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

Centre for Atmospheric Research

Seasonal variability of aerosols and their radiative impacts on sub-saharan African climate during the period 2000-2015 using MODIS data

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ABSTRACT

Anthropogenic and natural aerosols both have direct and indirect impact on daily lives. They are seasonally generated, especially in sub-Saharan Africa. This paper presents an analysis using Moderate Resolution Imaging Spectroradiometer (MODIS) data to characterize the intra-seasonal variability of aerosols and their radiative impacts on the sub-Saharan Africa regional climate using long term (2000 to 2015) data. The aerosol optical depth (τ), single scattering albedo (ω_o), cloud fraction (N_{cloud}) and angstrom exponent (α), as well as radiative transfer model are used for this analysis. The aerosol loading (τ) is generally higher in the West African sub-region than in the other parts of the sub-Saharan Africa. The analysis of MODIS data at twelve (12) sub-Saharan African stations (Bambey, Ouagadougou, Capo Verdo, Cinzana, Maine-Soroa, Zinder Airport, Ilorin, Mbita, Nairobi, Pretoria, Wits University and Skukuza) shows that some part of the region is under dust influence all year long. The dust season is mainly between November and March, with peak periods of loading differing from stations to stations. The aerosol radiative forcing (ARF) on the sub-Saharan African climate results mainly in cooling. The months affected by this cooling are December to April. Although there is a sharp difference between ARF values from station to station, Ilorin has the highest station average negative forcing i.e., cooling effect (-262.6 Wm^{-2}) while Wits University (-3.2 Wm^{-2}) has the least. For raining season period, Mbita (-253.4 Wm^{-2}) has the highest station average and Wits University (-3.7 Wm^{-2}) has the least. Meaning that much less solar radiation reaches the earth's surface in Mbita than Wits during the period. The highest station average during dry season is Ilorin (-471.5 Wm^{-2}) and Nairobi (-1.7 Wm^{-2}) has the least. This indicates that much less solar radiation than expected is received in Ilorin during the period while there is an insignificant difference for that of Nairobi. The analysis of the forcing efficiency (ratio between τ and the ARF) suggests that the atmospheric radiative forcing is mainly influenced by the quantity and type of combination of the aerosols.

Key words: ***MODIS, Radiative forcing, Optical depth, Single scattering albedo and sub-Saharan Africa***

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INTRODUCTION

Sub-Saharan African region is one of the regions in the world with the highest dust and biomass burning smoke aerosol issues (*Woodward, 2001*). Massive dust plumes regularly propagate from the continent to the ocean and as far as America, particularly during the dry season in the so-called Saharan air Layer (*Drame et al., 2011*). These mineral particles exert a strong influence on the radiative balance and the climate. The years of rainfall deficits over West Africa are marked by anomalies in the dynamics of the monsoon system and mineral dust has kept increasing during drought years (*Prospero et al., 2002*). But the cause of this continuous dust increase is still unknown because it may be linked to the increase in wind intensity during dry years and/or a decrease in vegetation. A lot of studies using short time and spatially limited observed data have been conducted to characterize these particles and their impacts on the regional climate. Mineral dust particles were investigated during the SHADE campaign over the West Africa, while their radiative effects were measured in the solar spectrum by ground-based measurements (*Tanré et al., 2003*). The particles found in *Tanré et al. (2003)* during field measurements were only dust with relatively low absorption properties.

Aerosol optical depth, τ, is a measure of aerosol loading. Unpolluted atmospheric conditions should have τ values between 0.04 and 0.06 (*Tan et al., 2015*). Ångström exponent (α) provides first-hand information on the aerosol size distribution trend while the Ångström turbidity coefficient (β), corresponding to τ at unit λ (1 µm), is linked to the columnar mass loading of coarse-mode aerosols.

High α and low β indicate higher quantity of fine mode aerosol concentration. The α value varies from 1 to 3 for fresh and aged smoke, and urban aerosol particles, while it is nearly zero for coarse mode aerosols such as dust and sea salt (*Eck et al., 1999*) which is the slope of the logarithm of aerosol optical depth (xa. β ranges between 0 and 1, and is an indicator of the amount of aerosols present in the atmospheric column (*Kedia et al., 2014*).

