THE ROLE OF LAND-ATMOSPHERE AND AEROSOL INTERACTIONS ON MESO-SCALE CONVECTIVE WEATHER SYSTEMS ACROSS WEST AFRICA

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by
OLUSEUN SAMUEL IDOWU

B. Sc., University of Agriculture, Abeokuta, Nigeria, 1999
M. Sc., University of Pretoria, Pretoria, South Africa, 2009

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THE ROLE OF LAND-ATMOSPHERE AND AEROSOL INTERACTIONS
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Oluseun Samuel Idowu, Candidate for the Doctor of Philosophy Degree
University of Missouri - Kansas City

ABSTRACT

This dissertation investigates the modulating effects of land-atmosphere and aerosol interactions on meso-scale convective systems across the sub-Saharan West Africa region, and aims at providing a value-added contribution towards better understanding of the controlling mechanisms for these interactions, in order to improve predictability of the highly frequent, high-impact meso-scale convective systems. It is very well known that aerosols alter the surface energy budget resulting into complex and multi-scale interactions between the land-atmosphere and meso-scale convective systems, which are yet to be fully understood. In this study, we used a highly proven successful cognitive recognition artificial neural network intelligence problem solving tool – Self-Organizing Maps (SOM) in investigating the modulating effects of aerosol-land-atmosphere interactions for enhancing the predictability of meso-scale convective systems. The SOM method is not yet commonly used by climate scientists for solving climate research problems. For the first time in this research – at least to the best of our knowledge – we used the SOM method to solve climate research problems over Africa. Our results show very strong seasonal influence in determining the dominant controlling variable (e.g. soil moisture, aerosols) on the interactions between atmospheric aerosols, meso-scale convective systems and land-surface properties across the study region. It was also found that these controlling variables are generally very significant in modulating atmospheric interactions across the region during the monsoon (wet) seasons than during the non-monsoon (dry) seasons. Furthermore, results showed that even though there is noticeable control by aerosols on the interactions between land-atmosphere and meso-scale convective systems, available surface soil moisture exerts the most dominant control across the region especially during the active convective period (monsoon season) of the year. Results further showed that soil moisture has the potential to control the convective available potential energy (CAPE) up to about 79% during the monsoon season and up to about 67% during the non-monsoon seasons, while aerosols can control CAPE up to about 67% during monsoon and up to about 23% during the non-monsoon season.

This abstract of 324 words is approved as to form and content.

Syed E. Hasan, Ph.D.
Professor of Geosciences
College of Arts and Sciences

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the College of Arts and Sciences, have examined the dissertation titled "The Role of Land-Atmosphere and Aerosol Interactions on Meso-scale Convective Weather Systems across West Africa" presented by Oluseun Samuel Idowu, candidate for the Doctor of Philosophy degree, and certify that in their opinion it is worthy of acceptance.

<u>Supervisory Committee</u>

Syed E. Hasan, Ph.D., Committee Chair
Department of Geosciences

Jejung Lee, Ph.D.
Department of Geosciences

Jie Chen, Ph.D.
Department of Mathematics and Statistics

Kamel Rekab, Ph.D.
Department of Mathematics and Statistics

Anthony Lupo, Ph.D.
Department of Soil, Environmental & Atmospheric Sciences
(University of Missouri, Columbia)

Nathaniel Brunsell, Ph.D.
Department of Geography – Atmospheric Sciences Program
(University of Kansas)

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DEDICATION

This work is dedicated to:

God Almighty

And

My darling wife, **Olukemi Idowu** and our four lovely children

CHAPTER 1

INTRODUCTION

1.1 Background

Aerosols are natural and anthropogenic solid and/or liquid particles of different compositions, sizes, shapes and optical properties suspended in the air. Examples of natural aerosols include desert or soil dust, wildfire smoke, sea-salt, biogenic particles and volcanic ash. Anthropogenic (or manmade) aerosols, which mostly originate from highly populated industrialized and agricultural areas of intense fossil fuel and biomass burning include smoke from domestic fire and other combustion products, smoke from agricultural burning, soil dust created by overgrazing and deforestation and draining of inland water bodies. Atmospheric aerosols are quantified by their mass concentration or an optical measure called aerosol optical depth (AOD) (also called aerosol optical thickness, AOT).

Large-scale variability in land-surface characteristics significantly affects global climate despite that land covers only about 29% of the earth's surface. Land-atmosphere interactions determine how changes in surface boundary layer conditions affect atmospheric circulations and climate patterns. The major land-atmosphere interaction mechanism is the influence of surface albedo on the moisture flux convergence. From the equator to the subtropics, and vice versa, the Hadley cell circulations, which are thermally driven, are strengthened by changes in the magnitude of the surface albedo characteristics. For instance, high surface albedo reflects significant portion of the incoming solar radiation back to space thereby causing tropospheric cooling. In response to this cooling, surrounding air converges – resulting into localized subsidence, and as the air descends via subsidence, it becomes compressed, warmer and drier thereby inhibiting precipitation (Moorcroft, 2003; Brunsell et al., 2011). It has been argued that a mere 20% reduction in the desert surface albedo conditions by introducing vegetation could significantly weaken the controlling inhibiting mechanisms across the desert, reducing the magnitude of moisture flux convergence and consequently increasing precipitation across the Sahara (Charney et al., 1975). The intensity of the Hadley cell circulations have been closely linked with seasonal changes in the intensity of drought events across sub-Saharan West Africa region (SWA) (Lamb, 1983; Lupo et al., 2012).

Anthropogenic land-cover changes resulting from the increase in agricultural and other human activities provide significant changes to various land surface physical properties (e.g. surface roughness, surface albedo, leaf area index, rooting depths). This landscape heterogeneity caused by land-cover changes is a major forcing for the development of local convective cumulus clouds that could potentially trigger the development of meso-scale convective systems (MCS) (Pielke et al., 2007; Brunsell et al., 2011). Most atmospheric thunderstorms and cloud-to-ground lightning strikes occur over the land. The preference for deep convection over land is due to the sufficiently large convective available potential energy (CAPE) over land. Apart from the significant roles of the Hadley and Walker cell circulations in the equator-to-pole exchanges of surface energy – as earlier mentioned, thunderstorms, also called 'hot towers', serve as conduit for the transport of heat, moisture and wind energy from the equator to higher latitudes. The effects of the interactions between aerosols and the terrestrial ecosystems on meso-scale convective systems are therefore multidimensional and nonlinear since they usually extend beyond the location of the primary source of perturbations (Lamb, 1983; Niyogi et al., 2010).

Nearly all of the tropical cyclones that occur across the Eastern Pacific Ocean have their origin traced back to Africa. The warm Tropical Ocean provides the driving moisture for tropical convection while at the same time increasing the available moist static energy at the tropical cyclone boundary layer. The intensification or dissipation of a tropical cyclone is largely dependent on the environmental thermodynamic and dynamic conditions (e.g. vertical wind shear, ocean temperatures, relative humidity). Meanwhile, the dry and dusty air across the Sahara Desert and North Africa causes evaporative cooling thereby accelerating downdrafts and causing convection to rapidly collapse. On the other hand, however, the African easterly waves (AEW) acts as the seeding circulations for a large proportion of the tropical cyclones that occur across the North Atlantic Ocean. The year-to-year changes in the intensity and locations of the African easterly waves (AEW) have therefore been closely linked to tropical cyclone activities across the Atlantic and East Pacific Oceans (Freud & Rosenfeld, 2012; Lupo et al., 2012).

Atmospheric blocking is another sensitive phenomenon to the sea surface temperature (SST) anomalies and variations in tropical precipitation. Northern hemispheric blocking mostly influences the sign, magnitude and variability of tropical SST biases, which consequently modulates the Sahel temperature and precipitation. Meteorological causes of most of the drought cases across the Sahel have been attributed to the presence of blocking mechanisms that discourages adequate rainfall. On both local and large scales, Sahelian drought outbreaks have been closely linked with the southwest displacement of some important feature of the general circulation e.g. the southward displacement of the subtropical anticyclones. Sahelian droughts have also been closely connected to changes in the location and intensity of the tropical easterly jet (TEJ) and the African easterly jet (AEJ), which are known to alter the intensity, frequency of formation, and propagation of MCS. A very good example is the 1984 East Africa drought, which was blamed on the blocking of tropical cyclones in the western Indian Ocean, especially those that remain quasi-stationary for several days, thus sucking in moisture from central and Eastern Africa. On the other hand, rainfall enhancements in the Sahel tend to be maximized along windward slopes where cross-mountain flow is strongest. If the flow is blocked, the precipitation maximum may be shifted offshore away from the windward slope. Under more extreme flow blocking, the front may split, with the front aloft running ahead of the surface front, which could eventually destabilize the environment thereby leading to convective precipitation enhancement along the windward slopes. Blocking therefore significantly impact both the tropical (especially the Sahel region) and mid-latitude climatological distribution of temperature and precipitation (Lupo et al., 2012; Tao et al., 2012).

Aerosols directly and/or indirectly affect the Earth's radiation energy budget (Huang et al., 2009; Niyogi et al., 2010). For example, the direct effect of aerosols on the Earth's radiation budget involves the brightening of the planet by directly scattering the incoming solar radiation back into space within the short and long wave radiation spectrums (Charlson et al., 2007; IPCC, 2007; Myhre et al., 2003; Seinfeld et al., 2004; Ramanathan et al., 2007). The primary indirect effect of aerosols, on the other hand, involves the modification of cloud microphysical properties (e.g. cloud sizes, amounts, and brightness), thereby affecting cloud life cycles and their ability to reflect and absorb solar radiation (Haywood & Boucher, 2000). Non-absorbing aerosols such as sulfates, nitrates and organic carbon (e.g.

Pilinis et al., 1995) scatters solar radiation back into space causing a negative radiative forcing i.e. cooling of the earth system. Absorbing aerosols such as black carbon (or soot) from biomass burning, fossil fuels and mineral dust from arid regions absorbs incoming solar radiation, modifies temperature structure of the atmosphere, and also influences cloud cover causing a positive radiative forcing i.e. the warming of the earth system (Hansen et al., 1997; Johnson et al., 2004).

Apart from altering the surface energy budget, aerosols have multi-scale complex modulating effects on land-atmosphere interactions and coupling (see Hollinger et al., 1994; Gu et al., 2003; Douglas et al., 2006; Niyogi et al., 2006; Huang et al., 2009). For example and as explained by Niyogi et al. (2006), scattering (or absorbing) aerosols lowers (or increases) boundary layer (BL) temperature, enhances (or weakens) atmospheric capping inversion, and reduces (or increases) the BL height. They further argued that changes in radiation and temperature as a result of atmospheric aerosols could cause modification of surface energy balance or the Bowen ratio, which could in turn cause stronger land–atmosphere coupling, suppression of regional soil moisture, and higher surface albedo. These feedbacks invariably could lead to lower CAPE and could consequently suppress, alter and modify regional precipitation characteristics and patterns.

The complex effects of aerosols on clouds and precipitation processes especially on MCS and their land-surface interactions and feedbacks are being actively studied. For example see Niu & Li (2011), Freud & Rosenfeld (2012), Konwar et al., (2012) and Tao et al. (2012). It is quite challenging studying aerosol-land atmosphere interactions and feedbacks since aerosols are immensely diverse not only in their composition and origin but also in their spatial and temporal distribution.

This dissertation investigates and analyzes the impacts and modulating mechanisms of aerosols on atmospheric convective processes and land surface interactions and feedbacks across the SWA region. The dynamics of the Sahelian dust particles and their role in the inter-annual variability of rainfall regimes and their resultant effects on land-surface characteristics are also closely examined. The study contributes to the scientific understanding of the mutual interrelationships and feedbacks between aerosols, convective systems and land-atmosphere interactions to help improve the predictability of the highly frequent, high-impact weather systems across the study region.

