Centre for Atmospheric Research

2018 MONOGRAPH OF ATMOSPHERIC RESEARCH

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

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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

Variation of aerosol optical depth obtained from ground and satellite-based measurements at 550nm over Ilorin

Centre for Atmospheric Research

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ABSTRACT

This study investigates the spatio-temporal variations of aerosols over Ilorin (8.32^{0}N, 4.34^{0}E) Nigeria, based on Moderate Resolution Imaging Spectro-radiometer (MODIS) satellite sensor imageries taken on board TERRA ship over the study location and AERONET Cimel sun-photometer aerosol optical depth (AOD) measurement located on the ground at the site for years 2003, 2005, 2006 and 2007. The AOD over Ilorin was retrieved from the corresponding land area pixels using Deep Blue Algorithm for brighter surface. AERONET AOD was interpolated from 500nm wavelength to MODIS AOD wavelength at 550nm and both were compared for daily and monthly data for the years considered. The MODIS AOD data was validated following NASA validation procedure and the Root Mean Square Error (RMSE) was calculated. AERONET AOD data was used as ground truth source, It was observed that AOD data retrieved from MODIS overestimated the values for low AOD (<1.0) and underestimated it for high AOD values (>1.0), though the annual behavior of occurrence was similar. The underestimation of AOD by MODIS with respect to AERONET might be caused by the strength of surface reflectance sensed by the MODIS. The harmattan and dry season behaviors were found to show high AOD values while the rainy season showed low AOD values. AERONET shows higher AOD value in the harmattan period than MODIS for the years of study, and lower values during the rainy season. The validation procedure gave the linear equation between AERONET and MODIS with a slope of 1.03, intercept of 0.04 and good correlation value of R= 0.62. Years 2003 and 2005 had RMSE value of 0.3, while 2006 and 2007 had high RMSE values of 0.5 and 0.4, respectively. The values for 2003 and 2005 agree with the RMSE values obtained in literature for coastal regions within the range of 0.2 to 0.3. The RMSE values above 0.3 obtained here may be due to high soot concentration from the biomass burning during the dry season, and gas flaring in the Niger Delta oil producing region of Nigeria which might not be well in-cooperated in the Algorithm used for MODIS AOD retrieval.

Keywords: Inter-comparison; AOD; MODIS; AERONET; VALIDATION.

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INTRODUCTION

The presence of aerosols in the atmosphere cannot be disputed and it influences the changing climate and Earth radiation budget. Air quality affects visibility, health and other environmental factors. Aerosol can have direct cooling effect by reducing the amount of solar radiation that reaches the earth surface or by trapping re-irradiation that would have gone into space. Aerosol and other pollutants act as atmospheric forcing agent by scattering, reflecting and absorption of coming or outgoing radiation to and from the earth's atmosphere. Aerosols can remain in the air for a short or long period of time depending on their sizes and composition. Temporal and spatial studies are necessary to properly quantify and where possible characterize the magnitude and nature of the aerosol. Absorption properties can help to understand the impacts of these aerosols on the climate components of the region. The knowledge of spatial and temporal distributions of aerosols on regional and global scale is essential to understand the dynamics of aerosols and associated influence on regional and global climatic conditions (*Kaufman et al., 2002*).

One of the methods of monitoring atmospheric aerosols is remote sensing, and this method can either be satellite-based or ground-based measurement considered as ground truth. Satellite measurement of aerosol has contributed to earth science, assessment of air quality, and management of some disasters on global, regional and local scale. It has capacity to improve our understanding of aerosol-induced climate effects, due to atmospheric aerosol loading, greenhouse gases, solar radiation, and land surface properties that alter the energy balance of the earth's atmosphere (*Papadimas et al., 2009*). Ground-based measurements of aerosols have been shown to play an important role in characterizing and quantifying aerosol optical and microphysical properties, aerosol loading and their radiative effects over any particular region (*Jethva et al., 2007*), while satellite-based remote sensing techniques provide systematic retrieval of aerosol optical properties on regional and global scale (*Kaufman et al., 2002*).

