THE METEOROLOGICAL CONTRIBUTING FACTORS TO AEROSOL VARIABILITY AND MODELLING IN NIGERIA

by

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DEDICATION

This Work is dedicated in memory of my late parent (Alh. Usman Balarabe, Musa Balarabe and Abubakar Balarabe), my father (LT Balarabe), my family (Zainab, Salim and Salimah) my special friend (Salimah Abdullahi Matazu) and to the entire Balarabe's family.

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LIST OF SYMBOLS

Hpa	Hector pascal
$Kgha^{-1}$	Kilogram per hector
km	kilometre
km^2	kilometer square
mm	milimeter
m/s	Meter per second
nm	Nanometer
N	Number of data point
N_r	Number of data point for regression
N_v	Number of data point for validatation
$Tgyr^{-1}$	Terra gram per year
$<$	Less than
$>$	Greater than
$\leq$	Less than or equal to
$\geq$	Greater than or equal to
$^{\circ}C$	Degree celcius
$^{\circ}N$	Degree North
$^{\circ}S$	Degree south
$^{\circ}E$	Degree East
$^{\circ}W$	Degree west

%	Percentage
α	Angstrom exponent
µm	Micrometer

LIST OF ABBREVIATION

AAI	Absorbing Aerosol Index
ADEOS	Advance Earth Observing Satellite
AERONET	Aerosol Robotic Network
AI	Aerosol Index
ANFIS	Adaptive Neural-Fuzzy Inference System
ANN	Artificial Neural Networks
$Angstrom_{440-870}$	Angstrom Exponent
AOD	Aerosol Optical Depth
AOD_440	Aerosol Optical Depth at Wavelength 440 nm
AOD_500	Aerosol Optical Depth at Wavelength 500 nm
AOT	Aerosol Optical Thickness
ARCGIS	Aeronautical Reconnaissance Coverage Geographic Information System
ARL	Air Resources Laboratory
AVHRR	Advanced Very High Resolution Radiometer
BMA	Biomass burning aerosol
Br	Bayesian regularization
CALLIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite observations
CCN	Cloud Condensation Nuclei
CSM	Cerebrospinal Meningitis
DA	Dust Aerosol
D_p	Diameter of dust particle
DSF	Dust storm frequency
EP	Earth Probe
ESRL	Earth System Research Laboratory

EARLINET	European Aerosol Research Lidar Network
FTIR	Fourier Transform Infrared
GOCART	Global Ozone Chemistry Aerosol Radiation and Transport Model
GUI	Graphic User Interface
HYSPLIT	Hysplit Single Particles Lagrangian Integrated Trajectory model
IDDI	Infrared Dust Differencing Index
IR	Infrared
ITCZ	Intertropical Convergence Zone
LAI	Leaf Area Index
LM	Levenberg– Marquardt
MA	Maritime Aerosol
MATLAB	Matrix laboratory
MIRS	Multi-angle Image Spectrometer
MIXA	Mixed Aerosol
MLR	Multiple Linear Regression
MODIS	Moderate Resolution Imaging Spectrometer
NASA	National Aeronautic and space Administration
NCAR	National centre for atmospheric research reanalysis
NCEP	National centre for Environmental prediction
NPP	Net Primary Productivity
NOAA-NCDC	National Oceanic and Atmospheric Administration-National Climate Data Center.
OMI	Ozone Monitoring Instrument
PIRATE	Portable Infrared Aerosol Transmission Experiment
PM	Particulate Matter
PW	Precipitable Water
RH	Relative humidity
RMSE	Root Mean Square Error

SAL	Sahara Air Layer
SPD	Wind speed
TMP	Temperature
TOMS	Total Ozone Mapping Spectrometer
UIA	Continental/Urban/industrial aerosol
UNDP	United Nation Development Program
USA	United state of America
UV	Ultra-violet
VIF	Variance Inflation Factor
VSB	Visibility
wMAPE	Weighted Mean Absolute Percentage Error

FAKTOR-FAKTOR PENYUMBANG METEOROLOGI KEPADA KEBOLEHUBAHAN DAN PERMODELAN AEROSOL DI NIGERIA

ABSTRAK

Satu kajian aerosol jangka panjang adalah satu tugas yang sukar kerana stesen pemerhatian aerosol yang terhad dan musim (yang menyebabkan kehilangan data dan pencemaran awan). Bagi menangani masalah ini, kajian ini pertamanya bertujuan untuk menganalisis ciri-ciri dan jenis aerosol menggunakan rekod jangka panjang (1998-2013) kedalaman optik aerosol (AOD) dan eksponen angstrom α, dari Aerosol Robotic Network darat (AERONET). Kajian ini menunjukkan bahawa atmosfera Nigeria sangat tercemar yang mengandungi kebanyakannya zarah kasar sebagaimana yang ditunjukkan oleh frekuensi tinggi pada berlakunya eksponen angstrom di bawah 1 (78 dan jenis 81%) semasa Harmattan (November-Mac) dan musim panas (April-Oktober). Analisis selanjutnya menunjukkan bahawa zarah-zarah tersebut adalah kebanyakanya aerosol debu semasa Harmattan dan musim panas (82% dan 79%). Kedua, kebolehubahan ruang dan masa bagi indeks aerosol min bulanan (AI) (penunjuk kualitatif bagi kehadiran aerosol debu dan asap) dan parameter meteorologi (kelajuan angin, penglihatan, suhu dan kelembapan relatif) yang diperolehi daripada Total Ozone Mapping Spectrometer (TOMS) dan Ozone Monitoring Instrument (OMI) dalam tempoh 1984-2013 bagi Nigeria telah dianalisis. Data meteorologi diperolehi daripada pusat data iklim National Oceanic and Atmospheric Administration-National Climate Data Center (NOAA-NCDC). Hasil kajian menunjukkan bahawa min bulanan AI mempunyai kitaran tahunan yang berbeza dalam setiap zon di Nigeria (Sahel, Utara tengah, Selatan dan pantai), dengan nilai paling rendah semasa musim panas dan nilai tertinggi semasa musim Harmattan. Ia juga mendedahkan satu trend peningkatan AI yang ketara yang bersepadan dengan trend penyusutan bagi penglihatan untuk setiap zon dan musim. Analisis trend suhu tahunan dan bermusim, kelajuan angin dan kelembapan relatif menunjukkan trend peningkatan umum. Analisis ruang menunjukkan corak bermusim yang kukuh bagi taburan bulanan dan kebolehubahan aerosol penyerap dan parameter meteorologi di sepanjang arah utara ke selatan. Akhir sekali, model statistik terubahsuai berdasarkan regresi linear berganda (MLR) dan rangkaian neural buatan (ANN) telah dibangunkan untuk membolehkan anggaran nilai AI di Nigeria berdasarkan data dari pemerhatian stesen bumi. Kajian literatar menunjukkan bahawa kajian ini merupakan yang pertama model bagi korelasi statistic (MLR) dan janaam computer (ANN) untuk ramalan AI. Pekali dijana daripada model telah digunakan pada set data lain untuk pengesahsahihan silang. Nilai-nilai AI untuk tahun-tahun tanpa data telah diterbitkan, menggunakan model bulanan TOMS, diplotkan dan dibandingkan dengan kitaran AI bulanan yang diukur. Ketepatan model telah ditentukan dengan menggunakan pekali penentuan R^2, ralat punca min kuasa dua (RMSE) untuk kalibrasi dan pengesahan serta ralat peratus min mutlak berpemberat (wMAPE) yang dikira pada aras keyakinan 95%. Keputusan telah menunjukkan bahawa MLR boleh meramal AI pada tahap kejituan yang tinggi bagi setiap bulan. Selanjutnya, MLR didapati berkesan untuk menerbitkan AI menggunakan data keseluruhan dan bermusim kecuali pada data keseluruhan TOMS dan data musim OMI bagi zon selatan dan pantai. ANN menunjukkan tahap kejituan yang tinggi untuk ramalan AI pada kedua-dua data keseluruhan dan bermusim di dalam semua zon. Perbandingan model MLR dan ANN menunjukkan bahawa ANN menghasilkan keputusan ramalan yang lebih baik dibandingkan dengan model MLR di dalam semua zon dan musim. Tambahan pula, rangkaian suap-depan didapati mengatasi rangkaian lata. Oleh itu, model yang dicadangkan boleh digunakan untuk pemantauan cuaca yang berkesan di Nigeria.