1.2 Motivation for the Research Study

In recent years, a lot of research attention especially in the climate community has been dedicated to the understanding of the significant role aerosols play on atmospheric convective and land-surface interactions and feedbacks (Lee et al., 2008; Rosenfeld et al., 2008; Fowler et al., 2009; Freud & Rosenfeld, 2012; Konwar et al., 2012; Niu & Li, 2011; Tao et al., 2012). Several studies (for example Ray et al., 2010; Freud & Rosenfeld, 2012; Tao et al., 2012) have shown that aerosols semi-directly, directly and/or indirectly alter the Earth's radiation budget thereby exhibiting complex modulating effects and feedbacks on land-surface characteristics, land ecosystems and heat and momentum exchanges, which also significantly affect the intensity and severity of the triggering and dissipating mechanisms of rain-bearing mesoscale convective systems. As earlier mentioned, the study area – the SWA region, is the global hot spot for aerosols. Bordered in the north by the Sahara Desert (the world's largest dust source region), the study area also has the highest amount of biomass burning per square kilometer in the entire world. Records (e.g.

Zhang et al., 2008; Freud & Rosenfeld, 2012; Tao et al., 2012) show that nearly all of the tropical cyclones and hurricanes that occur in the Eastern Pacific Ocean can be traced back to those meso-scale convective developments across the SWA where aerosols are abundantly available. Unfortunately, however, there have been very few studies over this region especially when compared with Europe and Asia, at least to the best of our knowledge, that specifically connect aerosols with atmospheric convective variables and land atmosphere interactions and feedbacks.

Most of the available previous studies (e.g. Dunion & Velden, 2004; Matsuki et al., 2010) have dealt with how aerosols affect either the atmospheric convective variables or the land-surface variables separately rather than looking at their implications and modulating effects on both the convective variables and land-surface characteristics altogether as presented in this dissertation. This study therefore provides a unique opportunity whereby the modulating effects of aerosols are closely investigated as they interact and give feedbacks and exchanges between atmospheric convective and land-surface variables. This is a significant contribution to the scientific understanding of the mutual interrelationships and feedbacks between aerosols and convective systems, which is expected to improve the predictability of the highly frequent, high-impact weather systems that originates from the study area and traveling across the entire globe.

1.3 The Aim and Objectives of the Study

It is very well known that aerosols alter the surface energy budget, which consequently results into multi-scale and complex modulating effects on the land-atmosphere interactions and coupling – which is yet to be fully understood. Hence, the primary goal of this research is to closely examine the role of aerosols and land-atmosphere interactions on meso-scale convective systems across the SWA region. This is aimed at providing some of the critical knowledge and information needed to improve our understanding of the multi-scale and complex aerosols-land-atmosphere interactions, in order to improve our predictability of the highly frequent meso-scale convective systems across the region. Some of the research questions to be answered in this dissertation include:

(1) What are the competing roles of aerosols and land-atmosphere interactions on meso-scale convective systems across the region?
(2) Can we firmly establish and quantify seasonal control of aerosols and land-atmosphere-interactions on meso-scale convective systems across the region?
(3) Can we clearly establish connections between the distribution of aerosol concentrations and land-atmosphere interactions on meso-scale convective systems across the region?

Based on the these questions, we hypothesize in this research that:

(1) There are significant exchanges between aerosols and land-atmosphere interactions, which competitively affect meso-scale convective systems across the region.
(2) There is a very strong seasonal control on how the interaction between aerosols and land-atmosphere affects meso-scale convective systems across the region.
(3) There is a close connection between aerosol concentrations and land-atmosphere interactions and their effect on meso-scale convective systems across the region.

These hypotheses provide value-added contributions to our understanding of the mutual relationships between aerosols and land-atmosphere, for better predictability of the high-impact meso-scale convective systems across West Africa. The overall aim of this dissertation will be achieved through the following objectives:

Objective 1

Determine the most dominant mesoscale convective and land-atmospheric variable(s), which interact and interrelate strongly with atmospheric aerosols across the SWA region.

Objective 2

Statistically quantify the interactions between atmospheric aerosols, land-atmosphere and meso-scale convective variables across the region.

Objective 3

Investigate the seasonal trends, differences and/or similarities, if any, in the existing interrelationships and interactions between aerosols, land-atmosphere and meso-scale convective variables across the region, and then closely connect them with improving the predictability of meso-scale convective systems across the region.

The spatial redistribution of aerosols in the atmosphere is closely linked to the large-scale atmospheric dynamical patterns (Marticorena et al., 2011). The Saharan Air Layer (SAL) is an example of the large-scale dynamical pattern responsible for the distribution and redistribution of aerosols across West African region extending sometimes into the Tropical North Atlantic. The SAL is a dry and dusty air mass from the Sahara Desert and North Africa blowing across the Tropical North Atlantic Ocean every 3-5 days during the dry season i.e. October-November-December

(OND) and January-February-March (JFM). There are three major mechanisms associated with the SAL, which inhibits the formation or reduce the intensity of tropical cyclones. The first mechanism is the introduction of dry air, which promotes downdrafts and disrupts convective organization within tropical cyclones. Tropical cyclones need moist warm air, specifically in the mid troposphere in order to form convective clouds. The SAL, however, contains dry air in the middle troposphere, which acts to erode convective clouds, sapping all of the moisture as clouds rise through the middle troposphere. The second mechanism that influences tropical cyclones is the mid-level jet found within the SAL. The mid-level easterly jet is a result of the thermal wind balance between the warm, dry air in the SAL, and the cooler, moist tropical air to the south. Increasing wind velocities, especially at 3-5 km causes lower level circulation to move ahead of upper level circulation, decoupling the storms vortex, and thus disrupting the heat engine organization of tropical cyclones. The third mechanism associated with the SAL is the radiative effects of the dust in the SAL, which may enhance the preexisting trade wind inversion and act to stabilize the environment, thereby suppressing deep convection (Talbot et al., 1986; Dunion & Velden, 2004).

For the purpose of this study, the area extending from longitude 15.00°West (W) to 15.00°East (E), and latitude 5.00°North (N) to 20.00°North (N) has been selected as study area and is defined as the sub-Saharan West Africa (SWA) region. The detailed geographic and climatic description of this study area is presented in Chapter 2. The study region (the SWA) is very critical to the study of aerosols-land-atmosphere interactions because it is universally known as the global hot spot for aerosols. Apart from this region being bordered in the north by the Sahara Desert (which is the world's largest atmospheric mineral dust source), it has the highest intensity of biomass burning per square km across the globe (Huang et al., 2009; Matsuki et al., 2010; Stier et al., 2005; Foltz & McPhaden, 2008; Ichoku et al., 2008; Niyogi et al., 2010). Most of the mineral dust aerosols over this region originates from the northernmost portion (Lat. 12.00-20.00°N), areas closest to the Sahara desert while the carbonaceous aerosols, mostly from biomass burning, originates from the central (Lat. 8.00°N to 12.00°N) and the equatorial portions (Lat.3.00°N to 8.00°N) of the study region (Prospero & Lamb, 2003; Washington & Todd, 2005).

The paucity of aerosol measurements over the SWA region led to several observational field campaigns. To mention just a few, there was the Saharan Dust Experiment (SHADE), which focused on the measurements of mineral dust outbreaks across the region. Another major and recent field campaign is the African Monsoon Multidisciplinary Analysis (AMMA) project that was also launched to provide valuable data sets of both in-situ and remote sensing measurements including satellites across the region. The Dust and Biomass Experiment (DABEX) was also developed as part of the AMMA dry season Special Observation Period (SOP-0) (see Hourdin et al., 2010). There was also the Dust Outflow and Deposition to the Ocean (DODO-1) project. All these field-campaigns have led to increase availability of aerosols observational and modeling data. Meanwhile, scientists have yet to formulate a clear-cut explanation on the complex dynamics, interactions and feedbacks between aerosols, land-surface characteristics and the atmosphere. Aerosols indirect effect on clouds is probably the largest of all the uncertainties about global climate forcing (National Research Council, 2005). Scientists have yet also to completely understand why some convective cloud clusters move rather slowly and some like the squall lines move fast across the SWA region and aerosols are being hypothesized to play a major role in this characteristic convective system behavior. Because of these knowledge gaps, accurate prediction and detection of potential areas of initiation and formation of these convective weather systems remains very difficult, even though there has been tremendous improvements as new research results are implemented.

1.4 Organization of the Dissertation

Our results from closely examining the aerosols and land-atmosphere interactions and their effects on meso-scale convective systems across the SWA region are presented here in this dissertation. As mentioned before, we know that aerosols plays crucial role in the atmospheric hydrological cycle and radiation budget. Again, our study region – which is the SWA region, is known as the global hot spot for aerosols. Most of the devastating high-impact super storms and hurricanes that had affected Europe and North America have their origins traced back to meso-scale convective developments across our study region. Hence, as we better understand the interactions and interrelationships between aerosols, land-atmosphere and meso-scale convective systems across the region, through the efforts in this work, we can help improve the predictability of these severe and high impact convective storms. Chapter 1 provides a conceptual overview of the research statement while clearly stating the hypotheses together with the aims and objectives of research study.

Chapter 2 presents a comprehensive literature review of the previous and relevant research studies. The scientific review of past efforts and summary of current understandings of the effects of aerosols and land-atmosphere interactions on convective precipitation processes, from both theoretical microphysical and observational evidences are also presented as part of this chapter. In addition, a conceptualized schematic diagram was developed and presented in this chapter to explain our background knowledge on the complex multi-scale modulating effects of aerosols and land-atmosphere interactions on meso-scale convective processes across the region.

Chapter 3 gives detail description on the geography and climatology of the study region. The three major identified climate zones (i.e. the wet equatorial, wet and dry climate and the semi-arid climate zones) across the study region were also clearly discussed. Also as part of this chapter, we have discussed the linkages and close connections between the Inter-Tropical Convergence Zone (ITCZ) and prevailing weather patterns across the region.

Chapter 4 presents a comprehensive description of the data collection, data analysis and the research methodology used in this study. Also in Chapter 4, a very short synopsis was given on the two major data sources used in this study – i.e. the ERA-Interim reanalysis data –obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the MODIS Aqua Aerosols Optical Thickness data that was obtained from the US National Aeronautics and Space Administration (NASA). Another important aspect of this chapter is the section that discusses our use of the highly proven successful (Hewitson & Crane, 2002) cognitive recognition artificial neural network intelligence problem solving method – Self-Organizing Maps (SOM) (Kohonen, 2001). The SOM is gradually becoming popular in climate research and we have for the first time (with this research), at least to the best of our knowledge, used this method to investigate climate research problems in Africa.

In Chapter 5, the results and discussion was presented. The highlight of the results is summarized under the discussion and summary section (section 5.7) of the chapter. Future research directions and concluding remarks are outlined in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A review of the relevant literatures outlining fundamental theories and background on the mechanisms involved in the coupling of aerosols, land ecosystems and atmospheric convective systems is presented in this section. Previous studies and the summary of current understanding of the effects of aerosols on convective precipitation processes from both microphysical theoretical and observational evidences are also presented.

2.2 Aerosols, Terrestrial Ecosystems and Atmosphere Interactions

Complex interactions and feedback exists between aerosols, meso-scale convective systems and terrestrial ecosystems. A conceptual framework was developed by Barth et al. (2005) to study the feedbacks between terrestrial biosphere and atmosphere using biogenic aerosol pathway – see Fig. 2.1. Aerosols-atmosphere and terrestrial ecosystem interactions are very important to both direct and indirect radiative processes. As such, the interactions between aerosols and terrestrial ecosystems play a significant role in controlling the flux exchanges between the land-surface and the atmosphere. It is therefore important to clearly understand these processes and how they interact and interrelate with each other in order to better understand the changing climate, regional and global atmospheric chemistry, land cover changes, including biodiversity and ecological changes (Niyogi et al., 2010).