Aerosol optical depth (AOD) is a measure of the extinction of solar beam by dust and haze and how much of direct sunlight is prevented from reaching the ground by these aerosol particles. It is a dimensionless number that is related to the amount of aerosol in the vertical column of atmosphere over the observation location. A value of 0.01 corresponds to an extremely clean atmosphere, and a value of 0.4 would correspond to a very hazy condition (*Jo, et al., 2013*). AOD is among the most important key parameters which reflects the characterization of atmospheric turbidity, and identifies the climatic effects of aerosols. The aim of this work is to study the behavior of aerosol and its optical property over Ilorin (8.32^0N, 4.34^0E) using both remote satellite based and ground based sensing techniques and then validate satellite measurement using data from the ground-based measurement.

METHODOLOGY

Data Collection

The data used in this study was collected from polar orbiting MODIS-TERRA satellite sensor over Ilorin city, Nigeria and an AERONET station located inside the University of Ilorin, Ilorin Nigeria (8.35^0N, 4.32^0E) for the years 2003, 2005, 2006 and 2007. Ilorin was chosen to make use of an AERONET station as ground truth and the satellite data chosen based on the nearly coincident overpass times with high spatial resolutions.

MODIS

Moderate-Resolution Imaging Spectra Radiometer (MODIS) is one of the payload scientific instrument sensors in NASA Earth Observing System (EOS) satellite, Terra platform launched on December 18, 1999 for imaging in the morning, while the Aqua platform launched on May 4, 2002 is for imaging in the afternoon. Terra is a polar orbiting satellite in a sun-synchronous orbit at an altitude of 705 km with a 98.3 degree inclination and a period of 98.88 minutes (*Earth System Monitor Satellites, 2004*). The sun-synchronous orbit allows Terra to pass directly overhead of a given location and it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Both Terra and Aqua image the same area on earth at its approximate 10:30 a.m. and 1:30 p.m. local time respectively as described in details by *Justice et al., (2002)*.

AERONET

AERONET (AErosol RObotic NETwork) is a federation of ground-based aerosol remote sensing network established by National Administration for Space and Astronomy (NASA) which is expanded by collaborators from other agencies all over the world in order to incorporate large spatial coverage which is required to validate the satellite measurements and to increase the accuracy of the retrieval on a regional scale (*Holben et al., 1998*). The program provides a long-term, continuous and readily accessible public domain database of aerosol optical, microphysical and radiative properties for aerosol research and characterization, validation of satellite retrievals, and synergism with other databases. The network imposes standardization, calibration, processing and distribution of instruments. It employs CIMEL sun-sky spectral radiometer which measures the direct sun radiances and sky luminance at eight spectral channels centered at 340, 380, 440, 500, 670, 870, 940 and 1020 nm. The instrument automatically computes the position of the sun and tracks its movement. It is programmed to collect data in automated sequence, which includes almucantar and principal plane scenarios (*Holben et al., 1998*).

Optical Depth

Optical depth is calculated from spectral extinction of direct beam radiance at wavelength based on the Lambert-Beer-Bouguer law which is termed as the “direct method”. AOD is determined by correcting optical depth for attenuation due to Rayleigh scattering, absorption by ozone and gaseous pollutants. Uncertainties in the direct sun measurements are within ± 0.01 for longer wavelengths greater than 440 nm and ± 0.02 for shorter wavelengths less than 440nm (*Holben et al., 1998; Eck et al., 1999*). The voltage (V) measured by a sun photometer is proportional to the spectral irradiance (I) reaching the instrument at the surface. The estimated top of the atmosphere spectral irradiance (I_o) in terms of voltage (V_o) is obtained by sun photometer measurements. The total optical depth (τ_z) can be obtained using the following equation according to Beer-Lambert-Bouguer law:

$$V(\lambda) = V_o(\lambda)\, d_2 \exp[-\tau(\lambda)_z * m] \quad (1)$$

where V is the digital voltage measured at wavelength λ, V_o is the extraterrestrial voltage, d is the ratio of the average to the actual Earth-Sun distance, τ_z is the total optical depth, and m is the optical air mass (Holben, 1998).