THE METEOROLOGICAL CONTRIBUTING FACTORS TO AEROSOL VARIABILITY AND MODELLING IN NIGERIA

ABSTRACT

A long-term aerosol study is a difficult task due to limited aerosol observation stations and seasons (resulting in missing data and cloud contamination). To address these problems, this study first aimed at analyzing the characteristics and type of aerosols using long-term (1998-2013) record of aerosol optical depth (AOD) and angstrom exponent α, from ground-based Aerosol Robotic Network (AERONET). The study showed that Nigeria atmosphere is highly polluted containing mostly coarse particles as indicated by high frequency of occurrence of angstrom exponent below 1 (78 and 81%) during Harmattan (November-March) and summer (April-October). Further analysis revealed that these particles are mostly dust aerosol (DA) for both Harmattan and summer seasons (82% and 79%). Secondly, the temporal and spatial variability of the monthly mean aerosol index (AI) (qualitative indicator of the presence of dust and smoke aerosols) and meteorological parameter (wind speed, visibility, temperature and relative humidity) obtained from the Total Ozone Mapping Spectrometer (TOMS) and Ozone Monitoring Instrument (OMI) during the period of 1984-2013 for Nigeria were analyzed. The meteorological data were obtained from the National Oceanic and Atmospheric administration-National climate data center (NOAA-NCDC). The results show that the monthly mean AI has a distinct annual cycle in each zone of Nigeria (Sahel, North central, Southern and Coastal), with lowest values during the summer season and the highest values during the Harmattan season. It also revealed a significant increasing trend of AI with Corresponding decreasing trends of visibility for every zone and season. An increasing trend in annual and seasonal temperature, wind speed and relative humidity were also observed. Spatial analysis showed a strong seasonal pattern of the monthly distribution and variability of absorbing aerosols and meteorological parameters along a north to south gradient. Finally, a modified statistical models based on multiple linear regressions (MLR) and artificial neural networks (ANN) were developed to allow the estimation of the values of AI in Nigeria based on the data from ground observations. Available literatures showed that these are the first statistical (MLR) correlation and computer generated (ANN) models for AI prediction. The generated coefficients from the models were applied to another data set for cross-validation. The AI values for the missing years were retrieved, using TOMS monthly models, plotted and compared with the measured monthly AI cycle. The accuracies of the models were determined using the coefficient of determination R^2, the root mean square error (RMSE) for calibrations and validations and the weighted mean absolute percentage error (wMAPE) calculated at the 95% confidence level. The results revealed that in each month, MLR can predict AI with high level of accuracies. Furthermore, the MLR models were also found effective for AI retrieval in the overall and seasonal data except in the TOM's overall data and OMI summer data for southern and coastal zones. ANN showed high level of accuracies for AI prediction in both overall and seasonal data in all the zones. Comparison of MLR and ANN models revealed that ANN produced better prediction results compared to the MLR model in all the zones and seasons. Furthermore, feed forward network was found to outperform the cascade network. Therefore, the proposed models can be use for effective weather monitoring in Nigeria.

CHAPTER 1

INTRODUCTION

1.0 Overview

Aerosols are tiny (micro and submicron) sized particles (solid or liquid) suspended in the atmosphere. There is no standard definition of particles size of aerosols. Aerosols are injected into the atmosphere from both natural and anthropogenic sources (Oyem and Igbafe, 2010). They are distributed in the atmosphere by turbulence movement of air masses. Aerosols are removed from the atmosphere by ice, dew and precipitation as well as dry sedimentation. This cycle can be presented in a simple illustration form in Figure 1.1

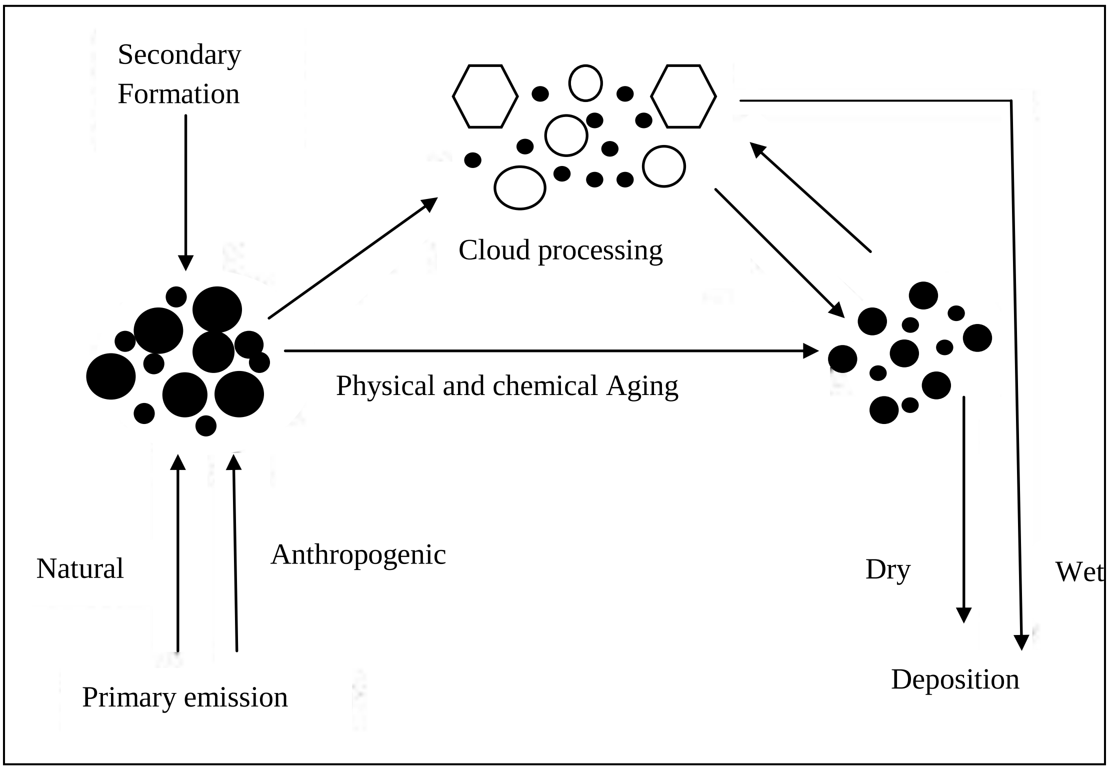

Figure 1.1: Atmospheric cycle of aerosol (PÖschl, 2005).