It has been assumed that an increase in cloud droplet number concentration can result in an increase in cloud fraction (N_{cloud}) by decreasing the efficiency of precipitation formation [Albrecht, 1989 as seen in (*Gryspeerdt et al., 2016*)]. It is equally possible that a decrease in cloud droplet size can also lead to an improved evaporation and a reduction in N_{cloud} (*Gryspeerdt et al., 2016*).

The spectral single scattering albedo (ω_o), or the ratio of scattering to extinction, is commonly presented in the literature since it can determine the sign of the aerosol radiative effects. However, very often the aerosol that contributes the absorption is not the same as the aerosol that dominates the scattering. For example, pure light absorbing carbon (LAC) particles typically have a ω_o of 0.2 (*Bergstrom et al., 2007*) while its value for scattering is (*Moosmuller and Chakrabarty, 2014*). The extinction coefficient (γ) is defined as the sum of absorption coefficient (α) and scattering coefficient (β) (*Moosmüller et al., 2012*),

The fine mode fraction (FMF) value can vary from 0 (single coarse mode aerosol) to 1 (single fine mode aerosol), and provides quantitative information on the nature of the aerosol size distribution (*Kedia et al., 2014*). Anthropogenic aerosols, which contribute about 20 - 40% to the global τ, are smaller in size and more absorbing than natural aerosols (Myhre et al., 2009).

Radiative Forcing (RF) is the measurement of the capacity of a gas or other forcing agents to affect energy balance, thereby contributing to climate change. Aerosol radiative forcing (ARF) is intended as a useful way to compare different causes of perturbations in the climate system. Over the last two decades, aerosols have been accepted as a key factor responsible for the global climate change (IPCC, 2007) because they play a vital role in the solar and thermal radiative transfer in the atmosphere.

Radiative forcing due to atmospheric aerosols and the resulting climatic effect remains largely uncertain due to uncertainties in aerosol models employed in climate models (IPCC, 2001). These reservations are basically due to insufficient information on the aerosol features at regional level as well as the inadequacy with which the existing models represent the spatio-temporal heterogeneity (*Kaufman, Tanré, & Boucher, 2002; Solmon, Giorgi, & Liousse, 2006*). A better understanding of aerosol optical, microphysical and radiative properties is a crucial challenge for climate change studies (Boiyo, Kumar, & Zhao, 2018).

Modeling approaches have been used by some authors (*Myhre et al., 2008; Myhre et al., 2009; Camara et al., 2010*) to study aerosol's spatio-temporal distribution and their impacts on the climate. Despite these studies, the spatio-temporal distribution of aerosols and their radiative impacts on the climate is still an investigative topic. The TS modeling is a useful tool in planning, operating and decision-making of climate fluctuations and is being used in data generation in so many fields (*Soni, Parmar, & Kapoor, 2015*).

This work presents an analysis using Moderate Resolution Imaging Spectroradiometer (MODIS) data to characterize the intra-seasonal variability of aerosols and their radiative impacts on the sub-Saharan African regional climate using long term (*2000 to 2015*) data.

For wavelength (λ) expressed in μm, the simplest method to quantify the changes in spectral aerosol optical depth (τ) is to estimate Ångström parameters (α and β) using Eqn. (1) (*Boersma & de Vroom, 2006; Kumar et al., 2014; Tijjani et al., 2014*).

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

MATERIALS AND METHODS

Data collection

Aerosol Robotic Network (AERONET) and Moderate Resolution Imaging Spectroradiometer (MODIS) data were used in this work. The data were downloaded from the website of Multi-sensor Aerosol Products Sampling System (MAPSS) (*http://giovanni.gsfc.nasa.gov/mapss/*). It provides a consistent sampling approach that enables easy and direct inter-comparison and ground-based validation of the diverse aerosol products from different satellite sensors in a uniform and consistent way (*Petrenko et al., 2012*).

For the purpose of this long-term analysis, the stations were selected purely based on the availability of an extensive data record. Specifically, calculation of the monthly mean of the parameters (both from AERONET and MODIS) using all-point measurements was done. A monthly mean was considered valid only if there are more than five measurements for that month. To ensure a continuous time series, it was required that the data record should have at least 3 years of AERONET data measurements, with no less than nine monthly data points for each year during the 2000 to 2016 period. For the purpose of this research, forty (40) stations in the sub-Saharan Africa region were selected. Out of these stations, only twelve (12) stations met the requirements for selection, and they are spread in the following order: Eastern African region (2), Southern African region (3) and Western African region (7).