Other atmospheric constituents can scatter light and must be considered when calculating the AOD. The optical depth due to water vapor, Rayleigh scattering, and other wavelength-dependent trace gases must be subtracted from the total optical depth to obtain the aerosol component:

$$\tau(\lambda)Aerosol = \tau(\lambda)_z - \tau(\lambda)water - \tau(\lambda)Rayleigh - \tau(\lambda)O_3 - \tau(\lambda)NO_2 - \tau(\lambda)CO_2 - \tau(\lambda)CH_4 \quad (2)$$

Site description

Ilorin is located in the Guinea Savannah zone of West Africa with latitude 8.55^oN and longitude 4.57^oE. It is influenced by the dusty harmattan wind (*Falaiye et al., 2003*). The climate is a transition between the equatorial rain forest in the south and the Sahel Savannah in the north. The hot dry season commences from late October to late March when the North-Easterly (NE) winds from the Sahel dominate the climate pattern. However during the wet season from late April to October, the climate is dominated by the South-Westerly winds from the Atlantic Ocean which is characterized with high relative humidity of values exceeding 80% (*Akoshile et al., 2007*). The Ilorin AERONET station is located at the top roof on the Engineering building at an altitude ~350m above sea level to avoid any local interruption in the measurement.

Data Analysis

In this study, data of aerosol optical depth (AOD) over Ilorin was acquired from http://ladsweb.nascom.nasa.gov of MODIS and http://aeronet.gsfc.nasa.gov of AERONET. The wavelength 550nm was selected for this study because this wavelength makes the comparison of MODIS and AERONET data reliable and useful for deducing the effects of aerosols since it is close to the peak of the solar spectrum and is therefore associated with major radiative effects (*Papadimas et al., 2009*).

Interpolation Procedure

MODIS provides AOD at 550nm and AERONET provides its AOD at 500nm, consequently requiring interpolation of AERONET AOD from 500nm to 550nm for wavelength marching. This was done by using the Angstrom exponent ($\alpha_{500-870}$) provided by AERONET. The Angstrom power law equation (3) were used to obtain equation (4) which represent AERONET AOD at 550nm.

$$\alpha = -\frac{\log\frac{\tau\lambda_1}{\tau\lambda_2}}{\log\frac{\lambda_1}{\lambda_2}} \qquad (3)$$

$$\textbf{AOD}\ (\textbf{550 nm}) = AOD(500nm)(550/500)e^{-\alpha} \qquad (4)$$

where α is angstrom exponent at (500-870nm), AOD (550 nm) is the interpolated AOD of AERONET ($\tau\lambda_1$), AOD (500 nm) is the AERONET AOD at 500 nm ($\tau\lambda_2$) while λ_1 and λ_2 are the spectrum wavelengths at 550 and 500 nm respectively.

The comparison between MODIS AOD (retrieved) and AERONET AOD (interpolated) was done for the years 2003, 2005, 2006 and 2007.

The Root-Mean-Square-Error (RMSE)

The root mean square error was obtained from the mean values of the co-located spatial and temporal ensemble by considering AERONET data as the ground truth using the following equation.

$$\text{RMSE} = \sqrt{\text{SUM(AERONET AOD-MODIS AOD)}^2 / \text{N}} \qquad (5)$$

where N is the total number of AOD data points employed.

Validation Approach

AERONET AOD data available is at three different quality levels: (i) Level 1 (un-screened), (ii) Level 1.5 (cloud-screened) and (iii) Level 2 (cloud-screened and quality assured). The AERONET data used for MODIS AOD validation is only from direct sun radiation measurements of Level 2 quality. For a point to be included in the validation analysis, the AERONET and MODIS measurements must be matched in space and time.

The method of *Chu et al., (2002)* was adopted for this study, the MODIS retrieved AOD data at 10 km x 10 km resolution and AERONET direct measurements at 15 minute intervals were co-located in space and time (Holben *et al*., 1998). For the spatial matching, a circle of fixed radius of 27.5 km around the AERONET site was taken, a minimum of 20% of all possible MODIS satellite AOD retrievals of quality assured data within this area to use this point in the validation data set. All the qualified MODIS AOD values were averaged to compare against the AERONET AOD. On the other hand, for the temporal matching at least two AERONET direct sun level 2 measurements within ±30 minutes of the MODIS satellite overpass were taken a temporal window of 60 minutes. All the qualified AERONET measurements were then averaged to compare against the MODIS AOD retrieval.