According to previous studies, dust aerosol has become the most abundant aerosol type in the atmospheric column worldwide (Kaskaoutis et al., 2008). It is the most significant source of atmospheric aerosol in the western Sahel (including Nigeria) (Mbourou et al., 1997). The emission, distribution and circulation of atmospheric dust aerosols are influence by favorable weather conditions. The most observable of dust aerosol effect across Nigeria is visibility reduction which leads to a significant economic loss for Nigeria (Ogunjobi et al., 2012). It also affects regional and global climate system (Anuforom et al., 2007), respiratory tracts (Kaskaoutis et al., 2008), regional air quality, and human health (De Longueville et al., 2010; Chineke and Chiemeka, 2010).

Therefore dust aerosol has become an essential parameter in atmospheric aerosol studies that requires constant monitoring and evaluation. Based on this, there is considerable interest at the global, regional and local levels in climate variability and the distribution of aerosol, including dust (Kaskaoutis et al., 2008; Habib et al., 2006; Singh et al., 2012; Pal et al., 2012). However, the quantification of the dust aerosol effects are associated with large uncertainty (Habib et al., 2006; Kaskaoutis et al., 2008). Many research efforts (Oyem and Igbafe, 2010; Habib et al., 2006; Anuforom et al., 2007; Jung et al., 2009; Drame et al., 2013; Prospero et al., 2002) were geared towards minimizing these uncertainties. This is possible through measurements of aerosol optical and physical properties at ground-level, aircraft or satellite with different temporal scales. However, ground data such as AERONET is affected by low spatial density and most satellites have a short time record of aerosol observations that can be used for dust aerosol monitoring. To resolve these problems of spatial density and limitations due to the short time of aerosol observations, the use of satellites data Aerosol Index (AI) from the Total Ozone Mapping Spectrometer (TOMS) and Ozone Monitoring Instrument (OMI) is necessary.

Habib et al. (2006) and Anuforom et al. (2007) indicate that AI is inversely proportional to the visibility, assuming a uniform distribution of aerosol in an atmospheric column. However, Anuforom et al. (2007) obtained significant negative correlations between the TOMS AI and visibility (R = 0.92) on the one hand and TOMS AI and rainfall (R = 0.72) on the other hand in the Sahel zone of Nigeria. Ogunjobi et al. (2012) also found significant correlations between the TOMS AI and visibility in 8 selected meteorological stations in Nigeria. The relationship between the OMI AI and latitude over Greece was studied by Kaskoutis et al. (2008). Based on some authors recommendations (Tariq and Ali, 2015; Tan et al. 2015a), other meteorological variables need to be taken into considerations.

Therefore, a new algorithms were developed in this study using multiple linear regression (MLR) based on four selected meteorological data on ground observations. Another set of algorithms were generated using similar as described above but for the retrieval of OMI AI data using both MLR and artificial neural network (ANN).

1.1 Problem statements

Previous literatures (Anuforom et al., 2007; Ogunjobi et al., 2012) described Nigeria as one of the most dust aerosol laden region of West-Africa where aerosol studies are of great interest. This is due to the various sources of dust aerosol at the sources in the Sahara and Sahel as well as local emissions. It has been reported in many literatures (Ogunjobi et al., 2012; Zheng et al., 2015; Adefolalu, 1984) that low visibility caused by dust have adverse effects on the economy, traffic safety, human health and much more in Nigeria (Ogunjobi et al., 2012; Adefolalu, 1984).

It is noted that despite the multiple sources and the negative effect cause by dust aerosol in Nigeria and other sub-Saharan West Africa, study of aerosol is limited in the region due to limited aerosol observation stations at the ground (as there is only one AERONET station in Nigeria). To cover up this problem, the use of satellite data such as Moderate Resolution Image Spectroradiometer (MODIS) is necessary. However, most of these satellites are also affected by short time observations of aerosol as such cannot be used for a long-term aerosol studies. The use of TOMS and OMI AI data can resolve the problems of spatial density and short-term of aerosol observations. This is because; TOMS instrument flew in space from November 1978 to August 2004 for AI detection after which OMI continues from 2004 to the present. Despite the continuous use of AI in studying dust phenomena, the use of the TOMS data for long-term study is difficult due to the large gap of missing data from April 1993 to August 1996 and early calibration problems detected in the TOMS Earth-probe signal after July 2000 (2001-2003) (Kiss et al., 2007). These leave gaps in our long-term TOMS AI data record and can create challenges in aerosol studies associated with dust. Eventhough simple linear regression approach were used for TOMS AI estimation (Anuforom et al., 2007: Ogunjobi et al., 2012), however this problem of missing data has been left out. To overcome this problem of missing data, this work aimed at developing a new AI multiple linear regression models that allow the estimation of the missing values of AI observations for Nigeria with potential global applications. New algorithms are also developed in this study for a daily OMI AI prediction to overcome the problem of missing data due to cloud contamination using both MLR and ANN approach.

The inadequacy of information on dust aerosol in West Africa and the need for further research in this regard have also been pointed out by Anuforom et al. (2007) and Tariq and Ali (2015). This information is a valuable input to climate models that are tools for investigating this phenomenon. Therefore in addition to the model development and need to fill in the knowledge gap, this study provides also details on aerosols characteristics and type, temporal and spatial variability of dust aerosol parameter (AI) under different weather conditions for effective model development for weather monitoring.

1.2 Research objectives

The main aim of this study is to develop models that allow estimation of AI for dust weather monitoring in Nigeria with potential global applications. To achieve that, the specific objectives are set;

(i) To determine the characteristics, type and sources of aerosol over Nigeria using Aeronet data at Ilorin station and HYSPLIT MODEL.

(ii) To evaluate the monthly, seasonal, inter-annual and 30-years temporal behaviour and variability of AI (dust aerosol concentration indicator) and selected meteorological parameters.

(iii) To determine the monthly and overall spatial behaviour of AI and various meteorological parameters.

(iv) To develop MLR models for TOMS and OMI AI retrieval as well as ANN (feed forward and cascade models for OMI retrieval using two different training algorithms (Bayesian regularization algorithm and Levenberg–Marquardt algorithm).