Terrestrial ecosystems serve as both a sink and a source (dependent on the type of aerosol) for atmospheric aerosols. When coupled with the atmosphere, they act as controlling interface for atmospheric heat and moisture flux exchanges. Land surface characteristics such as albedo, surface roughness, and latent/sensible heat fluxes significantly controls the rate of moisture transport into the atmosphere, how these moisture are processed, and how they eventually return back to the surface (Barth et al., 2005; Douglas et al., 2006; Fowler et al., 2009).

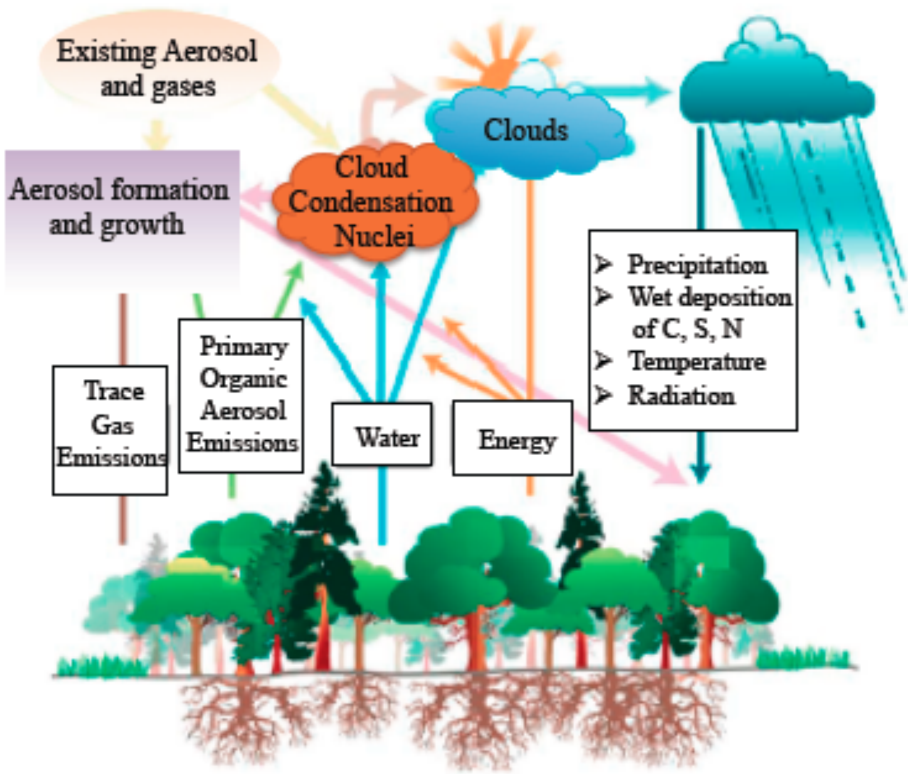

Fig. 2.1. Schematic diagram of the coupling between terrestrial ecosystem and the hydrologic cycle via energy and water exchange and aerosols processing. Redrawn from Barth et al., 2005.

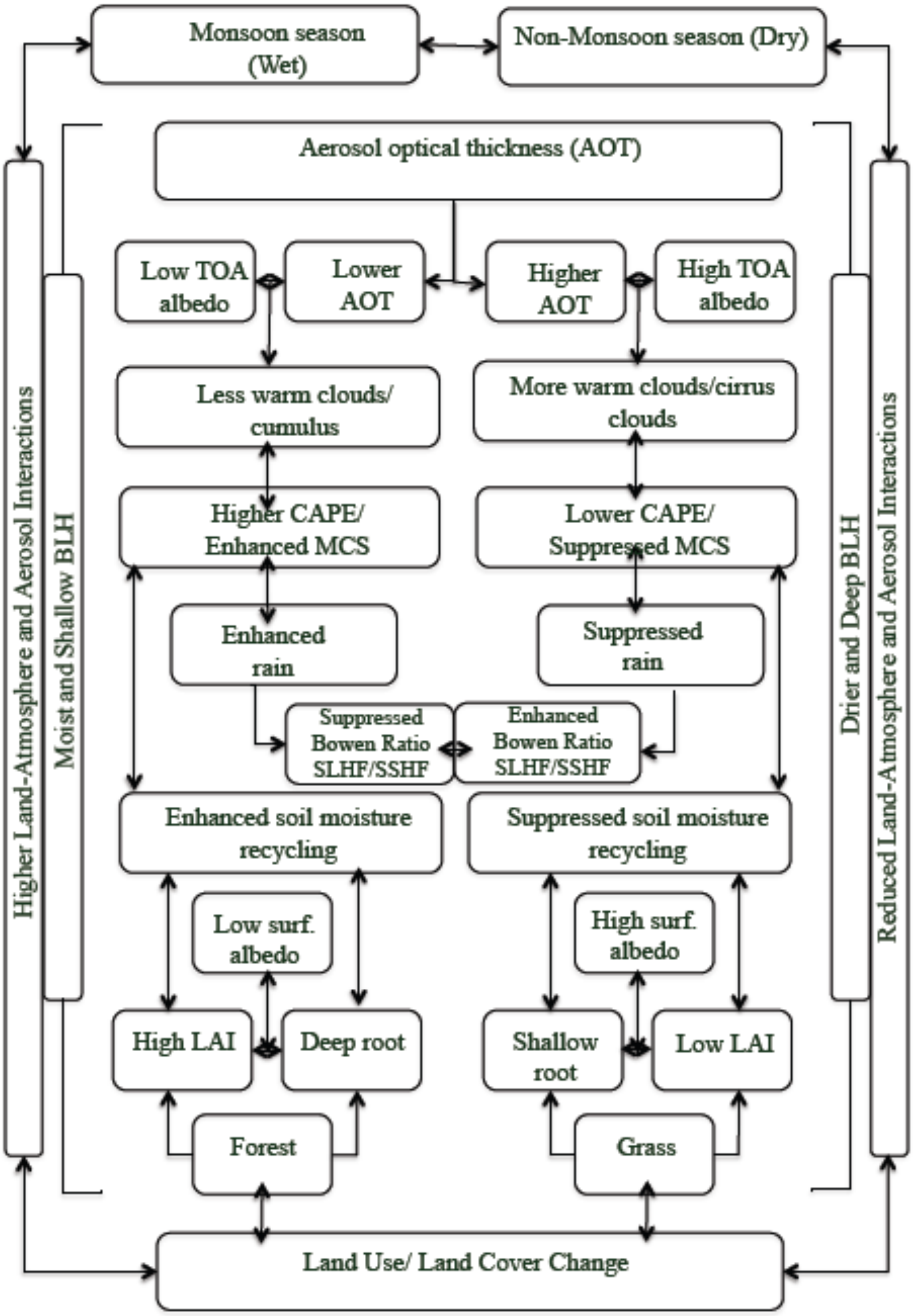

Fig. 2.2. Schematic representation of the role of land-atmosphere and aerosol interactions on meso-scale convective weather systems across the sub-Saharan West Africa (SWA). CAPE convective available potential energy, BLH boundary layer height, TOA top of the atmosphere, MCS meso-scale convective systems, LAI leaf area index, SLHF surface latent heat flux, SSHF surface sensible heat flux. Modified from (Niyogi et al., 2006; Pielke et al., 2007).

Moisture and heat flux exchanges between aerosols, terrestrial ecosystems and atmosphere presents complex, multi-variate and multi-scale climate research problems. For instance, accurately representing aerosols direct, semi-direct and/or indirect effects and their interactions with atmosphere and terrestrial ecosystems remains one of the largest uncertainties in climate models (IPCC, 2007). We are yet to fully understand how the interactions and feedbacks between aerosols-atmosphere and terrestrial ecosystem influences local and regional meso-scale convective systems. However, we understand, to some extent, how soil water content controls infiltration rates, deep percolation and runoff and how they control the heat budget of both the soil and near-surface atmosphere thereby controlling the coupling between land-surface flux exchange processes and the planetary boundary layer (PBL). We also know that soil water volume controls terrestrial ecosystem dynamics especially in conditions of scarce water availability and in environments where soil water contents reduces transpiration rates, carbon assimilation and biomass productions (Fowler et al., 2009). With this knowledge, the controlling effects of aerosols on biogeochemical and atmospheric hydrological cycles have been examined in the context of energy and water exchanges between terrestrial ecosystems and the atmosphere (Duyzer, 2005).

Evapotranspiration is not only controlled by surface hydrology but also by vegetation structure, plant physiology and the prevailing atmospheric conditions such as solar radiation, air temperature and humidity. Evapotranspiration rate from a particular region can considerably change with a noticeable gradual change in vegetation patterns when the soil dries and the vegetation pattern changes. Fowler et al. (2009), for example, discussed in detail how plant stomatal structures act as sinks to atmospheric aerosols thus affecting atmospheric moisture flux exchanges. Again, most indicators of atmospheric conditions are modulated by the absence and/or presence of clouds or cloud optical properties, and precipitation. Thus, the amount of suspended moisture in the atmosphere coupled with the amount of moisture returning back to the earth surface affects many of the key properties of the land-atmosphere (Barth et al., 2005).

Pielke et al. (2007) examined how the terrestrial ecosystem controls flux exchanges between aerosols and the atmosphere using both theoretical background and climate model experiments. They used early, very simple to complex recent efforts land-surface models, including the coupling of biophysical processes to investigate atmospheric carbon exchange. It was found that most of available land-surface models were not able to completely resolve aerosols effects on the atmosphere and terrestrial ecosystem interactions. They suggested that the inability of these models to completely capture the complex interactions between aerosols and the terrestrial ecosystems was due to the complex spatiotemporal variability of land-ecosystems.

Climate models use simplified sub-grid scale parameterization schemes when representing the chemical and physical components of interactions between terrestrial ecosystems and the atmosphere. These models cannot completely resolve the complex interactions and processes existing between aerosols and the atmosphere because of the limited available computational power and the insufficient observations for model initial conditions. A good representation of the characteristics and coupled interactions between aerosols, land ecosystems and the atmosphere in climate models through continuous improvement of the model parameterization schemes is a key component to increasing our understanding of the complex atmospheric processes (Idowu & Rautenbach, 2009; Giorgi et al., 2009).

Despite the above-mentioned limitations in climate models, they remain viable tools in predicting and studying climate processes. For example, scientists used land-surface models to study the earth's carbon cycle especially how the natural terrestrial carbon sinks moderates CO_2 increases in the atmosphere (Prentice et al., 2001). It has also been shown (e.g. Fowler et al., 2009) that little perturbations to terrestrial ecosystems coupled with aerosols, could strongly affect the sensitivity of the local environments to such perturbations. Furthermore, increasing global environmental challenges such as threats to biodiversity, flooding, soil erosion/nutrient loss to both surface and underground water have been closely linked with characteristics changes in terrestrial ecosystem and their interactions with aerosols and atmosphere. Changes in land-surface characteristics result in corresponding changes in available surface energy consequently leading to available surface moisture being partitioned into sensible and/or latent heat, evaporation and/or runoff (Pielke et al., 2007; Chen et al., 2011; Tao et al., 2012).

2.2.1 Deposition of aerosols onto terrestrial surfaces

Aerosols are major condensation nuclei in the atmosphere, acting as the critical source of pollutant deposition onto and re-suspension from terrestrial ecosystems. Aerosols deposition is the pathway process whereby suspended aerosols in the atmosphere are collected or deposited onto solid surfaces decreasing their suspended concentration in the atmosphere. Aerosols deposition process can be classified into two types – dry and wet deposition. Dry deposition occurs when suspended aerosols in the atmosphere are transported and deposited onto terrestrial surfaces without mixing with water. The turbulence rate, aerosols dominant chemical composition, and nature of the surfaces onto which they are being deposited plays significant influence on dry deposition process. Atmospheric aerosols are mostly depleted by dry deposition process (Lovett, 1994; Rosenfeld et al., 2008; Tao et al., 2012)

Wet deposition, also called wet scavenging, is the process whereby suspended aerosols are removed from the atmosphere through hydrometeors such as rains, clouds or fog. Wet deposition or wet scavenging is the most efficient atmospheric aerosols cleaning/removal mechanism. It is a little more complicated and important than the dry deposition. Wet deposition is involved in all of the processes of aerosols uptake both beneath and within clouds and their contribution to cloud forming processes because of their hygroscopic nature and how they eventually lead to rain or snow as deposited materials unto terrestrial or marine ecosystems. Understanding the processes of aerosols deposition and re-suspension is therefore an important impetus to our understanding the global aerosol cycle, which is also an important key to our understanding the modulating roles of aerosols during the initiation and dissipation of meso-scale convective systems (Lovett, 1994; Rosenfeld et al., 2008; Tao et al., 2012).