RESULTS AND DISCUSSION

Daily Averaged data comparison

The AOD data obtained from MODIS and the one obtained from the interpolation of AERONET were compared for the years 2003, 2005, 2006, and 2007. The year 2004 was skipped due to unavailability of AERONET AOD data to make good comparison.

(a) Year 2003

In 2003, both MODIS and AERONET AOD values were low at the beginning of the year, with values less than 1.0 from January to end of February. It increased to higher values thereafter. It was also fluctuating rapidly throughout the month of March for both MODIS and AERONET AOD with values reaching as high as 1.68. It later dropped to lower values towards the end of the month. It fell drastically in the month of April into May and beyond which is the beginning of the raining season. MODIS showed an isolated peak on 27th April. Unavailability of AERONET AOD data for the months of May through September in the year made it impossible to compare with MODIS AOD values. However more AERONET AOD data was available in October of 2003 and was compared with MODIS satellite retrieved AOD data. Both again showed similarity in behavior, as clearly shown in Figure 1 (a).

(b) Year 2005

The year 2005 started with high values of AOD for both AERONET and MODIS for the first two weeks to as high as 1.5 and 2.2 and dropped for the next three weeks to about 0.3 to 0.8 before relatively fluctuating at higher values. The values fluctuated between about 0.2 to 0.6 for MODIS between May and end of the year. The AERONET values were generally much lower than MODIS data through the raining season except for some scattered high points. Both however behaved in the same way, increasing and reducing rapidly within the range of 0.3 to 1.8 for the next period of 86 days (several months) from March to May pre-raining season when there was harmattan dust. MODIS AOD values were higher than AERONET AOD values for the raining season period that spanned for 5 to 6 months from May to October. However, AERONET AOD values rose and eventually exceeded MODIS AOD values in the change of season that followed between November and December and continued to the beginning of the following year as shown in Figure 1 (b).

(c) Year 2006

Similarly for 2006, both AERONET and MODIS started with low AOD values of less than 1.0 for the first 57 days (January and February) except for days 8 and 50 when AERONET had values 1.1 and 2.3 respectively which may be due to sudden dust out-break. The next 16 days of this year experienced high values of AOD with AERONET having the highest on day 70 with AOD with value 3.5 and MODIS recorded value 2.8 on day 68 of the year in March as well. A very good agreement pattern of AOD values was observed for both MODIS and

AERONET for the early period of raining season in April and May. There is significant difference between the AOD retrieved by MODIS and AERONET with MODIS having higher values than AERONET throughout the period of raining season on days 176 to 299. MODIS data showed gradual drop as the raining season proceeded from day 212 to 311 (i.e, July to October). AERONET, however, showed some spikes during the period. Both MODIS and AERONET values started to rise from November to December in similar way to the end of the year as shown in Figure 1 (c).

(d) Year 2007

Figure 1 (d) shows the variation of AOD in 2007. It was noticed that AERONET AOD values were higher than MODIS AOD values for the first 65 days of the year (January to early March) though similar pattern was observed. This was followed by excellent measurement agreement between the two sources from day 68 to 145 (March to May) when it was dry and least humid, and at the incoming of raining season. Like previous years, there exist a difference between AERONET AOD and MODIS AOD for the period 145 to 305 days in the year 2007 during peak of the raining season with MODIS having higher AOD values than AERONET. This was later followed by a sudden rise for both and AERONET values were higher than MODIS values towards the end of the year.

In general, looking at the years considered (*2003, 2005, 2006 and 2007*), it is obvious that MODIS instrument overestimates for low AOD during raining season and underestimates for higher AOD values during the dust episode which may be due to amount of reflected signals from the earth surface (Surface reflectance), though the annual behavior was similar for all the years of study for both MODIS and AERONET taking the AERONET data as ground truth.

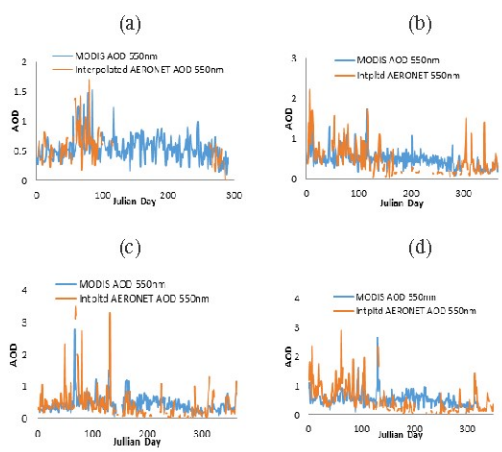

Figure 1: Plot of Daily Interpolated AERONET AOD at 550nm compared with MODIS retrieved AOD at 550nm for the years 2003, 2005, 2006 and 2007 presented (a), (b), (c) and (d) respectively.