1.3 Study area

Nigeria is located in Africa between the latitudes 4-14^{o} N and the longitudes 3-15^{o} E as presented in Figure. 1.2. It is one of the largest countries in Africa covering about 14% of total West African land (Adelekan, 2013). It is bounded by Niger Republic, Cameroon, Republic of Benin and Gulf of Guinea (Atlantic Ocean), to the north, East, West and south respectively. Some of the major sources of the dust from Sahara and Sahel to Nigeria includes PSA 1 which covered sources from Tunisia and northern Algeria including the ‘zone of chotts, PSA 2: includes Foothills of Atlas Mountains and western coastal region (Western Sahara, western Mauritania), PSA 3: Southern Algeria and northern Mali PSA 4: Central Libya, PSA 5: Western Chad including the Bodélé depression and PSA 6: Southern Egypt, northern Sudan.

Furthermore, approximately 12 of the 36 states of Nigeria to the north fall entirely or partially within the Sahel which is close to the Sahara desert, and they are described as the most important global dust source regions (Prospero et al., 2002). These states constitute about 30% of Nigerian total land area of 923,768 km^2 (Anuforom et al., 2007). Therefore, aerosols are transported regularly from these sources across Nigeria towards the Atlantic Ocean

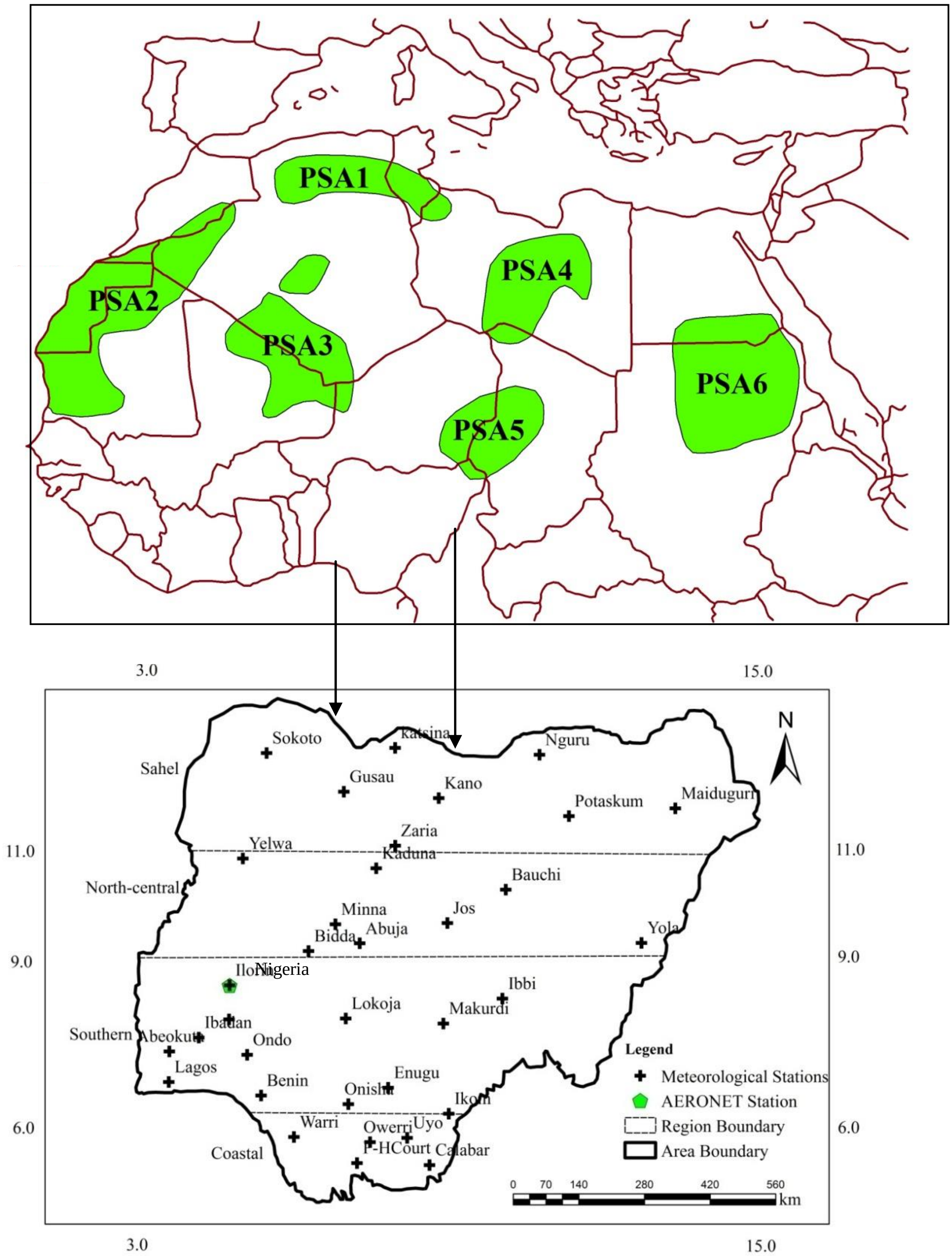

Figure 1.2: The map of northern Africa with major dust sources based on TOMS AI (Scheuvens et al., 2013) and location of Nigeria with 33 meteorological stations across Sahel, north central, southern and coastal zones of Nigeria.

Nigeria is the most populated country in Africa with about 170 million people spread across the country (Commission, 2006). The population growth rate of Nigeria is about 2.5% per annum and as at 2010 urban population was about 49% of the total population which is projected to increase by 3.8% annually (Guariguata et al. 2014). Nigerian topography varies from high in the east, north, and west where land is generally over 1500 m, 600 m, and 300 m above sea level respectively. The low-lying areas are found in the centre and southern part of the country and are generally below 300 m except Udi plateau in the south which attain a height of over 300 m (Adelekan, 2013). The prominent economic, and social activities in Nigeria are many which includes farming mostly in northern part, oil palm plantation and rubber plantation mostly found in the southern part, manufacturing and oil industries to mention but a few.

1.4 Climate of Nigeria

Previous studies (Odekunle, 2004; Adelekan, 2013) have shown that climate of Nigeria is greatly affected by sea and interaction of dry north-easterly wind (Tropical continental air mass) and moist south-westerly wind (Tropical maritime air mass) system. These two air masses usually originate from the high-pressure belt north of the Tropic of Cancer and the high-pressure belt located off the coast of Namibia. The former is always dry as a result of a little moisture it peaks along it path, and the later peaks up moisture over Atlantic ocean crosses the equator and enters Nigeria (Odekunle 2004). The influence of the two air masses in the country is determined largely by movement of inter tropical convergent zone (ITCZ) which serves as a moving boundary between them. The interplay between the two air masses gives rise to two distinct and well-defined seasons in Nigeria, namely, the dry seasons (dust-laden), also known as Harmattan, and the summer (wet or rainy season). These seasons also correspond to northern hemisphere winter and summer (Anuforom et al.,2007; Ogunjobi et al., 2012). In the southern zones of Nigeria, the Harmattan seasons occur between November and February, whereas the summer season occurs between March and

October. In the northern zones, the Harmattan season occurs between November and May, while the wet season takes place between June and September (NFNC, 2003).