The long time-series (2000-2015) of MODIS measurements was used in this study to characterize and study the properties and climatic impacts of aerosol over the sub-Saharan African region (see Table 1). The study covers twelve (12) stations: Dakar (BAM), Cinzana (CIN), Capo Verdo (CAP), Ilorin (ILO), Ouagadougou (OUA), Maine-Soroa (MAI), Zinder Airport (ZIN), Mbita (MBI), Nairobi (NAI), Pretoria (PRE), Skukuza (SKU) and Wits University (WIT). These stations are ideally placed to study the spatio-temporal distribution of coarse (mineral dust) and fine (biomass burning) particles over the region. The distribution of AERONET stations with level 2 data that were used are shown in Table 1.

Data analysis

The MODIS τ was validated by AERONET τ to know how they compare to each other. Also, the climatology of the MODIS parameters were also analyzed. Equation (2) was used for estimating the direct aerosol radiative forcing, ΔF_R at the top of the atmosphere (Chylek & Wong, 1995; Tijjani & Akpootu, 2012; Akpootu & Momoh, 2013).

$$\Delta F_R = -\frac{S_0}{4} T_{atm}^2 (1 - N_{cloud}) 2\tau \{(1 - A)^2 \beta\omega - 2A(1 - \omega)\} \qquad (2)$$

where S_o is the solar constant with a value of 1368 Wm^{-2}, T_{atm} is the transmittance of the atmosphere above the aerosol layer with a value of 0.79 (*Penner et al., 1992 as cited by Akpootu & Momoh, 2013*), N_{cloud} is the cloud fraction and is averaged for each month from the extracted MODIS data. τ is the aerosol

Table 1:Aeronet stations in the Sub-Saharan Africa and their coordinates

S/No	Country	Aeronet station	Longitude	Latitude	Altitude	Region
1	Kenya	ICIPE_Mbita	34°E	0°S	1125 m	East Africa
2		Nairobi	36°E	1°S	1650 m	
3	South Africa	Pretoria_CSIR_DPSS	28°E	25°S	1449 m	Southern Africa
4		Skukuza	31°E	24°S	150 m	
5		Wits University	28°E	26°S	1775 m	
6	Burkina Faso	Ouagadougou	1.4°W	12.2°N	60 m	West Africa
7	Cape Verde	Capo Verdo	22.9°W	16.7°N	60 m	
8	Mali	Cinzana	5°W	13°N	285 m	
9	Niger	Maine-Soroa	12°E	13°N	350 m	
10		Zinder Airport	8°E	13°N	456 m	
11	Nigeria	Ilorin	4°E	8°N	350 m	
12	Senegal	Bambey_ISRA	16°W	14°N	30 m	

optical depth and is also averaged for each month. ω is the average single scattering albedo of the aerosol layer for each month. A is the albedo of the underlying surface which has a value of 0.22 for land retrievals and 0.06 for oceans retrievals *Penner et al., 1992* as seen in (*Chylek et al., 2007*)both increasing atmospheric concentration of greenhouse gases and decreasing loading of atmospheric aerosols are major contributors to the top-of-atmosphere radiative forcing. We find that the climate sensitivity is reduced by at least a factor of 2 when direct and indirect effects of decreasing aerosols are included, compared to the case where the radiative forcing is ascribed only to increases in atmospheric concentrations of carbon dioxide. We find the empirical climate sensitivity to be between 0.29 and 0.48 K/Wm(-2]. The land albedo value is used in this work because all the study area are land stations. β is the fraction of radiation scattered by aerosol into the atmosphere which was calculated from eqn. (1). The other parameters were extracted from the retrieved MODIS data.

RESULTS AND DISCUSSIONS

Validation of data

Table 2 shows the statistics of the comparison of the two data set used in this study. High coefficients of determination ($R^2 > 0.500$) observed for the data indicates that there are good agreements between MODIS and AERONET data. It also provides confidence that aerosol optical and radiative properties over the study area can be analyzed using MODIS aerosol retrievals (*Bibi et al., 2016; He et al., 2017*). A slope of 0.798 implies an underestimation of the measured parameter by 20.2% compared to sun photometer, whereas a slope of 1.019 show that MODIS sensor overestimates τ with respect to AERONET by 1.9%.