Comparison of monthly Averaged data

Looking at the monthly averaged AOD values for year 2005, the values from AERONET were high for the first four (4) months of the year, this was followed by another 6 months (May to October) where MODIS retrieved AOD values was higher than AERONET AOD values, then AERONET overtook more than MODIS for the remaining 2 months (November and December). The period of six months when MODIS AOD is more than that of AERONET, was as a result of rainfall that washed away the aerosols presence in the atmosphere which gives much more retrieval because of the high reflectance from the ground sensed by satellite sensor which could not be observed in earlier months of the year due to presence of dust/aerosols that were thick enough to absorb and scatter reflectance from the ground surface. This was dust washed away at the onset of rainy season. After the rainy season the dust from the Sahel/Sahara begins to be transported by the harmattan wind. This causes the Aerosols in the Atmosphere to start rising again in quantity while the dryness affects the humidity level resulting in Aerosol rise in the atmosphere beginning in November through December to early following year. Data for year 2003 was incomplete but the behavior is similar to that of year 2005 for MODIS and AERONET.

The AOD values are less than 1.0 for the monthly AOD average values as shown in Figures 2 (a) and (b) for both AERONET and MODIS. The highest AOD values in these years occurred in the months of March and January respectively for years 2003 and 2005. AERONET has value 0.72 and MODIS 0.77 in the month of March 2003 whereas AERONET had value 0.84 and MODIS 0.60 respectively in the month of January, 2005.

High values relative to other months were observed for both MODIS and AERONET in March for years 2003, 2005, 2006 and 2007. The values are shown in Table 1 where maximum and Minimum with months of occurrence are shown and in Figures 2 (a) to (d). However, in the year 2007, both sensors gave same value in April, November and December. Also the AOD values started low in January to highest in March for years 2003 and 2006 while it started high from the beginning of the year in years 2005 and 2007. While we do not have other years values, it seems to indicate some oscillatory with asymmetric periodicity behavior as to its being high or low at the beginning of the year.

The monthly depiction of the plots shows that the first quarter of the year for all the years of study, AERONET has higher AOD values than MODIS. This period corresponds to dry seasons. However at the onset of raining season in the month of May running through October MODIS had higher values than AERONET. The period of November and December at the onset of dry season referred as harmattan season, the two data sources had nearly equal values of AOD and particularly showed agreement in the year 2007. This implies that the change of phase occurs about the end of the year between November and December. The two sensors can then be said to show peculiar sensitivity to the prevailing aerosol at particular times of the year. The harmattan dust and bush burning particles seem to show significant effect at the ground level where the Cimel AERONET sensor is located while the MODIS looking down from space has clearer vision in the raining season when most of the dust and other air suspended aerosols are washed off by the rain.

Maximum and Minimum values obtained from monthly AOD values for the four years of study.

Table 1 shows the maximum and minimum values retrieved from the two different sources of data (i.e MODIS and AERONET). The years of study were carefully analyzed starting from 2003 where MODIS gave 0.77 as the maximum in the month of March and 0.32 as minimum in the month of October. However, AERONET gave 0.72 in the same month of March with its minimum as 0.20 in the month of October. For the year 2005, MODIS maximum was 0.66 in March and minimum as 0.23 in December. The corresponding values for the years are shown in Table 1.

Summarily, when the annual measurements for four years were considered, both MODIS and AERONET had their maximum in the month of March for the whole years of study. The highest value of MODIS AOD was 0.77 in March 2003 and the minimum in December 2005 while corresponding values for AERONET were maximum 1.02 in March 2006 and minimum 0.10 in August 2007.

It was observed from Table 2 the overall mean found to be greater than 0.4 for both MODIS and AERONET AOD values which satisfy the condition set for AERONET version 2 algorithm. The standard deviation of MODIS is less than that of AERONET which means that the disparity within MODIS data is lower than AERONET's which may be due to some missing data.