Due to the variations in the length of the two seasons (Ogunjobi et al., 2012) across latitude, rainfall as well as its intensity usually begins in the south and move northward while dry season advances from north to south (Odekunle, 2004). Other climatic elements such as temperature, wind speed and relative humidity also varies with season and latitude across the country. During the Harmattan season, the entire country experiences large quantities of dust and smoke from biomass burning that is transported by the prevailing north-east trade winds. During this period, favourable weather conditions also contribute to more dust emission and distribution in the atmosphere. This is in addition to anthropogenic activities that normally arise from high energy demands and increase the pressure on land for agricultural purposes and infrastructure. Therefore, Nigeria can be regarded as one of the most heavily aerosol-laden regions of West Africa, where aerosol studies are of great interest. The period of dust transport over Nigeria is characterize by lower than normal temperatures in the early morning and night time, and hotter weather during the day time.

1.5 Scope of the study

In this study, AI prediction models were developed using ground meteorological parameters. The parameters are wind speed, visibility, temperature and relative humidity. The data are derived from 33 meteorological stations distributed across Nigeria in addition to 31 meteorological stations from neighboring countries of Cameroon, Niger, Chad, and Benin Republic downloaded from NOAA website (http://gis.ncdc.noaa.gov/map/viewer/#app). Aerosol optical depth (AOD), Angstrom exponent α and precipitable water used for the aerosol classification were downloaded from AERONET site at Ilorin Nigeria. The fact that aeronet stations are limited to spatial density, there is only one station in Nigeria, and this station is situated at approximately middle position as such can be used to characterize aerosol in sub-Sahara West Africa. Since from our analysis and based on literature dust is the dominant aerosol type in Nigeria, our analysis further concentrates on dust aerosol. Thus the long-term record of aerosol index from TOMS website http//toms.gsfc.nasa .gov/ and OMI website ftp://jwocky.gsfc.nasa.gov/pub/omi/data/ aerosol were subsequently used as the qualitative measure of dust concentration as used in many literatures.

In the context of this research, Saharan dust means soil dust generated by wind erosion process in the Sahara desert and blown into the atmosphere. It also includes dust generated within the semi-arid Sahel region of West Africa and transported across Nigeria by wind. The Sahel as will be mention in this work stand for semi-arid zone of West Africa stretching from approximately latitude 10^{o}N to 20^{o}N and longitude 16^{o}W to 20^{o}E. It is the transition zone between the dry arid Sahara desert to the north and more humid savannah to the south. Those states of Nigeria lying north of latitude 11^{o}N fall within the West African Sahel. The states are Bauchi, Borno, Kano, Kebbi, Jigawa, Kaduna, Katsina, Niger, Yobe, Sokoto and Zamfara state.

Discrimination of different aerosol with view of determining the dominate aerosol was carried out on the basis of climate change that give rise to seasonal change. This was limited to Toledano et al. (2009) classification criteria using scattering plots of AOD and Angstrom exponent. The fact that many problems associate with dust outbreak exist in literatures that require further research to contribute to what is presently known about Saharan dust in Nigeria. This study focuses only on the meteorological aspect of the problem. How it affect aerosol types, sources, temporal and spatial trend and variability as well as modelling. Other problems such as quantification of aerosol effect on visibility, air qualities etc are beyond the scope of this study. The proposed models are limited to MLR and ANN using the meteorological data described above.

1.6 Novelty and significance of the study

This study is the first empirical correlation models to use in-situ meteorological observations to predict TOMS missing AI. Furthermore, it is also the first based on available literature to use MLR for AI prediction for both TOMS and OMI. However, a similar approach was used by Fuyi et al. (2015a) to develop a model for AOD retrieval. Moreover, the used of ANN as a tool to produces different models that can be used for the predicting OMI AI has also appeared to be unique.

The models are developed based on four selected types of meteorological data from ground observations, namely, (i) wind speed, (ii) visibility, (iii) temperature, and (iv) relative humidity. The AI prediction models based on these measurements are necessary so that missing AI values can be predicted as long as these meteorological parameters are available. These selected meteorological parameters for the study are important factors for indicating the activities of dust particles in the study zones.

The new proposed models are significant because they enable the development of a long-term AI data base for better monitoring and understanding of absorbing aerosol trends (spatial and temporal) and variability over an extended period. The retrieve data can also be used for various meteorological applications, the aviation industry, and air pollution studies.

Understanding the aerosol characteristics and type in a particular region and time is very essential to help improve the accuracy of aerosol prediction models at a regional level. It can also make the determination of the effect of each aerosol in the atmosphere easier. The study of the temporal variations and spatial distribution of the monthly AI in relation to the meteorological parameters is significant in Nigeria because this will increase the understanding of dust activity in this area. Regional studies on the AI monthly variations and spatial distribution have been conducted at different locations such as India Habib et al. (2006); Greece Kaskaoutis et al. (2010) and Pakistan Tariq and Ali et al. (2015). Understanding the AI distribution at a local scale is therefore significant. Furthermore, this study will enable us to gain an in side as well as scientific understanding of changing pattern and extent of aerosol distribution that is vital in our Nigerian aviation industries. It can also be used in the evaluations of the effectiveness of the control strategies for aerosol pollution.

1.7 Outline of the thesis

The content of this thesis is divided in five chapters. In chapter 1, the work presents the introduction of the study that is discussed under various sub-headings: Outline of the study, problem statement, research objectives, scope of the study, novelty and significance of the study, as well as layout of the thesis. In the background, the outline of the thesis is given. It also highlights review from previous literatures that enabled discovery of the knowledge gaps which constitutes the study research problem. Based on this gap, the study objectives were itemized and presented in this chapter. Chapter 2 provides broad reviews of relevant and related works on aerosol issues were documented in this chapter. The chapter enabled an excellent insight into the effort of the previous researchers in lieu of discovering knowledge gap that is considered as the basis for this study. The reviews were group into various parts namely: 1. Global and regional sources of aerosol, 2. Aerosol emission, transport and circulation 3. Aerosol classification methods and several criteria suggested in literature 4. The computation of AI and previous studies on AI estimation and related parameters are also described. 5. Previous studies on the use of ANN in modeling are described in detail.

Furthermore, chapter 3 provides the description of the study area, climate setting, description of Meteorological and Aerosol Data Sites and Sources were presented. Data pre-processing procedure, research procedures and all techniques/method used to achieved the designed objectives are described in detail. However, in chapter 4, the results and discussion of the study are presented. Results on aerosol characteristics and discrimination were first presented. Knowing the dominant aerosol types, results of the long-term trend, mothly and seasonal variability of AI and related meteorological parameters were discussed. This is followed by the result on the spatial distribution of the aerosol and related meteorological parameters. Inter-relationship between aerosol and meteorological parameters and how they influence aerosol variability were discussed. The result on the proposed monthly TOMS and daily OMI AI are discussed. Examination and validation of the proposed models are presented in this chapter. Discussion of comparison of daily OMI AI model with ANN was carried out. Finally, our models were compared with other existing model and errors were accessed and finally, the summary of the work and limitations and sources of errors as well as suggestion for future direction are presented in chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

One major task of this work is the application of meteorological parameters to develop models for the prediction of TOMS and OMI AI for dust monitoring. In view of this, various criteria from the previous works for classifying aerosol were discussed. Various techniques of dust weather monitoring in the related literature are reviewed in this chapter. Relevant background works on regression techniques (simple, multiple and ANN) are covered. This way it is hope that the knowledge gaps which this work aims to fill are identified. However, it is important note that a general review on some of the most important aspect of dust aerosol studies such as dust sources and characteristics of the area, emission, transportation, removal and effect are first reviewed.