It can also be seen from Table 2 that the performance of MODIS with respect to AERONET is better in the West African stations (OUA, CIN, MAI, ILO and CAP) by virtue of their respective R^2 values.

Table 2: Statistical values for the validation of MODIS τ with that of AERONET, including the coe翻?cient of determination (R^2), linear regression slope and intercept

Site	Country	R^2	Slope
OUA	Burkina Faso	0.943	0.798
CIN	Mali	0.952	0.942
MAI	Niger	0.910	0.817
ZIN	Niger	0.906	1.019
ILO	Nigeria	0.935	1.083
BAM	Senegal	0.922	0.976
CAP	Cape Verde	0.937	0.711
PRE	South Africa	0.829	0.537
WIT	South Africa	0.649	0.426
SKU	South Africa	0.868	0.824
MBI	Kenya	0.855	1.016
NAI	Kenya	0.755	0.642

Spatio-Temporal Distribution of the MODIS Aerosol Optical Depth

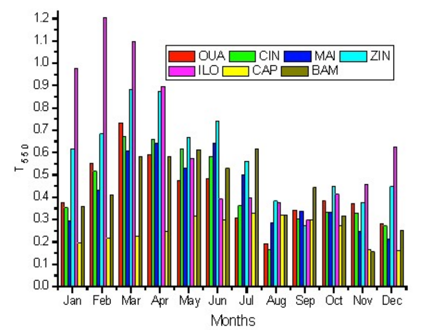

Figure 1a: Histogram of the seasonal cycle of the τ over the selected AERONET stations in West Africa averaged between 2000 and 2015.

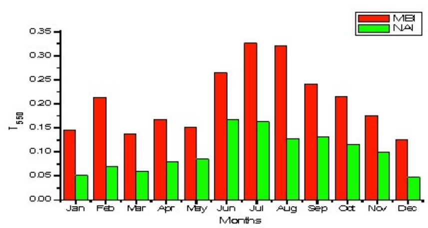

Figure 1b: Histogram of the seasonal cycle of the τ over the selected AERONET stations in East Africa averaged between 2000 and 2015.

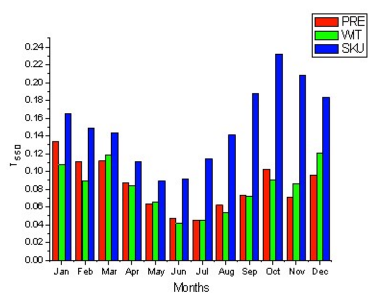

Figure 1c: Histogram of the seasonal cycle of the τ over the selected AERONET stations in Southern Africa averaged between 2000 and 2015.

Figures 1(a) – (c) show the seasonal cycle of the MODIS aerosol loading (τ) averaged between 2000 and 2015 for AERONET stations in West Africa, East Africa and Southern Africa, respectively.

It can be observed from figure 1(a) that the aerosol loading trend of the seven West African stations followed that of the two seasons (dry and raining). The onset of raining season in this part of Africa is April, and the loading starts decreasing from this month up to September. This is due to the washing out of aerosols by rain. An increase in the loading is then observed from October to March, which signifies the dusty season with a peak between February and March. The τ is highest during February in ILO (1.20); during March in ZIN (0.88), OUA (0.73) and CIN (0.67); during June in MAI (0.64); during July in BAM (0.62) and CAP (0.33).

In Figure 1(b), we can see the loading trend of the two stations in East Africa. There are two distinct raining (March to May and September to November) and dry (December to February and June to August) season in this part of Africa, and the loadings are directly related to this. The τ is highest during June in NAI (0.17) and July MBI.

Similarly, Figure 1(c) represents the loading in the three stations in Southern Africa. The dry season in this region is between May and September while the other months are raining months. The loading trend shows an increase in loading from June to October, and then a decrease up to May. The τ is highest during October in SKU (0.23); January in PRE (0.13) and March and December in WIT (0.12).

Table 3: The aerosol optical depth (τ) averaged between 2000 and 2015 during the wet season, dry season and overall for the considered AERONET stations.