Scattered Comparison between spatio-temporal MODIS and AERONET AOD

The year 2005 was selected for validation of satellite MODIS AOD data with AERONET Sun-photometer AOD been the

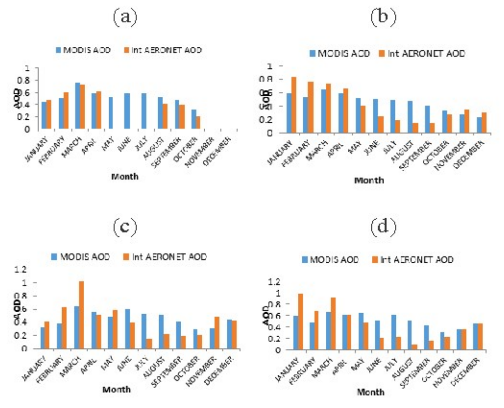

Figure 2: Bar plot of MODIS and AERONET Monthly AOD at 550nm for the years 2003, 2005, 2006 and 2007 presented a, b, c and d respectively.

ground truth data because of the complete and significant observation it exhibited out of all the years considered in this study. The spatial and temporal match-up was done by taking the average of AERONET Sun-photometer data taken at ±30 minutes of MODIS satellite over-pass, to march the 10 x 10 km window of MODIS AOD centered over Ilorin AERONET site. The derived Spatio-temporal AOD data enable correlation of the two data and to analyze the local spatial behavior of the AOD over Ilorin as shown in Figure 3. It gave the equation y = 1.03x + 0.04 and R^2 value of 0.39, the correlation R value of 0.6 was obtained for the year 2005.

Table 1: Maximum and Minimum values from Monthly AOD values for the four years of study from both MODIS and AERONET.

SOURCE	YEAR	MONTH	MAXIMUM	MONTH	MINIMUM
MODIS	2003	March	0.77	October	0.32
AERONET		March	0.72	October	0.20
MODIS	2005	March	0.66	December	0.23
AERONET		January	0.84	August	0.14
MODIS	2006	March	0.64	October	0.30
AERONET		March	1.02	July	0.16
MODIS	2007	March	0.66	October	0.32
AERONET		January	0.98	August	0.10

Figure 3 above shows scattered plot of 146 data points of temporally and spatially coincident AERONET retrieved data against MODIS retrieved AODs at 550 nm wavelength. It was observed that both AERONET and MODIS retrieved AOD are in better agreement at low AOD values (< 1.0) than at high AOD values (> 1.0). This clearly demonstrates the correlation between AERONET and MODIS data in the plot shown. The satellite showed similar observable trend with AERONET ground based data as the ground truth. The reliability demonstrated implies that both techniques can be used to assess aerosol temporal and spatial distribution in order to understand the global perspective with appreciable agreement.

Root Mean Square Error (RMSE)

The RMSE for the years 2003 and 2005 was 0.3 which agrees with the RMSE values obtained by Chu *et al*., (2002) for coastal regions within the range of ~ 0.2 to 0.3 despite its excluding the dust region considered as having high brightness. In this work the high reflectance region Ilorin was considered. The years 2006 and 2007 have high RMSE values of 0.5 and 0.4 respectively. The difference between 0.3 to 0.5 might be due to higher soot concentration from biomass burning, Saharan dust that is transported to the region by wind during harmattan season, or smoke from gas flaring sites of Niger Delta which is one of the largest flaring sites in the world which might not have been incorporated in the retrieval algorithm of deep blue used in retrieving MODIS AOD values over land and vegetated regions.

Tables 2: Descriptive Statistics of MODIS AOD and Interpolated AERONET AOD for the Years of study (2003, 2005, 2006 and 2007).

Year	Source	Datapoint (N)	Range	Minimum	Maximum	Mean	Std. Dev.	Valid (N)
2003	MODIS	290	1.43	0.10	1.53	0.54	0.21	106
	AERONET	106	1.68	0.00	1.68	0.57	0.28	
2005	MODIS	336	1.68	0.07	1.75	0.49	0.22	239
	AERONET	266	2.17	0.04	2.20	0.46	0.38	
2006	MODIS	331	2.74	0.07	2.81	0.46	0.25	248
	AERONET	270	3.47	0.04	3.51	0.47	0.50	
2007	MODIS	332	2.59	0.06	2.65	0.53	0.24	268
	AERONET	300	2.90	0.01	2.91	0.50	0.45	
Average	MODIS	365	1.14	0.09	1.23	0.49	0.15	353
	AERONET	353	1.84	0.02	1.86	0.43	0.30	

Table 3.5: RMSE values calculated using equation 5 for the years of study.