2.1 Global sources of dust aerosol

According to other studies dust aerosol has become the most abundant aerosol type in the atmospheric column worldwide (Kaskaoutis et al., 2008). It is the most significant source of atmospheric aerosol in the western Sahel (including Nigeria) (Mbourou et al., 1997). Dust has a number of effects upon environment at global, regional and local scale. The extent of this effect is proportional to physical, optical and chemical properties of the particles, these properties varies as a result of different dust sources and the transport path (Schepanski et al. 2007). It is thus important to adequately describe the sources regions of dust aerosol. The major regions of dust aerosol emission into the atmosphere occur at specific locations on the earth and their distributions are not uniform over the earth surface. Aerosol satellite data and images have been helpful in revealing these major source regions at global scale. Data from TOMS has been of important in this regard. The sources includes

Natural (undisturbed) and anthropogenic (Disturbed soil surface). Disturbed soils are those affected by erosion, deforestation, cultivation and frequent shift in vegetation due to droughts and rain. The MODIS Deep Blue estimates of dust optical depth by Ginoux, et al. (2012) show that anthropogenic disturbance of soil may account for up to 25%; natural sources globally account for 75% of the observed global atmospheric dust emission.

Previously effort has been made to identify and characterize these source areas for dust aerosol emission and these include Prospero et al. (2002); Washington et al. (2003); Ginoux et al. (2004 and 2012); Tanaka and Chiba (2006); Goudie (2009) etc. Prospero et al. (2002) analyzed the frequency of occurrence (FOO) of high absorbing aerosol index (AAI) for various parts of the earth and suggested that the persisted of high AAI in the study areas are associated with major source regions using TOMS AI data for 1979 to 1993. In addition, the periods of most intense dust activities in each source region were identified. The authors identified 9 potential dust sources regions around the globe. The geomorphic and geographical features of the sources region using topographic maps and other sources of information about the terrain and fluvial activities in the area were also investigated. From the study, large number of dusty region extending from the west coast of northern Africa through the Middle East into central Asia seems to be most active in July. The authors described these regions as the global dust belt of the world. They have showed that, the global dust bell extends from the west-coast of Northern Africa over the Middle East, Central and Southern Asia, China. Outside this region there is remarkably little large-scale dust activity. It is also noteworthy that the southern hemisphere is almost devoid of major dust emission activities.

The study according to Washington et al. (2003) however, combines space-borne TOMS AI, National centre for Environmental prediction/National centre for atmospheric research (NCEP-NCAR) reanalysis, and metrological data from ground stations to illustrate and characterize the key source regions of global soil dust (Table 2.1). In their approach long-term mean values of AI were used, where region of high frequency of high AI occurrence or regions of maximum AI as revealed in the Table were used to identify major dust source region. In addition to the work of Prospero et al. (2002), the study also estimated the areas covered by each source region.

Table 2.1: Maximum mean AI values for major global dust sources determined from TOMS (Washington et al., 2003).

Location	Mean A1
Bodele Depression of southern central Sahara	> 3.0
West Sahara in Mali and Mauritania	> 2.4
Arabia (Southern Oman/Saudi border)	> 2.1
Eastern Sahara (Libya)	> 1.5
Southwest Asia (Makran coast)	> 1.2
Taklamakan/Tarim Basin	> 1.1
Etosha Pan (Namibia)	> 1.1
Lake Erye Basin (Australia)	> 1.1
Mkgadikgadi Basin (Botswana)	> 0.8
Salar de Uyuni (Bolvia)	> 0.7
Great Basin of the United States	> 0.5

Furthermore, the study in accordance with Ginoux et al. (2004) also identified these major dust source areas based on the approach by Prospero et al. (2002). The only point of difference is that this study does not directly used AI, however the authors simulated the global distribution of dust aerosol using Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model. From the model, an index was calculated that allow quantitative comparison with TOMS AI. The model was also able to identify and characterize the geomorphologic nature of the major dust source similar to Prospero et al. (2002). They found that about 65% of the global dust emission is associated with North Africa, followed by East Asia which contributes about 25%. The distribution of dust aerosol at global scale in relation to source regions is also provided in the work of Mladenov et al. (2011) (Figure 2.1).

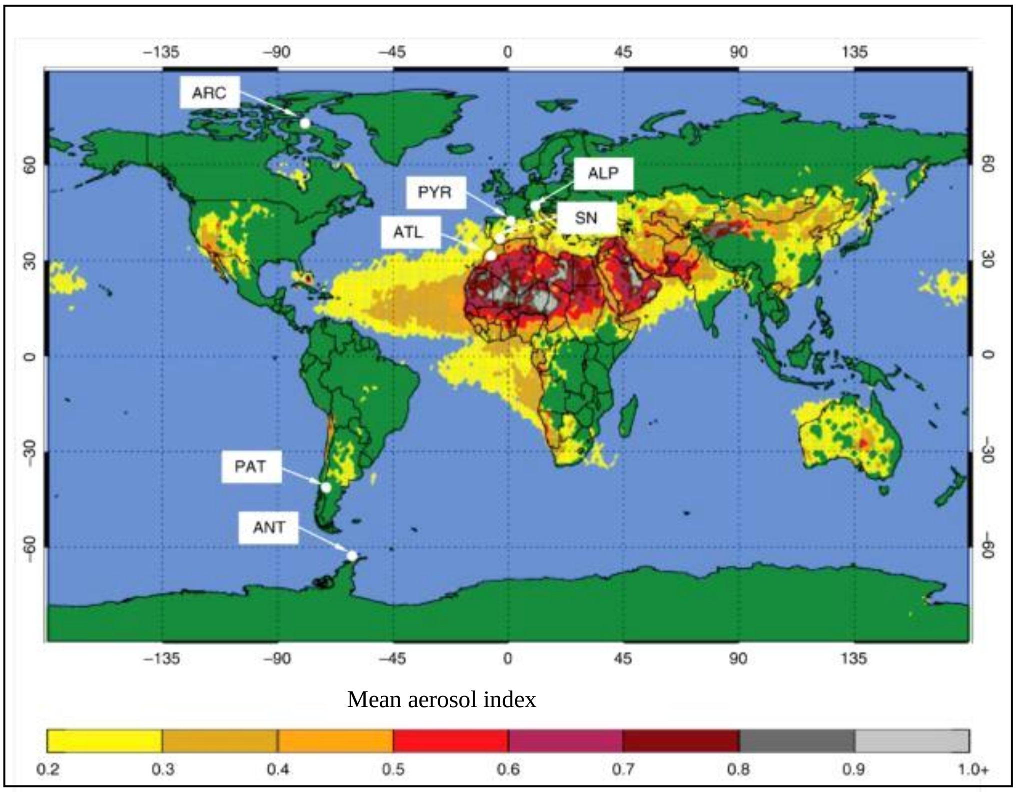

Figure 2.1: Global distribution of dust aerosol from TOMS AI (Mladenov et al., 2011).