2.2.2 Aerosols as Cloud Condensation Nuclei

Aerosols are cloud condensation nuclei (CCN) in the atmosphere and are mostly hygroscopic in nature – meaning that they are water seeking and are thus good surfaces upon which water vapor condenses. The cloud initiating capabilities of aerosols is strongly dependent on their size/mass concentrations and their water-soluble component. They have substantial effect on cloud properties and precipitation initiation because of the role they play as CCN. High concentrations of anthropogenic aerosols are known to both decrease and increase rainfall due to their radiative characteristics. Clouds with low CCN concentrations sometimes rain out too quickly to become mature long-lived clouds. On the other hand, highly polluted clouds evaporate much of their water before reaching the ground as precipitation because of reduced surface heating resulting from the aerosol haze layer (Rosenfeld et al., 2008; Tao et al., 2012).

In general, clouds form when air ascends due to adiabatic expansion, cooling and then condensation of atmospheric water vapor. As cloud droplets grow, they can condense, collide and then coalesce with each other until they are heavy enough to fall under gravity against the uplift velocity suspending them. Rather than form as clouds, ice crystals develop when cloud temperature falls sufficiently below zero. Ice crystals grow by water vapor deposition and collision with each other and under favorable temperature conditions and height can sometimes reach the ground as rain. Sometimes, cloud droplets growth depends on the existing aerosol particles acting as CCN. Thus, as aerosol concentrations increases cloud composition changes e.g. the size distribution of cloud droplets, which to a large extent determines the precipitation-forming processes (Tao et al., 2012).

The Kohler (1936) theory cited by Tao et al. (2012) was used to explain the fundamental relationships between aerosol mass concentrations, water-soluble contents and their cloud forming capabilities. It was noted that finer and larger aerosol constituents are much more significant for cloud nucleation than intermediate constituents (Tao et al., 2012). The Kohler (1936) curve (not shown) illustrates how equilibrium saturation ratio over any solution drop surface is a function of the drop radius. The Kohler curve also describes how solute chemical composition that influences not only the Raoult effect – by altering the water activity but also the Kelvin effect – by altering the surface tension, could adjust how aerosols influences cloud formation. The curve also shows temperature as another major aerosols influencing characteristics. For example, an aerosol particle may become warmer than its environment due to either the latent heating from vapor condensation or absorption of solar radiation by its soot or mineral dust component. This warming affects all the three major controlling factors to aerosols cloud forming capabilities – i.e. the saturation vapor pressure, the surface tension, and the solution activity. A more comprehensive explanation of the Kohler curve and theory and how it can be used to explain aerosols capabilities in modifying the formation of cloud droplets can be found in Tao et al. (2012).

Mineral dust aerosols are the dominant aerosol type across the SWA region due to its proximity to the Sahara desert – the world's largest single source of mineral dust aerosols. Dust are generally uplifted and transported across the atmosphere from surfaces such as deserts, semiarid areas and agricultural lands by strong winds. Evidence suggests that mineral dust aerosols can be raised up to considerable tropospheric altitudes where they act as significant CCN (Matsuki et al., 2010). Several studies (for example Rosenfeld et al., 2008; Freud & Rosenfeld, 2012; Tao et al., 2012) have shown that aerosols play significant roles in modifying cloud microphysics and dynamics. The schematic illustration of the effects of aerosols on clouds and cloud systems of different types is shown in Fig 2.3.

Aerosols in their insoluble phase are known to significantly help in the initiation of atmospheric ice crystals. These insoluble aerosols known as ice nuclei are usually exhibiting four major modes – namely 1) the deposition mode, 2) condensation-freezing mode, 3) freezing mode and 4) the contact mode. In the deposition mode – water is directly absorbed from vapor phase onto aerosols surfaces acting as ice nuclei and are then transformed into ice. The condensation-freezing mode – is a hybrid process whereby water is required at the super saturation stage. This means that the insoluble aerosols act as both the cloud condensation nuclei and as the ice nuclei.

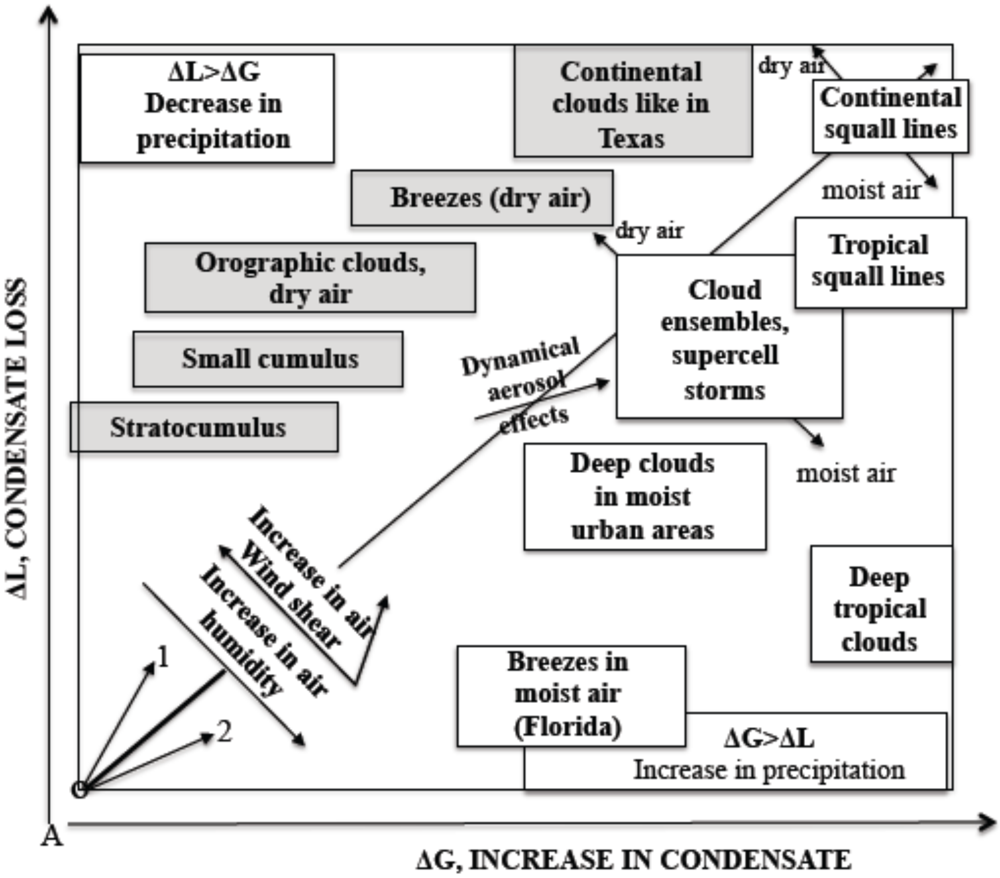

Fig. 2.3. A schematic illustration of the effects of aerosols on clouds and cloud systems of different types. The zone above the diagonal corresponds to a decrease in precipitation with aerosol concentration. The zone below the diagonal corresponds to an increase in precipitation with an increase in the aerosol particle concentration. Redrawn from (Khain et al., 2008; Tao et al., 2012).

In the contact mode – aerosols as the ice nuclei initiate ice phase exactly at the moment of contact with the super cooled droplet (DeMott et al., 2003; Fowler et al., 2009; Liu et al., 2012; Tao et al., 2012).

Biological aerosols – i.e. aerosols from bacteria, pollen, fungi, spores and phytoplankton, and soot particles from anthropogenic or natural burning processes also play significant roles in atmospheric nucleation of ice droplets and ice crystals (Fowler et al., 2009; Tao et al., 2012). Biological aerosols are mostly in high concentrations over forested areas, as in the southern portion of the SWA region. These types of aerosols induce the nucleation of cloud droplets and ice particles via physical processes. It has been shown that active microorganisms, for example, bacteria, yeasts and fungi forms part of atmospheric water phase and are actively involved in the cloud microphysics (Fowler et al., 2009; Hoose et al., 2010; Tao et al., 2012). It has also been suggested that living microorganisms are transformation biocatalysts to organic compounds.

2.3 Aerosols Opposing Effects on Clouds and Precipitation

In general, the radiative effect of aerosols on clouds is to suppress precipitation – as aerosols decreases the amount of solar radiation reaching the ground, less heat is available heat for evaporation and initiation of convective systems. The fraction of the solar radiation not reflected back into space by aerosols is absorbed into the atmosphere – mainly by carbonaceous aerosols, leading to the heating of the boundary layer. This heating stabilizes the low atmosphere and suppresses the generation of convective clouds. As suggested by Zhang et al. (2008), warming of the lower troposphere by absorbing aerosols strengthens monsoon circulation thereby causing a local increase in precipitation, despite the global reduction of evaporation resulting from increasing radiative heating by aerosols. For scattering aerosols, which mainly scatter radiation back into space, the resultant surface cooling effect can also alter atmospheric circulation systems. This mechanism is said to be responsible for the cooling of the North Atlantic and hence the pushing of the InterTropical Convergence Zone (ITCZ) southward, thereby contributing to the drying in the Sahel (Idowu & Rautenbach, 2009; Freud & Rosenfeld, 2012).

Aerosols exhibit important microphysical effects. For example, the rate at which cloud drops are converted into raindrops decreases as CCN increases. This is because as CCN increases, lots of smaller drops are nucleated and they are slower to coalesce into raindrops. This effect has been known to reduce the amount of precipitation from shallow and short-lived clouds. Hence, highly polluted areas experience reduced rainfall. According to Rosenfeld et al. (2008), urban/industrial air aerosol exhibits less rainfall suppression than smoke aerosols from forest fires. However, they concluded that establishing a very clear causal relationship between aerosols and precipitation in order to determine the precipitation sign change in a climatological sense is not at all trivial. A recent review of aerosols radiative forcing on climate change (National Research Council, 2005) argued that the concept of radiative forcing needs to account for (1) the vertical structure of the radiative forcing, (2) regional variability in the radiative forcing, and (3) the nonradiative forcing.

2.3.1 The Direct, Indirect and Semi-Direct Effects of Aerosols

As earlier mentioned, aerosols have many different effects on cloud cover, liquid path and solar energy flux. The direct effects of aerosols occur due to their absorbing and scattering effects on atmospheric radiation (IPCC, 2007; Penner et al., 2006). Aerosols absorb and scatter atmospheric radiation both at the shortwave and longwave spectrums. Most aerosols are non-absorbing in nature and are responsible for negative radiative forcing since they scatter shortwave radiation back into the space. When shortwave radiation is absorbed, positive radiative forcing occur and there is a resultant positive heating rate in the atmosphere; which is important for the semi-direct effect. The principal absorber of shortwave radiation is black carbon, although mineral dust and some organic aerosols also absorb in the shortwave. The interaction with longwave radiation is negligible for most aerosols except for large dust particles, which exert a positive radiative forcing by reducing outgoing longwave radiation (Kaufman et al., 1997).

