall

Overall

	AOD	ALPHA	Beta	NO_2	CO	SO_2	O_3	T_{max}	RH	RF	WS	SR
AOD	1	-.50	.94	.26	.52	-.05	.17	.55	-.50	-.40	.12	.27
ALPHA		1	-.73	-.07	-.17	-.08	-.34	-.50	.26	.11	-.22	-.49
Beta			1	.22	.47	-.03	.26	.64	-.48	-.37	.19	.38
NO_2 ($molcm^{-2}$)				1	.68	.23	-.26	.54	-.70	-.62	-.50	.01
CO ($molcm^{-2}$)					1	-.02	-.29	.76	-.75	-.75	-.37	.15
SO_2 (DU)						1	-.04	.11	-.17	-.20	-.29	.07
O_3 (DU)							1	-.09	.17	.26	.37	.02
T_{max} (°c)								1	-.77	-.71	-.26	.57
RH (%)									1	.67	.38	-.22
RF (mmh^{-1})										1	.40	-.28
WS (ms^{-1})											1	-.22
SR (wm^{-2})												1

Warm Dry Season

	AOD	ALPHA	BETA	NO_2	CO	SO_2	O_3	T_{max}	RH	RF	WS	SR
AOD	1	-.51	.97	.47	.41	-.09	.61	.26	-.31	-.40	-.19	-.03
ALPHA		1	-.68	-.12	.34	.13	-.77	.04	-.27	-.22	-.49	.26
BETA			1	.42	.25	-.13	.68	.22	-.20	-.29	-.01	-.07
NO_2				1	.36	-.01	.20	.33	-.40	-.27	-.26	-.01
CO					1	.20	.01	.59	-.75	-.75	-.50	-.36
SO_2						1	-.01	.03	.12	.11	-.14	-.24
O_3							1	-.23	.22	.12	.20	-.34
T_{max}								1	-.52	-.65	-.32	-.28
RH									1	.52	.44	.22
RF										1	.47	.09
WS											1	-.09
SR												1

Cool Dry Season

	AOD	ALPHA	BETA	NO_2	CO	SO_2	O_3	T_{max}	RH	RF	WS	SR
AOD	1	**-.71**	**.97**	.42	.31	-.13	.01	.32	-.44	-.22	.14	-.38
ALPHA		1	**-.83**	.03	.28	.09	-.40	-.05	.32	.02	-.18	-.19
BETA			1	.28	.12	-.13	.13	.27	-.40	-.18	.21	-.21
NO_2 ($molcm^{-2}$)				1	**.60**	.21	-.34	.25	**-.59**	-.35	-.40	**-.69**
CO ($molcm^{-2}$)					1	-.14	-.49	.04	-.17	-.31	-.33	**-.78**
SO_2 (DU)						1	-.04	-.06	-.10	-.11	-.23	.05
O_3 (DU)							1	-.06	.01	.35	.23	.24
T_{max} (°c)								1	-.46	-.08	.11	-.17
RH (%)									1	.07	.23	.49
RF(mmh^{-1})										1	.12	.34
WS (ms^{-1})											1	.02
SR (wm^{-2})												1

Wet Season

	AOD	ALPHA	BETA	NO_2	CO	SO_2	O_3	Tmax	RH	RF	WS	SR
AOD	1	-.38	-.07	-.17	.02	-.31	-.01	-.01	-.07	-.08	.17	.08
ALPHA		1	-.19	-.32	-.20	-.14	-.18	**-.74**	.46	.03	.25	-.44
BETA			1	.25	.44	.33	.01	.47	-.38	-.11	-.01	.32
NO_2				1	.14	.31	.27	.41	-.21	-.05	.22	.12
CO ($molcm^{-2}$)					1	-.04	-.05	.28	-.41	-.18	.17	-.04
SO_2 (DU)						1	.04	**.51**	-.47	-.27	-.16	.33
O_3 (DU)							1	-.11	.06	.19	.16	-.08
T_{max} (°c)								1	**-.61**	-.11	-.37	**.63**
RH (%)									1	.17	.11	-.25
RF(mmh^{-1})										1	-.01	-.11
WS (ms^{-1})											1	**-.64**
SR (wm^{-2})												1

Table 3: Partial correlation matrices of aerosol properties and pollutant with meteorological parameters serving as control variables

	Overview								Warm Dry Season						
Control Variables		AOD	ALPHA	BETA	NO_2	CO	SO_2	O_3	AOD	ALPHA	BETA	NO_2	CO	SO_2	O_3
Tmax , RH, RF, WS & SR	AOD	1	-.24	.91	-.02	.14	-.24	.40	1	-.90	.99	.70	-.01	-.59	.83
	ALPHA		1	-.56	.01	.24	-.05	-.41		1	-.92	-.81	.11	.34	-.86
	BETA			1	-.02	.03	-.22	.44			1	-.72	-.04	-.58	.83
	NO_2				1	.23	.33	.09				1	-.15	-.02	.78
	CO					1	-.20	-.02					1	-.18	-.18
	SO_2						1	.01						1	-.14
	O_3							1							1

	Cool Dry Season								Wet Season						
Control Variables		AOD	ALPHA	BETA	NO_2	CO	SO_2	O_3	AOD	ALPHA	BETA	NO_2	CO	SO_2	O_3
T_{max}, RH, RF, WS & SR	AOD	1	-.96	.99	.05	-.05	-.18	.45	1	.23	.81	-.24	.21	-.11	-.04
	ALPHA		1	-.97	.12	.02	.32	-.49		1	-.33	-.26	-.35	-.16	-.39
	BETA			1	-.01	-.13	-.21	.47			1	-.06	.51	-.08	.11
	NO_2				1	-.20	.66	-.06				1	-.01	-.08	.37
	CO					1	-.09	-.37					1	-.01	-.13
	SO_2						1	-.50						1	.31
	O_3							1							1

Table 4: Model Summary

Dependent Variable: AOD

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.982(a)	.965	.958	.04806

Predictors: (Constant), SR, O3, SO2, CO, WS, ALPHA, RF, RH, NO2, Beta, Tmax

CONCLUSION

The behaviours and connections within atmospheric aerosols, air pollutant concentrations, and meteorological variables over Ilorin Sub-Sahel region were investigated. Combined dark target and deep blue MODIS (Terra and Aqua) retrieval algorithm is found to be the best for the region when compared with AERONET measurement.

Biomass burning has been found to be highest emitter of CO in the region with little from vehicle exhaust which is the major source of NO_2. Their seasonal behaviours follow the trend of AOD revealing the dependency of aerosol loading on them. Ozone season has been uncovered in the region to be the warm dry period when the concentration and relation with other pollutants improved.

Generally, seasonal behaviour of SO_2 has been below the background level but there exist far above normal emission in some days during the period in review. Applying Pearson correlation analysis to the variables, linear relationships were revealed corresponding to interdependencies of aerosol properties and air pollutants in different meteorological conditions which are significant either at 0.01 or 0.05 level. Using all the variables in a regression model to predict AOD over the region gives good R-square and adjusted R-square value showing contribution of the variables in aerosol formation.

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