The regions identified includes lakes such as ATL (Atlas), SN (Sierra Nevada), PYR (Pyrenees), ALP (Alps) PAT (Patagonian Andes), ANT (Antarctica), ARC (Canadian Arctic). Using MODIS deep blue estimates of dust optical depth by Ginoux et al. (2012) North Africa was found to account for about 55% of the global dust emission with 8% being man made mostly from the Sahel while elsewhere such as Australia, anthropogenic dust emission was estimated to reach about 75%. According to the authors, hydrological (ephemeral lakes) are also important sources of dust aerosol that account for 31% worldwide, 85% of them are anthropogenic while 15% are natural. During rainy season the lakes are inundated and in dry season they became desiccated. The dry soil particles are mobilized and injected into the atmosphere when there is wind speed of about 3.7 ms^{-1}-11.5ms^{-1} (Cowie et al., 2014). The study indicates increased in dust loading from these regions after the flooded areas have dried up. It also indicates that changes in the frequency and extent of inundation lead significant fluctuation in annual and seasonal atmospheric dust loading in the region. The study also revealed that globally, vegetated surface such as shrub and agricultural land account for 20% of the dust emissions.

The study by Tanaka and Chiba (2006) identify sources regions similar to that of Prospero et al. (2002), which dominate the injection of UV- AI (mainly soil dust and smoke from biomass burning) into the atmosphere using numerical simulation with Global Transport Model. The sources identified are located in (i) North and southern Africa (ii) Central Asia (iii) The Arabian Peninsula (iv) the Eastern and Western China (v) Australia and (iv) North and South America. The emission and atmospheric dust load from these sources were further estimated. According to the authors, Northern Africa (Sahara and sub-Sahara region are the greatest contributor to the total dust load in the atmosphere which account for about 58% of the global dust emission and 62% of the total global dust in the atmosphere. For Eastern Asia, the Total dust emission and load in the atmosphere is about 11% and 6%. This dominates the atmospheric dust load in the Asian pacific at about 70%, 60%, 50%, and 40% over China and Mongolia, Korea, Japan and over the North Pacific Ocean. An almost similar observation was made by Goudie (2009) using TOMS AI data where the author identified Sahara (especially Bodele) and western China as the strongest sources globally. Even though some other dry land that are important dust source regions were also identified by the author. These include the Middle East, South west Asia, the Etosha and Mkgadikgadi pan of South Africa, Taklamakan, Central Australia, Great Basin of USA and Salar de Uyuni of Bolivia. The dust emission strength of the identified sources are given in different literature in According to the author, global dust emissions vary between 1000 to 3000 $Tgyr^{-1}$ and Saharan dust emit between 500 to 1000 $Tgyr^{-1}$. The authors described China as the second biggest sources of dust aerosol.

In summary, the conclusions from the above reviewed literatures are particularly relevant to this research. It was concluded that Sahara-Sahel region of Africa are the major and most active dust sources globally. This area was observed to cover large areas dominated by highest mean TOMS AI value indicating high dust concentration and intense dust emission. The Sahara and Sahel contribute nearly half of the mineral dust aerosol in the atmosphere (Li et al., 2004; Goudie, 2009). Li et al. (2004), Kellogg and Griffin (2006) and Goudie (2009) estimated the global dust emission to vary between 1000 and 3000 $Tgyr^{-1}$ in which Sahara-Sahel region contribute as much as 500 to 1000 $Tgyr^{-1}$ and more than half generally originates over West-Africa (Li et al., 2004). The authors also conclude that some areas in the south-easterly of Sahara mainly Bodele Depression located between Tibesi and Lake Chad are the world largest and intense source of mineral dust event not only in the Sahara, but also in the world.

2.1.1 Active dust sources within the Sahara and Sahel

Although the Sahara and it`s margins have long been known to be the major dust source region in the world, however, there are particular areas within the Saharan region that are considered to be most active dust producing areas.

Identification of these dust sources and their period of intense activities is very relevant to this study considering the fact that the dust that affects Nigeria at all the seasons comes from Sahara and its southern fringes (i.e. Sahel) (Prospero and Mayol-Bracero, 2013). Although some of the dust may be locally generated, particularly from the extreme northern parts of the country, the contribution of such local sources to the atmospheric dust loading over Nigeria have not been quantified.

Table 2.2: Comparison of the regional annual mean dust emission (Tgyr^{-1}) between different studies (Tanaka et al., 2006).

	North Africa		Asia			America		Australia	Global
	North	South	Arabia	Central	East	North	South		
Tanaka et al. (2006)	1087 (57.9%)	63 (3.4%)	221 (11.8%)	140 (7.5%)	214 (11.4%)	2 (0.1%)	44 (2.3%)	106 (5.7%)	1877
Werner et al. (2002)	693 (65%)		101 (9.5%)	96 (9.0%)				52 (4.9%)	1060
Luo et al. (2003)	1114 (67%)		119 (7.2%)		54 (3.2%)			132 (8.0%)	1654
Zender et al. (2003a)	980 (66%)		415 (28%)			8 (0.5%)	35 (2.3%)	37 (2.5%)	1490
Ginoux et al. (2004)	1430 (69%)		496 (24%)			9 (0.4%)	55 (2.6%)	61 (2.9%)	2073
Miller et al. (2004)	517 (51%)		43 (4.2%)	163 (16%)	50 (4.9%)	53 (5.2%)		148 (15%)	1019

TOMS data identified the north central Sahel which extend from about 13-18^o N (an area of some 40000 km^2 including Bodele depression between Tibesti and lake Chad, alluvial plain of Faya-legeau in northern Chad and Bilma in Niger) (Schwanghart and Schütt, 2008) as being the most active dust sources.

Unlike other dust source regions, Bodele remain the major active dust source throughout the year (Washington and Todd, 2005). The primacy of Bodele as the most active and intense source of atmospheric dust has also emerge in other satellite derived data such as Multi-angle Image Spectrometer (MIRS) (Zhang and Christopher, 2003). The Infrared Dust Differencing Index (IDDI) (Brooks and Legrand, 2000) and MODIS (Koren and Kaufman, 2004).

Furthermore, the study in accordance with Cowie et al. (2014) provide further evidence which shows that the Sahelian region is a major source of atmospheric dust. According to the authors, even though dust emission from the Sahara region exceed that of Sahel in recent years, Sahel has been identified as the main factor in seasonal and inter-annual variability of dust export. The increasing importance of Sahel as a major dust source may be attributed to the series of drought in this region which intensified since 1970s. In addition, TOMS also identify large area in the Western Sahara and Western Sahel stretches from latitude 20-25^{o}N and longitude 0-7^{o}W, covering portion of Mali, Mauritania and southern Algeria. It also identify East of Sahel-Sahara-Stretching from latitude 13-25^{o}N and around 30^{o}E longitude covering the horn of Africa in southern Egypt and Nubian Desert in northern Sudan as important and active dust source region.