Aerosols direct effects are highest in the morning when cloud layers are thicker and more solar radiation is reflected upwards and absorbed by aerosols above the clouds. In the afternoon when clouds usually have lower albedo, scattering by aerosols becomes more important and their direct forcing becomes negative. Thus, the direct aerosol forcing is very sensitive to cloud thickness. There is a large uncertainty in the direct radiative forcing of aerosols because of our incomplete knowledge of their optical properties and their global mass mixing ratio distributions. The optical properties of aerosols are difficult to constrain since they vary with size distribution, chemical composition, and water uptake. The mass mixing ratio of aerosols are also uncertain because of uncertainties in their emissions rates and model parameters for processes such as deposition (Arndt et al., 2010).

In addition to aerosols directly absorbing solar radiation, they can also act as effective CCN thereby increasing the number of particles in clouds and cloud reflectivity. Anthropogenic aerosols such as sulfates are effective CCN. As cloud droplet concentrations increases, cloud optical depth and albedo also increases. Also, as the number of smaller droplets increases, the total surface area for a given mass of liquid water also increases. This is known as the first indirect aerosol effect, or Twomey effect. The Twomey effect enhances negative radiative forcing as a result of the resultant increase in planetary albedo. Hence, indirect aerosol effect leads to lower precipitation regime. Smaller cloud droplets have lower terminal velocity and are less likely to coalesce and precipitate. This is referred to as the second indirect effect, or cloud lifetime effect. It has a negative radiative forcing contributing to the negative forcing from the first indirect effect or Twomey effect. Aerosols can also increase the number of ice particles in a cloud thereby decreasing reflectivity by increasing the amount of transparent ice in the cloud (Twomey, 1977; Twomey et al., 1984; Tao et al., 2012).

Aerosols semi-direct effect was first suggested by Hansen et al. (1997) to describe the absorbing effects of aerosols on clouds. Aerosols indirect effects are quite different from the semi-direct effects. For aerosols indirect effect, increases in aerosol concentrations leads to increases in cloud albedo, which may extend cloud lifetime because of the microphysical processes. The semi-direct aerosols effects are called semi-direct because they result from the direct interaction of aerosols with radiation, which also influences climate indirectly by altering clouds. The semi-direct aerosol effect exhibit warming influence by dissipating the low clouds that scatter solar radiation back to space and do not significantly reduce outgoing longwave radiation. The semi-direct forcing and its mechanisms are poorly understood. For instance, the presence of a moderate amount of absorbing aerosol in stratocumuluscapped boundary layer can lead to a large positive semi-direct forcing that are several times greater in magnitude, and opposite in sign to the conventional direct forcing. Under cumulus conditions, semi-direct forcing can be much smaller, about equal in magnitude to the direct forcing. When absorbing aerosols are located above clouds they actually promote further cloud leading to a small a negative forcing.

CHAPTER 3

THE STUDY AREA

3.1 Introduction

This chapter presents a general overview of the climatological and geographical descriptions of the sub-Saharan West Africa (SWA) as the study region, and as indicated in Fig. 3.1. This region exhibits a typical West African climate and Nigeria covers an extended part of this region. As such, the climate of Nigeria represents most of the dominant climatic characteristics of the broader SWA region.

3.2 Climatology of sub-Saharan West Africa

3.2.1 Geography

The area extending from longitude 18.00 ° West (W) to 15.00 ° East (E) and latitude 5.00 ° North (N) to 20.00° North (N) is defined as the SWA (see Fig 3.1). As earlier mentioned, this region is bordered in the north by the Sahara desert, and in the south and west by the Atlantic Ocean. The following listed countries can be found within the study region: Benin Republic, Burkina Faso, Cape Verde, Cote d'Ivoire, Cameroon, Chad, The Gambia, Ghana, Guinea, Guinea. Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo and Sudan (Fig. 3.1). It is estimated that more than 290 million people are living in the SWA region, covering a total area of approximately eight million km^2 (ECOWAS-SWAC/OECD, 2006)

3.2.2 Topography and Drainage

The highest elevation point in the SWA region is at the Fako Mountain in Cameroon (also known as the Cameroon Mountain). It is about 4,095 m Above Mean

Sea Level (AMSL). On the other hand, the lowest elevation point is at the Djourab depression in the Chad Republic, which is about 160 m Below Mean Sea Level (BMSL). Apart from these two extreme elevation points, there are several other high grounds in the study domain, which includes mount Emi Koussi in Chad (3,415 m AMSL), mount Kinyeti in Sudan (3,187 m AMSL), and mount Chappal Waddi in Nigeria (2,419 m AMSL). In general, the WS topography (Fig. 3.1) ranges from low coastal plains to flat, hills, plateaus, mountains and desert plains.

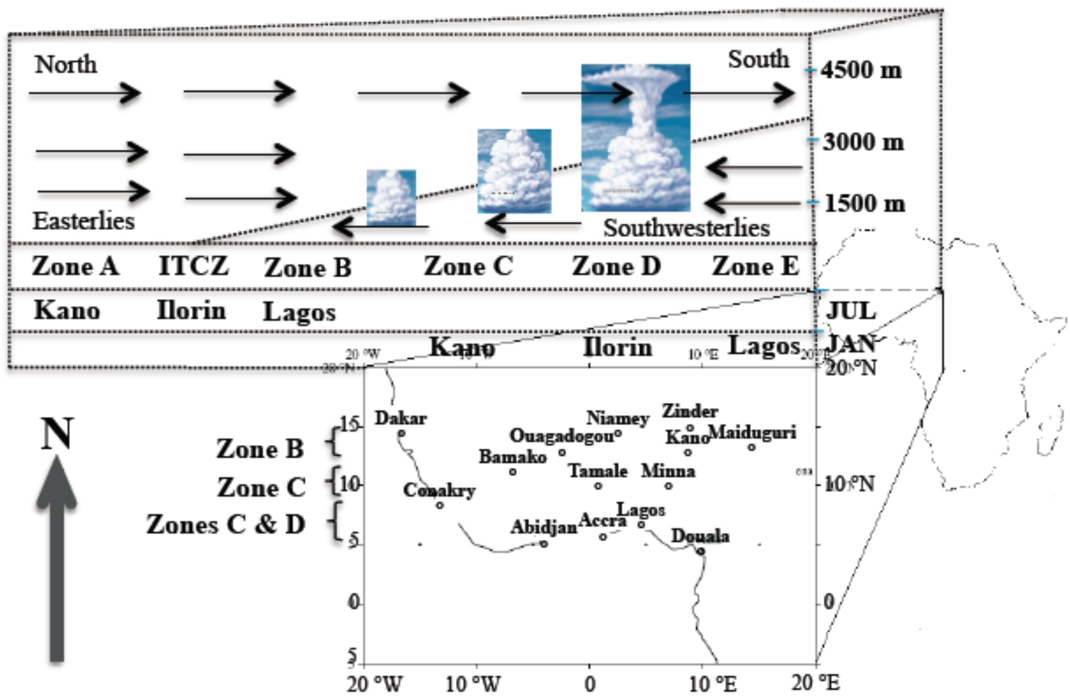

Fig. 3.1: Showing the study region – sub-Saharan West Africa and the location of the ITCZ with the five prominent weather zones (A to E) defined at different meridional locations over the region (after Ojo, 1977). The southwesterlies that brings moisture from the Atlantic Ocean form part of the West African Monsoon (WAM).

3.2.3 Climatology of the Study Region

The SWA region has diverse climatic characteristics – ranging from wet equatorial climates (from the southern coastline up to a latitude of 8.00ºN), to wet and dry tropics climates (between latitude 8.00ºN and 12.00ºN) in the central region, and semi arid climates (between latitude 12.00ºN and 15.00ºN) in the northern region (see Fig. 3.1).

3.2.3.1 The Wet Equatorial (WE) Climate Zone

The Wet Equatorial (WE) climate zone (located in the southernmost part of the SWA) receives significant amount of rainfall each year, with not more than three months recording a total monthly rainfall of less than 50 mm. The WE climate zone is very close to the equator and this means that the total outgoing long wave radiation at the surface is relatively high throughout the year. This does not only result in fairly uniform annual temperatures, but also allows for little variability between day and night (or maximum and minimum) temperatures. The WE climate zone falls within the equatorial belt of relatively lower surface pressures, also known as the Inter-tropical Convergence Zone (ITCZ). The ITCZ follows a distinct seasonal meridional propagation across the region. The ITCZ is often associated with rainfall because of extensive convection and cloud development that occur at the location of the ITCZ. The ITCZ is therefore an important driver of seasonal rainfall over Africa (Adefolalu et al., 1985; Odekunle, 2004; Parker, 2005; Omotosho, 2008).

Most of the available energy flux over the WE climate zone occurs as latent heat of evaporation from soil or water. The high evapotranspiration from the dense vegetation cover and higher outgoing long wave radiation in the lower layers of the atmosphere results into important vertical fluxes of water vapor and sensible heat

(Ojo, 1977; Lamb, 1983; Omotosho, 2008). The most dominant wind flow pattern, for most of the year, over the WE climate zone is warm, moist westerly to southerly winds, mostly associated with the West African Monsoon (WAM), which are responsible for high rainfall being recorded over the region. However, drier northeasterly winds prevail over the WE climate zone for a short period of the year (November and December), resulting in a season of lower rainfall totals (as low as 50 mm per month).

The mean annual rainfall totals over the WE climate zone are high, ranging from 5,000 mm over the coast of Liberia to about 1,200 mm near the latitude of 10°N. The WE climate zone receives its lowest annual rainfall from mid-December until late March (Griffiths, 1966; Pedgley, 1978; Odekunle, 2004; Brooks, 2004), from where rainfall again increases to a maximum in June, and a second maximum in September, which is generally lower than the peak in June. This indicates two rainy seasons, which are inter-linked to the south-north propagation of the ITCZ. Within the WE climate zone, one also finds the so-called "little dry season" from late July to August. Daily rainfall in excess of 200 mm may be experienced anytime from May to October, and rain may also fall for about 25 days during each month from June to October. Rainfall over the WE climate zone is mostly convective in nature and therefore mostly falls during late afternoon and night hours (Adefolalu et al., 1985; Le Barbe et al., 2002).

Mean annual temperatures over the WE climate zone ranges from 15°C to 37°C, the highest being recorded in March and October and the lowest in December and August. Relative Humidity (RH) over the WE climate zone is generally high, especially along the coast. The lowest RH readings, usually recorded during January in the afternoon, are in the order of 70%, which may increase to about 95% during the early hours of the day. However, RH values significantly decreases during the Harmattan period (November to February) when dry continental northeasterly winds prevail. The WE climate zone is exposed to sunshine, especially during the early afternoon hours, and most of the coastal and inland cities experience early morning fog from October to February, with a peak in fog event frequencies in January. The ITCZ influences the prevailing wind direction by means of the WAM. However, local effect of the land and sea breezes are also noticeable during the early morning hours and late at night. Over the coastal cities of the WS (situated within the wet equatorial climate zone), west to southerly WAM winds starts during July and, together with local topographic characteristics, can give rise to a maximum monthly rainfall experienced when the ITCZ is located in its most northern position (Nicholson, 1981; Janicot, 1992; Brooks, 2004).

3.2.3.2 The Wet and Dry Tropics (WDT) Climate Zone

The Wet and Dry Tropics (WDT) climate zone (located in the central part of the SWA) is a transfer region between the semi-arid conditions in the north and the wet equatorial conditions in the south. The area approximately extends across latitude 8.00°N to 12.00°N. The WDT climate zone has about seven to nine months of rainfall in excess of 50 mm per month. Average annual rainfall amounts over the WDT climate zone ranges from 1,000 mm to 4,000 mm. This high rainfall allows for better agricultural production than in the semi-arid areas to the north. Over this climate zone, warm and humid tropical maritime air mass from the Atlantic Ocean dominates during most of the year, giving rise to adequate rainfall for successful farming. However, for a short period each year (January-February and November-December), continental airflow dominates, which results in low humidity and lower rainfall (Trewartha, 1961; Odekunle, 2004; Omotosho, 2008). The WDT climate zone experiences both single and double annual peaks of maximum rainfall, and therefore has both one and two rainfall seasons per year. These seasons are also related to the meridional shift of the ITCZ.