Year	RMSE	Number of points (N)
2003	0.34	108
2005	0.32	238
2006	0.49	250
2007	0.43	265

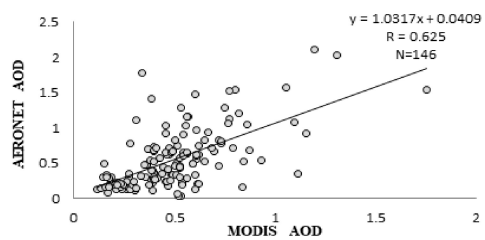

Figure 3: Scattered plot of spatio-temporal AOD data from AERONET and MODIS at 550nm.

CONCLUSIONS

In this study, the relationship between MODIS AOD and AERONET AOD was explored over Ilorin, Nigeria, a sub-Sahel location in the African continent, as a case study. Years 2003, 2005, 2006 and 2007 were selected for the station. It was quite obvious using AERONET Cimel sun-photometer AOD data as a ground truth source that AOD data retrieved from MODIS satellite instrument turns to overestimate for low AOD and underestimates for higher AOD values, though the annual behavior of occurrence was similar. The significant underestimation of AOD by MODIS with respect to AERONET might be caused by the amount of surface reflectance sensed by the MODIS sensor on board TERRA ship. However, the harmattan and the dry season behaviors were found to show apparent high AOD values with rainy season having low AOD. AERONET shows high AOD value in the harmattan period, than MODIS for the whole years of study, and vice versa during rainy season.

Comparing AERONET and MODIS temporal averages for the dataset used in this study, it revealed high AOD values at the beginning of the year during the harmattan season which later became higher during dry season and lastly dropped to a very small values during raining season and later rise towards the end of the year, this pattern behavior is due to washing away of certain relative quantity of aerosols in the atmosphere by rain during raining season and gathering of the dust during the dry season.

Validation method done for the year 2005 gave the equation $y = 1.0317x + 0.0409$ and R^2 value of 0.39, with good correlation value of R= 0.62 between the two sources of data (MODIS and AERONET). This correlation value obtained was better than other validation study carried out in other part of African countries with less correlation value of R= 0.56 by Ngaina et al., (2014).

The years 2003 and 2005 have the RMSE of 0.3, this value falls within the RMSE values obtained by Chu *et al* ., (2002) for coastal regions within the range between ~0.2 to 0.3, though they excluded dust occurrence regions like Ilorin in their validation due to high brightness of desert surface. In this work the high reflectance region Ilorin was considered and the years 2006 and 2007 were having high RMSE values 0.5 and 0.4 respectively, the difference 0.3 to 0.5 might be caused by high soot concentration from the biomass burning, Saharan dust that is transported to the region by wind during harmattan season and gas flaring of Niger Delta.

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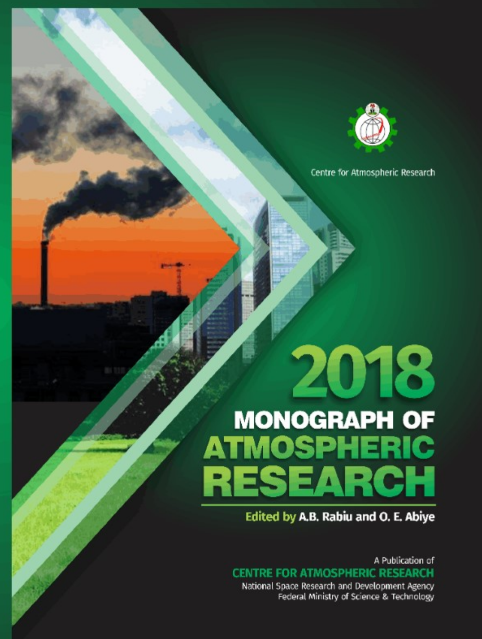

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