The analysis of Saharan and Sahel dust source region published by various authors (e.g Schepanski et al., 2007; Prospero et al., 2013; Gama et al. 2015), show that different part of this source region are active at different period of the year. In particular Schepanski et al. (2007) reveals that the dust source within the Bodele depression, along with the neighbouring Bilma and Faya-largeau areas becomes active from December to February, reaching maximum in January/February and begin to fades out in March/April annually. This period correspond to the season of high dust loading in the atmosphere over Nigeria and the resultant reduction in visibility. Also 900 to 700 hpa wind charts show that the atmosphere over most parts of the country are under the influence of the wind coming from these source areas.

According to the authors, dust emission usually commences from the eastern part around Egypt and Sudan as well as north central region in December and persists until March, from March/April, intense dust emission switches from these sources to those in Western Sahara (mainly Mauritania). At this time the trajectory of the dust transportation shifts west wards towards Cape Verde (15^{o}N 23.35^{o}W). The transportation of dust over Atlantic Ocean to the Caribbean, reaching the region of Puerto Rico in summer during the months of late May through August takes place along this trajectory. The study according to Gama et al. (2015) back-trajectories and AERONET direct-sun observations also revealed that the dust arriving cape Verde Island from October to March of every year is associated to a sources that is very active in the Sahelian zone (south of latitude 20^{o}N). The above observations suggest that the dust aerosols that affects Nigeria during the dry season originates from a different zone, from that transported to the Caribbean and Southern United States of America. This suggestion is supported by another study of dust source regions using reflectivity in the visible spectrum (Hsu et al., 2004). The authors found that there is more white coloured material in the Bodele Depression of Chad when compared to the other desert sources in Libya, Niger, and West Mauritania.

2.1.2 Characteristics of dust source regions

Dust source regions are characterized by certain physical and geomorphic/geogr-aphic features. These characteristics have been investigated by several authors (e.g Marticorena et al., 1997; Prospero et al., 2002; Goudie et al., 2003; Ginoux et al., 2004; Cowie et al., 2014). A fundamental condition for a source region is that dust particles must be available in significant quantities. This depends on the composition and surface conditions of the soil, as well as the topography of the area. Observations have shown that dust particles that are entrained into the atmosphere originate mainly in soils containing the clay-sized (diameter < 2.5μm) and silt-sized (2.5 < diameter < 60 μm) soil particles. The consideration of these sizes are based on the United States Department of Agriculture and the National Cooperative Soil Survey (USDA) standard. The atmospheric residence times of such particles exceed about 20 minutes (Zender et al., 2003). This means that when the particles are emitted from the soil surface, they remain suspended for sufficiently long time to be transported away from the source by the wind.

Most of these major dust source regions correspond to large sedimentary basins. Study by Goudie (2009) using TOMS AI data reveals that majority of these major source regions are found in arid regions and are centred over topographical low lands that are adjacent to strong topographical highlands. The above observations agreed well with the result of model simulation by Goudie et al. (2003) which show that within the Bodele Depression, the location of peak dust emission coincides with maximum potential sand flux and minimum topography.

Another important feature of major dust source regions is that they receive precipitation runoff from surrounding highlands. Although the source region themselves are arid or hyper-arid (with estimated annual average rainfall < 200 mm) (Washington and Todd, 2005; Rodríguez et al., 2014), there is evidence of fluvial action as shown by the presence of ephemeral rivers and stream, alluvial fans, plavas and saline lakes. These features explain mechanism through which the material removed from the surface are replenished, thereby sustaining the continues dust emission activity of the region. It is believed that precipitation in the highlands weathers the rocks and soil and washes the fine particles downstream to the low lying basin. In the dry season desiccation takes place thereby exposing the fine dry particles to wind deflation when the appropriate meteorological conditions are met. This is a possible explanation for the observation by Washington and Todd (2005) that there must be an efficient re-supply mechanism or feedback system that maintain the variability of dust from these sources year after year.

Tegen et al. (2002) also investigated the degree to which dust emission are controlled by vegetation cover and closed topographic depressions. The investigation was based on dust storm frequency (DSF) data derived from visibility measurement from over 2400 meteorological stations worldwide. The study showed that average DSF is inversely correlated with leaf area index (an index of vegetation density) (LAI) and net primary productivity (NPP). In non forested regions, the authors found that DSF increases as the fraction of closed topographic depression increases. This is attributed to the accumulation of the fine sediments in these areas. The finding demonstrate the importance of incorporating vegetation and Geomorphic setting as explicit controls on emissions in global dust cycle models.

2.2 Dust cycle in the atmosphere

Dust emission from dry and erodible soil surface is the first stage of atmospheric dust cycle. This is followed by lofting the dust particles to the higher altitudes, and then transportation away from the sources and finally eventually deposition. These processes have been considerably studied by several authors using both observational data and modelling techniques (Zender et al., 2003).

2.2.1 Production of dust from the source region

Production of mineral dust from dry soil surfaces in arid and semi arid areas by wind erosion involves saltation, sandblasting and entrainment. These phenomena depend on soil and surface properties such as roughness, vegetation cover and erodibility. Saltation and sand blasting processes are discussed extensively in several research publications

(Marticorena et al., 1997; Gillette et al., 1998; Alfaro and Gomes, 2001; Grini et al., 2002; Zender et al., 2003; Grini and Zender, 2004; Gherboudj et al., 2015).

Wind friction and threshold wind friction velocity are the key parameters in calculation of the rate of emission of dust from soil surface. This is because the total amount of dust mobilized into the atmosphere from any geographical location over a given periods depend on the frequency and intensity of the wind events. For dust emission to be initiated, threshold friction velocity which is a function of soil texture, surface roughness, soil moisture and grains size distribution has to be attained. Some research activities that have been under taken to quantify these parameters include Gherboudj et al. (2015); Cowie et al. (2014). In particular Cowie et al. (2014) focused on Sahel and Sahara regions and found that the threshold velocity for dust emission is about 3.7 ms^{-1} (lowest) in Sudan from the east to 11.5 ms^{-1} (highest) in the northern Algeria to the west respectively.

Lu and Shao (1999) and Shao and Dong (2006) analyzed the processes of saltation from energy perspective and propose that a substantial part of this kinetic energy is absorbed by the plastic deformation of the soil. However, Tegen et al. (2013) suggest that available observations are insufficient to confirm this hypothesis of dependency of dust emission by saltation on the plasticity of the soil. The potential energy binding the dust particles to the soil surface is an important factor in soil dust emission by particles in saltation motion as it determines the ease with which dust is emitted. Cowie et al. (2014) have shown that the number of particles dislodge from the soil surface per saltation impact is proportional to the ratio of kinetic energy loss during the impact to the typical binding potential energy holding a dust particle to the surface.

Research into factors affecting frictional velocity and hence rate of dust emission, show that this parameter depends on (i) soil wetness (moisture), (ii) drag partitioning of the wind stress between erodible and non-erodible soil surface element and (iii) Owen effect. The effect of soil moisture on the threshold wind friction velocity is discussed extensively by Gherboudj et al. (2015). The increase in the threshold frictional velocity for saltation due to