Stations	average per station	Raining season	Dry season
Mbita	0.207	0.183	0.237
Nairobi	0.100	0.095	0.104
Pretoria	0.084	0.109	0.063
Skukuza	0.151	0.183	0.135
Wits University	0.081	0.105	0.060
Ouagadougou	0.425	0.397	0.463
Capo Verdo	0.254	0.298	0.193
Cinzana	0.431	0.433	0.429
Maine-Soroa	0.422	0.467	0.359
Zinder Airport	0.580	0.564	0.601
Ilorin	0.643	0.478	0.872
Bambey	0.431	0.488	0.352

Table 3 summarizes the seasonal mean of τ (550 nm) for the considered AERONET stations during dry and raining seasons, averaged between 2000 and 2015. During the raining season, stations in PRE, SKU, WIT, CIN, CAP, MAI and BAM has higher average seasonal aerosol loading values than during the dry season. This could happen as a result of two scenarios: 1) because of delayed/short raining season, or 2) increase in usage of fossil fuel and biomass burning. On the other hand, stations like MBI, NAI, OUA, ZIN and ILO has higher seasonal loading values during the dry season. As expected during raining season, there will be washout of aerosols in the atmosphere and suppression of others.

Ordinarily, dry season is supposed to be a season with the least humidity but raining season varies across the sub-Saharan African region. This is the reason why some stations has less loading during dry season.

Types of Particles

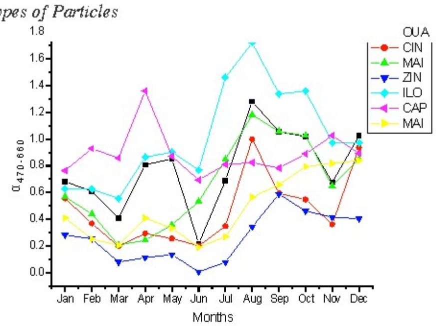

Figure 2a : Seasonal cycle of $\alpha_{470-660}$ averaged between 2000 and 2015 for the selected AERONET stations in West Africa.

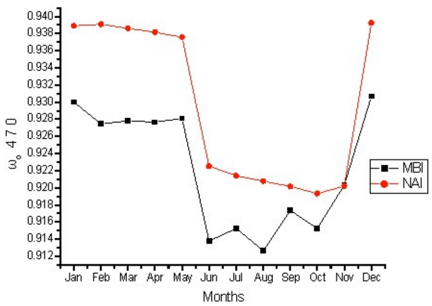

Figure 2b:. Seasonal cycle of $\alpha_{470-660}$ averaged between 2000 and 2015 for the selected AERONET stations in East Africa.

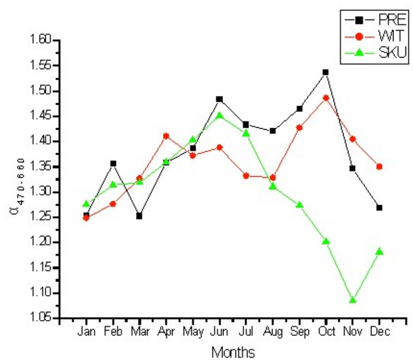

Figure 2c:. Seasonal cycle of $\alpha_{470-660}$ averaged between 2000 and 2015 for the selected AERONET stations in Southern Africa.

Figures 2(a) - (c) show the seasonal cycle of the MODIS α averaged between 2000 and 2015 for AERONET stations in West Africa, East Africa and Southern Africa respectively.

It can be observed from Figure 2(a) that the aerosol size trend of the seven West African stations followed that of the two seasons i.e., lower values of $\alpha_{470-660}$ during raining season and high values during the dry season. As expected, the onset of raining season brings about an increase in the fine mode (anthropogenic) aerosols in this part of Africa while the dry season brings about an increase in the coarse mode aerosols. This is due to the washing out of coarse mode aerosols by rain. The period between January and June in the West African divide is characterized by the presence of large (small values of α) particles that are the signature of mineral dust aerosols. When considering ZIN station, it can be observed that the station is under dust influence all year long, particularly during the raining period and sporadic biomass events during the dry periods.

In Figure 2(b), we can see the size trend of the two stations in East Africa. The two distinct raining seasons in this part of Africa brings about a further increase in the fine mode particle, which originally dominates throughout the years.

Similarly, Figure 2(c) represents the size trend in the three stations in Southern Africa. The concentration of the fine mode particles decrease during the dry season in this region. This could only mean that there is a reduction in the production of fine mode aerosols during this period.