The single annual peak of maximum rainfall over the WDT climate zone is recorded around latitude 10.00°N to 12.00°N, and July is the month of highest rainfall. In the double peaked maximum rainfall season (latitude 8.00°N to 10.00°N), June is generally the wettest month with some areas that experience maximum rain in September. February to April is a period with a high number of disturbance lines, which are well-defined belts of intense thunderstorms moving, at an average speed of 25 kmh^{-1} from east to west, with intense rain over relative short time intervals (Ojo, 1977; Janicot, 1992). These disturbance lines usually occur 300 to 600 km south of the ITCZ, where humid and hot air are deeper to allow for the development of unstable conditions with the associate heavy rainfall (Adejokun, 1966; Adefolalu et al., 1985; Brooks, 2004). The humid air that flows from the ocean, disturbance lines, the ITCZ and topography are the major atmospheric influences that contribute to rainfall development over the WDT climate zone.

The mean annual temperature over the WDT climate zone ranges from 30°C to 36°C, with a small variation of about ± 2°C to 4°C during the year. The mean annual minimum temperature is generally from 19°C to 21°C, but can sometimes increase to 23°C to 24°C. Temperature reaches its highest peaks in February, or March, and its lowest dips in December or January. The lowest maximum temperature occurs in July or August, while the highest minimum temperature occurs in April or May. Over the WDT climate zone, RH is extremely high throughout the year, reaching percentages of about 85% to 95% in most months, especially during the early hours of the day. Afternoon mean annual RH ranges from 50% to 75%, which are still relatively high. However, during December and January, some stations occasionally record an afternoon RH low of about 25% to 30% (Brooks, 2004).

3.2.3.3 The Semi-Arid (SA) Climate Zone

The Semi-Arid (SA) climate zone (located in the northernmost portion of the SWA) is close to the southern fringes of the Sahara desert (Fig. 3.1). Mean annual rainfall totals over the SA climate zone are normally less than 400mm. The beginning and end of the rain seasons are usually abrupt due to the rapid northward advancement and southward retreat of the ITCZ (Adejokun, 1966; Lamb, 1983). The dominant wind is associated with the advection of a dry and dusty continental air mass, mostly northeasterly in direction. The SA climate zone mostly experiences extensive diurnal variation in temperature, and is also very prone to natural hazards such as drought, sand storms and dust storms. The countries that fall within the SA climate zone are Senegal, Gambia, Mali, Burkina Faso, and Niger, the northern fringes of Nigeria, Chad and Sudan.

The highest monthly radiation total over the SA climate zone is usually recorded during April, and the lowest is recorded during July or August. The climate zone also has, on average, $7.5 h.day^{-1}$ to $9.3 h.day^{-1}$ sunshine. The mean annual maximum temperature over the SA climate zone ranges from 40°C to 47°C, which are extremely high, and the mean annual minimum temperature ranges from 7°C to

9°C. Squall lines are most frequent in April, May, June and October, especially during the late afternoon hours. These squall lines often produce maximum winds gusts of around 80 knots, which are usually very destructive (Odekunle, 2004; Lamb, 1983; Brooks, 2004).

3.3 The ITCZ and Weather Across the Study Region

As noted earlier, the ITCZ and the associated WAM, play an important role in the climatic characteristics of the SWA. The ITCZ retreats to its most southern position in January, and advances to its most northern position in July, when easterly trade winds crosses the geographical equator, and under the influence of the Coriolis force, turns westwards to form the WAM. As a result, moist onshore maritime air from the Atlantic Ocean enters the region in July, while dry and dusty offshore continental winds blows across the Sahara desert towards the region during January. According to the location of the ITCZ five weather zones (A to E) have been defined (see Fig. 3.1) (Adejokun, 1966; Ojo, 1977; Omotosho, 2008).

The weather zone located immediately north of the surface location of the ITCZ has been classified as weather zone A. Weather zone A is a predominantly dry region with dusty continental easterly to northeasterly winds from the Sahara desert. High cloud types mostly occur with the occasional occurrences of medium cloud types. The zone is usually cool with clear skies during night hours.

Weather zone B covers areas across the study region that is located directly south of the surface location of the ITCZ. This weather zone extends over a distance of about 200 to 300 km south of the ITCZ. The zone experiences a mixture of the dry easterly to northeasterly winds (at higher altitudes) and moist southwesterly winds (closer to the surface) (Fig. 3.1). Weather zone B is characterized with relatively high night temperatures and high humidity values. Early morning fog in the form of stratus (low) clouds is also often experienced.

The zone located at a distance of approximately 700 km to 1,000 km to the south of the surface location of the ITCZ is known as weather zone C. In this zone moist southwesterly winds are found at an altitude of about 6,000 m above the land surface. Weather zone C mostly experiences unstable atmospheric conditions, which are characterized by disturbance lines and local thunderstorm activities, resulting in variable and sporadic rainfall (Garnier, 1967). Weather zone C is generally characterized by high RH values, with little diurnal variability in temperatures.

Weather zone D is found at a distance of 1,000 km to 1,300 km south of the surface location of the ITCZ. It is also a zone with high RH values, and relatively low and mostly constant temperatures (Fig. 3.1). In this zone, the "little dry season" (as mentioned earlier) is experienced when inversion or stable conditions above the stratus (low) clouds inhibits the upward movement of air, which results in very little rain, but often in fog events.

The most southerly weather zone is known as weather zone E. This zone only affects a relatively narrow strip along the coastline of the SWA during July and August. It is a zone of decreasing stratocumulus and stratus clouds, and increasing altostratus, altocumulus and cirrus clouds. Drizzle and rain are the most frequently found over weather zone E.

Although defined in location, Garnier (1967) argued that the type, frequency and duration of weather zones A to E over the SWA fluctuate, because of fluctuations in position of the ITCZ due to the meridional propagation of the ITCZ. He therefore went one step further by classifying the region into four weather regions (regions **I** to **IV**) using the annual frequency distribution of the five weather zones (see Fig. 3.1).

Accordingly, the area over the SWA that is mostly affected by weather conditions defined in weather zone A for at least six months, weather zone B for almost a month and weather zone C for four months during the period of one year is classified as region **I**. Over region **II**, the weather conditions of weather zone B are experienced during the greatest part of the year, especially when the ITCZ advances northwards. The area that is predominantly influenced by the weather conditions of all the five weather zones (weather zones A to E) is classified as region **III**. In region **IV** weather conditions of weather zone C dominates, with occasional influence from the weather of zone A.

In summary, this chapter presents the diverse climatic characteristics of the study region. The most humid climate zone in the study region is the WE climate zone – extending between latitude 8.00ºN and 12.00ºN. It is also the zone with the highest annual rainfall amount with highly dense and forested vegetation. We have also discussed the WDT climate zone, which extends between latitude 12.00ºN and 15.00ºN. The WDT climate zone is in general not as humid as the WE climate zone and it also acts as intermediate zone (transition zone) between the very dry SA climate zone and the highly humid WE climate zone. The SA climate zone – extending between latitude 12.00ºN and 15.00ºN is the driest desert like climate zone. This zone annually experiences the greatest impact from the aerosols suppressing effects and thus has significantly low annual rainfall total.

As earlier mentioned, the study region is known as the global hot spot for aerosols, bordered in the north by the Sahara Desert, which is the world's single largest dust source region. Our study region is also the world's highest source of biomass burning per square kilometer. Records have shown that nearly all of the tropical cyclones and hurricanes across the Eastern Pacific Ocean have their origin traced back to the meso-scale convective developments across the SWA, where aerosols are abundantly available (Zhang et al., 2008; Freud & Rosenfeld, 2012; Tao et al., 2012). Because of its uniquely diverse climatic characteristics and the significant effects of abundant aerosols on MCS across the region, we justify the SWA region as the most appropriate region to investigate the role of aerosols-land-atmosphere interactions on meso-scale convective systems, as done in this dissertation.

CHAPTER 4

DATA ANALYSIS AND RESEARCH METHODOLOGY

4.1 Introduction

This chapter presents a comprehensive description of the dataset, data analysis and research methodology used in this study. The two main sources of data used were 1) ERA-Interim global reanalysis data, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), and 2) Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua data, produced by the National Aeronautics and Space Administration (NASA). Descriptions on both ERA-Interim and MODIS Aqua are presented in section 4.2. The atmospheric and surface fields investigated in the study were retrieved from ERA-Interim reanalysis while the Aerosol Optical Depth (AOD) data were retrieved from MODIS Aqua.

4.2 Data Description

Nine years of daily data for the period 2002 – 2010 from both ERA-Interim reanalysis and MODIS datasets and for 10 variables were retrieved and analyzed. Both the ERA-Interim and MODIS datasets were downscaled over the geographical location of the study region – the SWA region. As stated before and for clarification, the area extending from longitude 18.00°W to 15.00°E, and latitude 5.00°N to 20.00°N (see Fig 3.1) defines the study region. The following variables were retrieved from ERA-Interim reanalysis to investigate the interactions between aerosols, land-atmosphere and meso-scale convective systems. The variables were – convective available potential energy (CAPE), boundary layer height (BLH), total cloud cover (TCC), surface air temperature (TEMP), surface air dew point temperature (TEMPD), soil temperature layer 1(STL1), soil water volume layer 1 (SWVL1), surface sensible heat flux (SSHF) and surface latent heat flux (SLHF). The only variable retrieved from the NASA MODIS Aqua satellite data archive were the aerosol optical thickness (AOT or AOD) fine mode fraction version 5 at 550 nm to represent the distribution of aerosol concentrations across the study region.

Table 4.1
List of variables from ERA-Interim and MODIS Aqua datasets and their units

Variables	Units
Aerosol optical thickness (AOT)	unitless
Convective available potential energy (CAPE)	J/kg
Boundary layer height (BLH)	m
Total cloud cover (TCC)	%
Surface air temperature (TEMP)	K
Surface dew point temperature (TEMPD)	K
*Soil temperature layer 1 (STL1)	K
*Soil water volume layer 1 (SWVL1)	Kgm^{-3}
Surface sensible heat flux (SSHF)	Wm^{-2}
Surface latent heat flux (SHLF)	Wm^{-2}

** Layer 1 represents soil layer from 0 to 7 cm*

4.2.1 ERA-Interim Global Reanalysis Data

ERA-Interim is the most recent available global atmospheric reanalysis data for climate research. Initiated in 2006 and coordinated by ECMWF, ERA-Interim replaced ERA-40 reanalysis in order to significantly reduce or eliminate some of the known inaccuracies from ERA-40 data. For instance, ERA-40 is known to generate too-strong precipitation over oceans and too-strong Brewer-Dobson circulation in the stratosphere (Dee et al., 2011). With much-improved model configuration and data assimilation system, ERA-Interim now provides spatially and temporally high resolution, improved low-frequency variability and improved stratospheric circulation datasets of multiple variables when compared with ERA-40 datasets. Reanalysis data from ERA-Interim now extends back to 1979 and continues to be extended forward in near real time (Dee et al., 2011).

ERA-Interim reanalysis addressed most of the data assimilation problems encountered in ERA-40. Dee et al. (2011) listed some of the data assimilation problems addressed in ERA-40 by ERA-Interim to include the inefficient representation of hydrological cycle, the quality of stratospheric circulation, and the consistency in time of reanalyzed geophysical fields. ERA-Interim also the data selection, quality control, bias correction and performance monitoring problems encountered in ERA-40, all of which greatly impacts the quality of its reanalysis products. Improved gridded data products available from ERA-Interim include 3-hourly surface parameters that describes weather and ocean-wave as well as land-surface conditions, 6-hourly upper-air parameters that covers the troposphere and stratosphere and the vertical integral of atmospheric fluxes, including monthly averages for several other parameters and derived fields. For more information on the daily production of ERA-Interim, its online data availability and near-real-time updates of several derived climate indicators, refer to Berrisford et al. (2011), Dee et al. (2011), and https://climatedataguide.ucar.edu/reanalysis/era-interim

Reanalysis data provides true representative of the state of the atmosphere based on ingested observations. Reanalysis data are produced with a frozen/unchanging framework that dynamically generates a consistent estimate of climate state at each time step. Though this framework is constant, their raw data input sources are always unavoidably changing due to changing observational network. Some of the key strengths of reanalysis datasets include availability of large variety of global datasets, consistently high spatially and temporally improved resolution dataset, and continuously improved model resolution and biases. On the other hand, some of the shortcomings of reanalysis data include lack of observations (especially initial conditions 00Z), observational errors and insufficient information on these errors, problems with model assimilation methodology, and computational limitations and technical errors and mistakes. Despite these limitations, reanalysis datasets have proven very useful especially in areas where real time observational datasets are unavailable such as the SWA region (Dee et al., 2011).

4.2.2 MODIS Aqua Data

MODIS Aqua platform was designed in 2002 as part of NASA Earth Observation System (EOS) to provide a wide range of high-resolution daily global observations of atmospheric aerosols. MODIS Aqua data spatial resolution is 10 x 10 km (at nadir) with each granule output grid size of 135 by 204 pixels. MODIS uses seven of its 36 channels when retrieving aerosol properties over cloud and bare surfaces. But over vegetative surfaces, it retrieves aerosol optical depth (AOD) at the three visible channels with very high accuracies (Kaufmann et al., 1997; Chu et al., 2002; Martins et al., 2002; Remer et al., 2008). Due to relatively simple ocean surface, MODIS uniquely retrieves with greater accuracy aerosol optical depth over ocean surfaces and also accurately retrieves quantitative aerosol size parameters (Kaufmann et al., 1997; Remer et al., 2008). Aerosols fine-mode fraction has been very helpful in separating anthropogenic aerosols from natural aerosols and also in estimating anthropogenic aerosols direct effects on climate forcing.

In this study, AOD fine mode fraction, version 5 at 550 nm was extracted from MODIS Aqua during the period 2002 – 2010. We retrieved our data to cover these years since MODIS Aqua datasets are only available from 2002. The AOD data are retrieved from Level 2 Atmosphere Archive and Distribution System (LAADS). In general, MODIS data are stored in Hierarchical Data Format (HDF) with each parameter stored as a Scientific Data Set (SDS). Several library subroutines have been developed for retrieving HDF data. But for this study, we generated a MATLAB script that converts all extracted MODIS datasets from their original HDF format into ASCII format and then imported these converted datasets into R where we were able to easily handle the aerosols data in compatibility with extracted ERA-Interim reanalysis variables. For more information regarding MODIS Aqua specifications and components see http://modis.gsfc.nasa.gov.

4.3 Data Analysis and Methods

4.3.1 Data Analysis

Our datasets are seasonally stratified into monsoon and non-monsoon periods. This allows us to investigate and clearly understand seasonality changes of aerosol interactions and feedback on convective variables and surface parameters over the study region. Datasets for the month of July and for the period 2002 to 2010 from both ERA-Interim reanalysis and MODIS Aqua are used to represent the monsoon period, while datasets for the month of November and for the period 2002 to 2010 from both sources were used to represent the non-monsoon period. We were constrained to use only the July dataset in representing the monsoon season and only the November dataset in representing the non-monsoon season due to limited computer data processing space.

We know from the literature (discussed in chapter 3), and from our personal forecasting experience over the study area, that July months are the period when meso-scale convective indicators such as CAPE are expected to be highest. But during this same July months, aerosol concentrations (the AOT in this case) across the region are expected to be the lowest, especially when compared to that of November months. In contrary, during November months, convective indicators are expected to be lowest and AOT concentrations are expected to be highest. As suggested by Wilks (2011), this type of seasonal stratification allows the incorporation of uniquely different relationships between observed and predicted variables at different periods of the year.

Apart from investigating the seasonal effects of aerosols on convective systems and land-surface characteristics, we are also interested in investigating the seasonality control on the dominant modulating effects of aerosols on the convective indicators and land-surface variables. In order to do this, we subset the data using the maximum AOT value within the monsoon (July) and non-monsoon (November) for each year and correspondingly relate their interactions with the convective and land-surface variables.

4.3.2 Self-Organizing Maps (SOM)

Apart from using other data manipulation tools, the main statistical investigative tool used in this study is the Self-Organizing Maps (SOM), which is one of the rapidly growing competitive learning artificial neural network (ANN) models. ANN models are mathematical models, which performs information-processing procedures exactly as human brains i.e. the central nervous system. ANN models are therefore made up of interconnected group of artificial neurons that uses the brain connectivity computation approach (Hewitson & Crane, 2002; Datta et al., 2008). We settled for the SOM method since our research problem was a complex, nonlinear, non-discrete, multidimensional and multi-scale problem.

The SOM provides solutions in segment plots (neurons), which are results of non-linear and multi-scale regressions with respect to original data points. It finds sets of neurons and assigns each data object to the neuron, which provides the best approximation of the object. Thus, the final SOM outputs are neurons that define clusters. When compared with some of the most commonly used analytical methods in climate research, such as the Principal Component Analysis (PCA), the Alkaike Information Criterion (AIC) and the K-means cluster analysis, the SOM method was most preferred especially for our research investigation. As for the PCA, it is limited because it provides no information on how objects are compared, and the standard Euclidean distance measure is not always a dissimilarity measure. For the AIC method, even though it provides a measure of relative goodness of fit, it is limited because our problem is mostly non-linear. The K-means cluster analysis also provides its cluster solutions without treating input data as a continuum, and this is a huge deficiency for our research situation.

Kohonen (2001) developed the SOM and it has since proven very useful in solving many statistical, cognitive psychology and artificial intelligence problems. Although not very common in climate research, SOM offers a novel alternative approach to visualizing complex distribution of synoptic states while at the same time preserving the data as a continuum (Hewitson & Crane, 2002). Hence, points that are near to each other in input space are mapped to nearby map units in SOM. The SOM also has the capability to generalize, which means that they recognize and characterize inputs that have never been encountered by them before and can easily assimilate them unto a new map unit.

The SOM algorithm is done in such a way that a topographic or spatial organization is imposed on the neurons (or segment plots). A two-dimensional array SOM segment plots represented in an organized hexagonal lattice is shown in Fig. 4.1. The SOM algorithm is based on unsupervised competitive learning, which uniquely map high dimensional space unto map units while making sure that the geometric and spatial relations of the maps are unaffected by the continuous change in shape or size of the maps. These maps are commonly referred to as topology preserving maps. The basic property of topology preserving maps is that the relative distance between points is preserved. The SOM algorithm is explained in a simplified manner with the following steps:

Step 1: Initialize the Map

This is the first step in generating the SOM results. A sample vector is randomly selected and the map of weight vectors that best represents that sample vector is generated.

Step 2: Data iteration training process

a) Randomly select a sample

Following the first step, the time (t) is automatically adjusted since the number of neighbors and how much each weight can learn decreases over time. The whole process is repeated several times – usually for about 100 times.

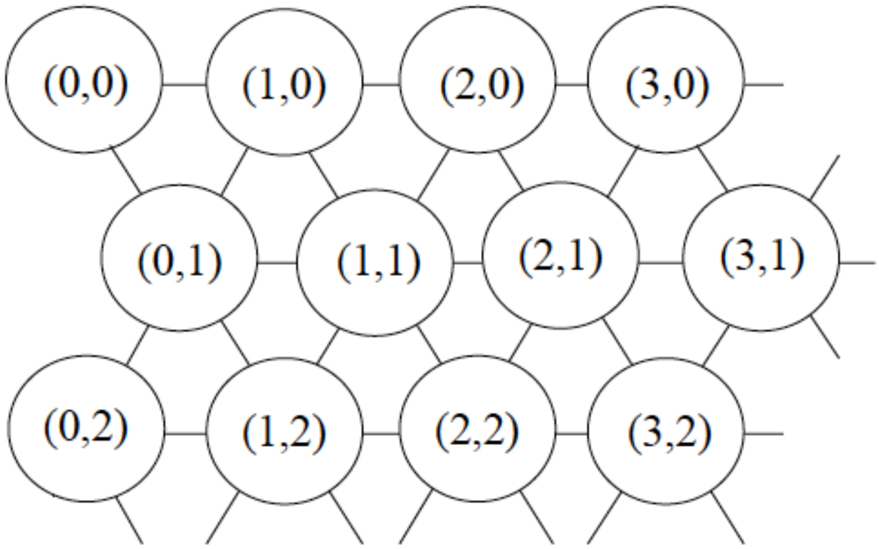

Fig. 4.1: Showing a two-dimensional hexagonal lattice array SOM segments plots. The distances between the neuron units are according to their topology relations.

b) Get the best matching unit

In this step, the iteration training process considers all of the weight vectors and calculates the distances from each weight to the chosen sample vector. The iteration training result with the shortest distance is then chosen as the best training solution.

c) Scale the neighbors

This aspect of the training solution is usually done in two parts. Firstly, the weight vectors that are neighbors are determined, and secondly the algorithm determines the closet possible distance of each weight vector to the sample vector. The most commonly used mathematical solution for the SOM neighborhood scaling includes the concentric squares, hexagonal and gaussian function approaches.

Step 3: Output result – End

This is the final stage. The SOM segment plots are generated as output results for interpretation.

According to Hewitson and Crane (2002), SOMs are analogous to cluster analysis. They argued that for an *N*-dimensional data points, SOMs will seek to place an arbitrary number of nodes within the data space such that the distribution of nodes will represent the multi-dimensional distribution function – meaning that nodes will be more closely spaced in regions of high data densities. For cluster analysis, however, the group that minimizes the within-group differences while at the same time maximizing the between-group differences is identified (Hewitson & Crane, 2002). Hewitson and Crane (2002) further argued that although SOMs are analogous to cluster analysis, they could be significantly different in that SOMs are not primarily concerned with data grouping or cluster identification, as in cluster analysis, but rather attempt to find nodes or data points that are representative of nearby observations, and when put together can describe the multi-dimensional distribution function of the data set. For more discussions on the mathematical formulations and others issues on SOMs, such as the similarities and differences between SOMs and cluster analysis, refer to Hewitson & Crane (2002) and Kohonen (2001).

For the first time and to the best of our knowledge, SOM is being used for aerosols research in this study over the SWA region. Similar to Hewitson and Crane (2002) approach, we used the SOM to locate the archetypal points that describes the multi-dimensional distribution of AOT on the other nine (9) convective systems and land-surface characteristics variables across the study region to investigate the interactions, interrelationships and feedback between aerosols and these variables. SOMs are generated for the monsoonal and non-monsoonal periods and the AOD effects on the convective parameters and land-surface parameters for the July months over the period 2002 – 2010 and for the November months over the same period are investigated and discussed.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

The results and discussion are presented in this chapter. As indicated before, one of the main goals of this study is to investigate and understand the interactions and feedback between aerosols, meso-scale convective parameters and land-surface properties. As mentioned in chapter 4, self-organizing maps (SOM) were the main analytical method used for this study. Our results and discussion therefore focus mainly on the interpretation of the SOM segment plots. SOM are a part of the artificial neural network computational approach. They provide a mapping topology, which is helpful in displaying complex exploratory and interacting results in such a way that is similar to the pattern recognition capabilities of the human brains (see Bishop, 1995; Wehrens & Buydens, 2007 and Hewitson & Crane, 2002). The SOM is gradually becoming more popular in climate research. For easy reference, we have again defined here those variables considered in this study, they are: aerosol optical thickness (AOT), convective available potential energy (CAPE), boundary layer height (BLH), total cloud cover (TCC), temperature (TEMP), dew point temperature (TEMPD), soil temperature layer 1 (STL1), soil water volume layer 1(SWVL1), surface sensible heat flux (SSHF) and surface latent heat flux (SLHF).