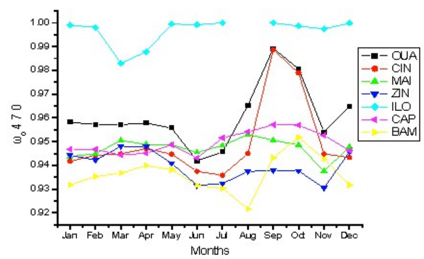

Figure 3a: Seasonal cycle of the ω_o (470 nm) averaged between 2000 and 2015 for the selected AERONET stations in West Africa.

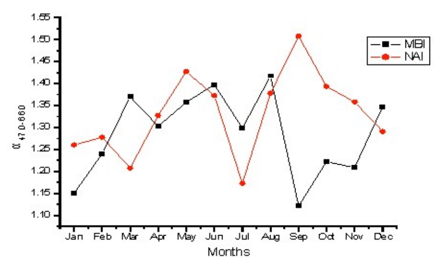

Figure 3b:-. Seasonal cycle of the ω_o 470 averaged between 2000 and 2015 for the selected AERONET stations in East Africa.

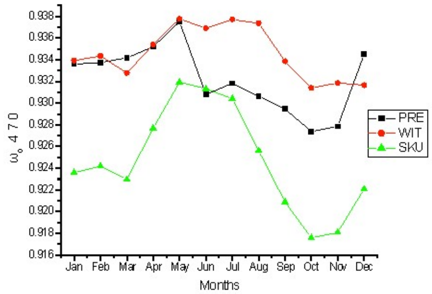

Figure 3c:-. Seasonal cycle of the ω_o 470 averaged between 2000 and 2015 for the selected AERONET stations in Southern Africa.

Figures 3(a) - (c) show the monthly mean MODIS single scattering albedo (ω_o) averaged between 2000 and 2015 for the selected stations. The period between January and June in the West African divide is characterized by the presence of scattering (strong values of ω_o) particles that are the signature of mineral dust aerosols. From May to October, the absorption increases slightly (ω_o) mostly in the East and South African divide. These particles correspond to a mixture of dust, urban and industrial pollution and biomass burning.

Aerosol direct radiative forcing

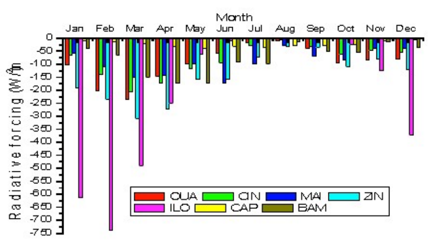

Figure 4a:. Histogram of the radiative forcing of the atmosphere averaged between 2000 and 2015 in West Africa.

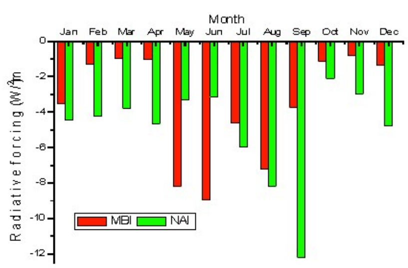

Figure 4b:. Histogram of the radiative forcing of the atmosphere averaged between 2000 and 2015 in East Africa.

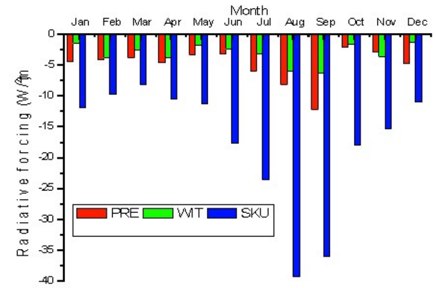

Figure 4c:. Histogram of the radiative forcing of the atmosphere averaged between 2000 and 2015 in Southern Africa.

Figures 4(a) – 4(c) show the atmospheric aerosol ARF in West Africa, East Africa and South Africa, respectively. A general cooling trend is observed and it is due to the reflecting properties of the particulate matters present in the atmosphere; this is called the direct aerosol effect. Maximum cooling is observed during dry season while the cooling is reduced during raining season. A general cooling trend is observed and it is due to the reflecting properties of dust particles i.e., a direct aerosol effect. The maximum cooling estimated for ILO during February is consistent with the maximum dust loading diagnosed during the month. The cooling is less pronounced in August at SKU station. A reduction of the cooling is noted due to the decrease of dust loading (increase in α above 1.0) over the region between the months of July and November.

Table 4. Average radiative forcing of the atmosphere for the AERONET stations averaged between 2000 and 2015 during dry season, wet season seasons and overall data. The radiative forcing unit is W/m².

Stations	average per station (W/m²)	Wet season (W/m²)	Dry season (W/m²)
Mbita	-46.882	-26.683	-66.556
Nairobi	-3.622	-2.604	-4.595
Pretoria	-4.962	-4.923	-5.015
Skukuza	-17.691	-15.719	-20.411
Wits University	-3.202	-3.043	-3.416
Ouagadougou	-96.616	-64.790	-141.173
Capo Verdo	-23.019	-30.859	-11.922
Cinzana	-86.810	-74.265	-104.569
Maine-Soroa	-90.646	-99.065	-78.731
Zinder Airport	-149.104	-121.215	-188.584
Ilorin	-262.606	-66.444	-471.507
Bambey	-80.419	-94.347	-60.919

Table 4 summarizes the mean radiative forcing estimated for all the stations, dry season and wet season. The averaged negative forcing is higher during the dry season for OUA, ZIN and ILO stations; while the cooling is stronger during wet season for ZIN, BAM and MAI stations. This shows that coarse mode aerosols were more in the atmosphere over the listed sites during the season being considered.

CONCLUSIONS

In this study, long-term (2000 to 2015) MODIS level 2.0 collection 6.0 Angstrom exponent (α) (470–660 nm), aerosol optical thickness (τ) (550 nm) and single scattering albedo (ω_o) (470 nm) observed at several AERONET stations in the sub-Saharan region have been analyzed. Firstly, suitable AERONET stations with sufficient large data series were selected in order to make a meaningful analysis. Analysis of the variability and radiative impacts of aerosols, including τ, α and ω_o was done. The 15 years measurement show obvious variation in the parameters considered.

The result of the validation of τ retrieved by MODIS and AERONET at the chosen stations shows good agreement at all stations with R^2 values between 0.649 and 0.952. It is also observed that MODIS underestimated τ at nine of the twelve stations.

Analysis of the variability of aerosol loading at each station shows that the τ maxima was recorded during the raining season in stations like PRE, SKU, WIT, CIN, CAP, MAI and BAM than during the dry season. MODIS data show that higher τ values associated with a lower α and higher values of ω_o were recorded from March to September showing the presence of a high concentration of coarse particles (mineral dust, sea salt). The raining season is characterized by the presence of mixtures (dust and biomass burning aerosols) of aerosol types and mostly larger values of α. The seasonal cycle of the size distribution in the region shows that most particles have large sizes i.e., mineral dust. Variation of ω_o showed that the atmosphere in the region was more of a reflecting one than absorbing, though some relatively absorbing episodes occur intermittently.

Aerosol radiative forcing (ARF) at the top of the atmosphere calculated from the model equation showed a general cooling trend over the region. The negative shortwave ARF (cooling) is stronger during the dust (dry) season. During this period, the mean value of the ARF ranges approximately from -3.202 W/m² to -262.606 W/m² at the top of the atmosphere over the study area. From April and November, there is a decrease in the cooling trend due to the decrease in dust concentration and increase in fossil fuel usage and biomass burning. This study also showed that with the same aerosol loading, the value of ω_o determined the type of ARF experienced.

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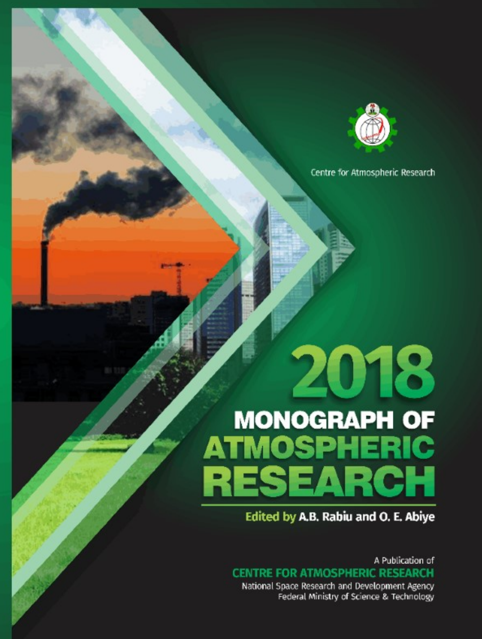

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