5.2 Interactions and feedback during Monsoon and Non-monsoon seasons

We have used the SOM segment plots in representing the interactions and changes between aerosols, mesoscale convective parameters and land-surface properties across the sub-Saharan West Africa (SWA) region for the monsoon (wet season) and non-monsoon (dry season) seasons. For both monsoon and non-monsoon seasons, SOM (Fig. 5.1 a and b) and SOM quality plots (Fig. 5.1 c and d) are presented. Fig. 5.1 (a and b) depicts the interactions and changes between the variables in a way that is similar to cluster analysis but with a more robust visualization and pattern recognition enhancement. SOM plots concentrate on the largest similarities (Kohonen, 2001).

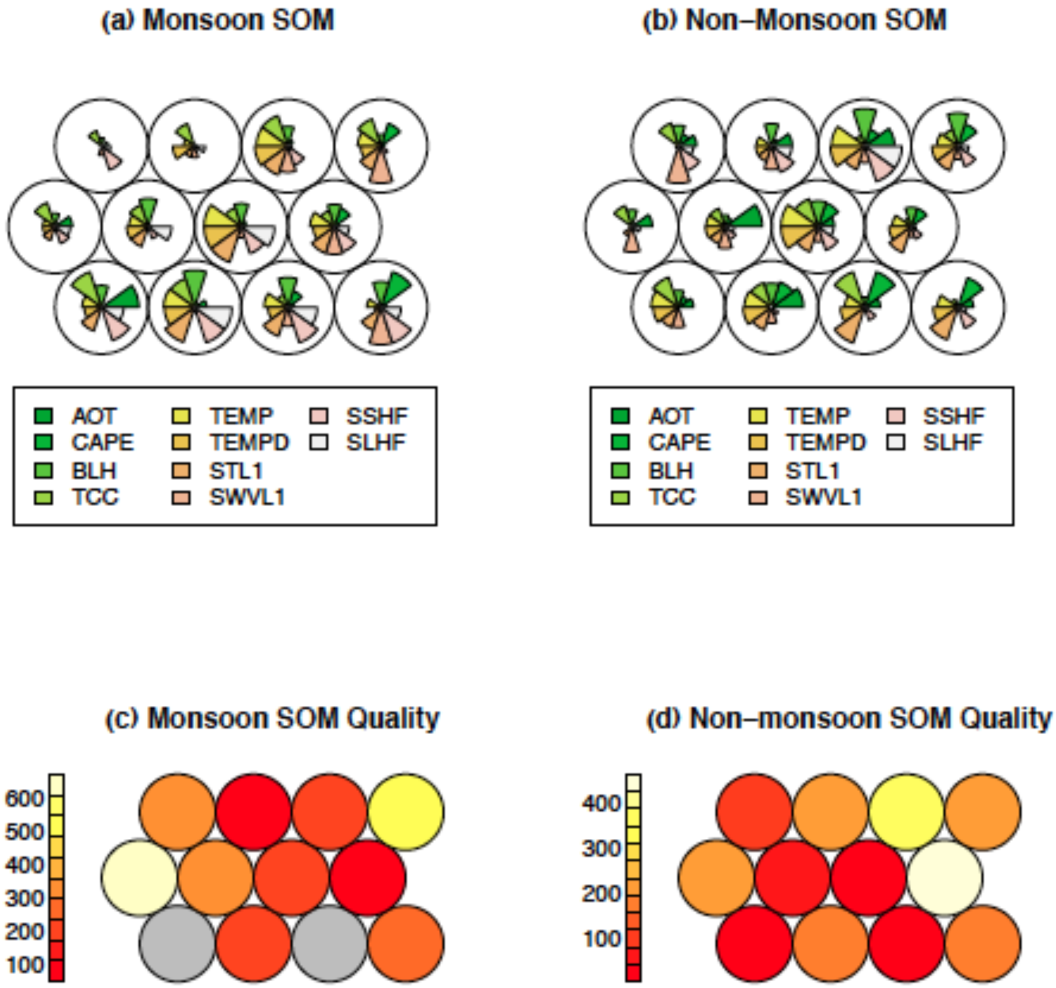

Fig. 5.1: Depicting the self-organizing map (SOM) segment plots for monsoon (a) and non-monsoon seasons (b). The bottom plots c and d shows SOM quality plots for monsoon and non-monsoon seasons respectively. The best quality SOM plots from the bottom plots were matched with the SOM segment plots (top) in order to determine the segment plot use for the dominant controlling variable.

Hence, SOM segment plots for variables with similar interacting properties are clustered closer together as shown in Fig. 5.1. Thus, the variable with the highest interacting control within a particular SOM segment plot is that variable that covers the largest portion of the segment plot.

Going through the results from each of the segment plots – for the monsoon season – the first SOM segment plot (Fig. 5.1 a – first row, first column) shows SSHF as the dominant controlling variable. The second SOM segment plot (Fig. 5.1 a – first row, second column) shows STL1 and TCC as the competing controlling variables. The third SOM segment plot (Fig. 5.1 a – first row, third column) shows no particular variable as the controlling variable. The fourth SOM segment plot (Fig. 5.1 a – first row, fourth column) shows soil moisture as the dominant controlling variable. On the other hand, for the non-monsoon season (Fig. 5.1 b), the first SOM segment plot (Fig. 5.1 b – first row, first column) shows SWVL1 (soil moisture) as the dominant controlling variable. The second SOM segment plot (Fig. 5.1 b – first row, second column) shows SSHF as the dominant controlling variable. The third SOM segment plot (Fig. 5.1 b – first row, third column) shows CAPE as the dominant controlling variable. The fourth SOM segment plot (Fig. 5.1 b – first row, fourth column) shows CAPE as the dominant controlling variable. This explains how we determined the dominant controlling variable from each of the SOM segment plots and for both seasons.

However, because we are strongly interested in determining the variable that has the highest and dominant controlling influence within a particular segment plot during each of the seasons, the SOM quality plots (Figs. 5.1 c and d) were generated. From Figs. 5.1 c and d, we determine the best quality segment plot. For example, the yellowish segment plot (Fig. 5.1 c second row first column) represents the highest quality segment plot for the monsoon season while the reddish segment plot (Fig. 5.1 c first row second and third columns, and second row third and forth columns) represents the lowest quality segment plots. We therefore determine the variable that has the greatest controlling influence within the highest quality SOM segment plot by matching the best quality SOM segment plots (Fig. 5.1 c and d) with the SOM segments plots (Figs. 5.1 a and b).

Our results show that during monsoon (Fig. 5.1 a) and for the best quality SOM plot (Fig. 5.1 c) – considering the first row fourth column and second row first column segment plots, soil moisture has the dominant controlling influence during monsoon season. Using the same approach to interpret the non-monsoon SOM plot (Fig. 5.1 b), soil moisture was also shown as the dominant controlling variable during the non-monsoon season. Hence, we conclude that soil moisture has the greatest controlling influence on atmospheric interactions during both monsoon and non-monsoon seasons across the SWA region. Considering the low quality SOM plots i.e. the red segment plots shown in Fig. 5.1, AOT was shown as the dominant controlling variable for both seasons. This suggests that even though soil moisture plays the dominant controlling influence on the interactions between other variables, AOT also has some inter-seasonal controlling influence but not as strongly influential as soil moisture since the results for AOT are obtained from the poorer quality SOM plots (see Fig. 5.1).

To further justify the quality of our SOM plots, the SOM counts and iteration quality plots presented in Fig. 5.2 were generated. As shown in Fig. 5.2 a and b (SOM counts plots for monsoon and non-monsoon seasons) and Fig 5.2 c and d

(SOM iteration quality plots during the data training progress for both seasons), mean distances to the closest SOM segment plots decreases as the iteration training progress increases. This indicates a good quality result since smaller mean distances to the closest unit means better iteration training process.

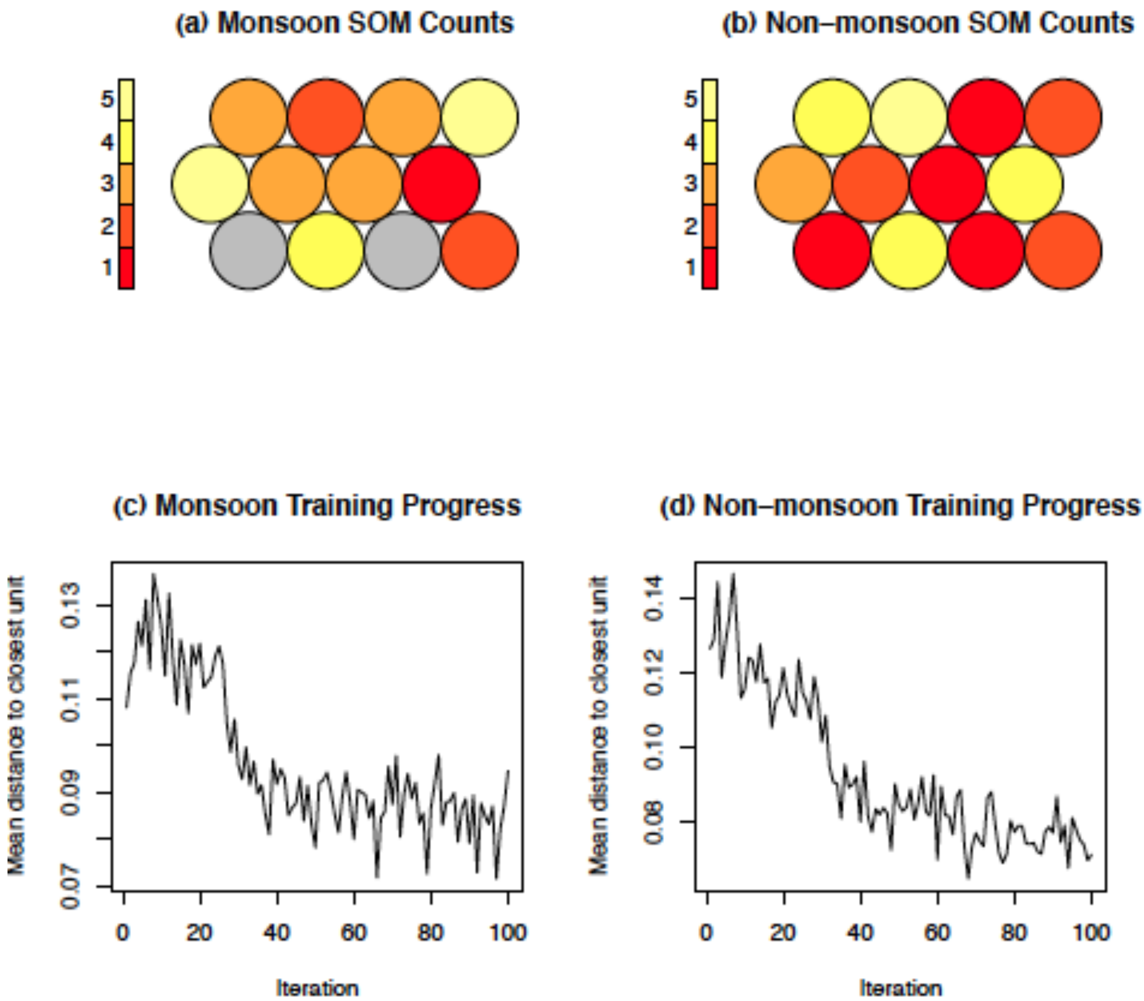

Fig. 5.2: Showing the SOM counts for monsoon (a) and non-monsoon (b). This was used to interpret how many colony count makes up each quality plot e.g. red – has one count but the best quality has 5 counts. The bottom plot shows the progress of the iterations and the relative distances between each segment nodes for monsoon (c) and non-monsoon (d).

The count plots, which also indicate the number of similar patterned nodes that are clustered together within a particular segment plots were also generated (Fig. 5.2 a and b). The higher the count numbers the better the quality of the segment plot. Thus, we see from Fig. 5.2, that the yellowish segment plots (i.e. the best quality segment plots) have the greatest count number.

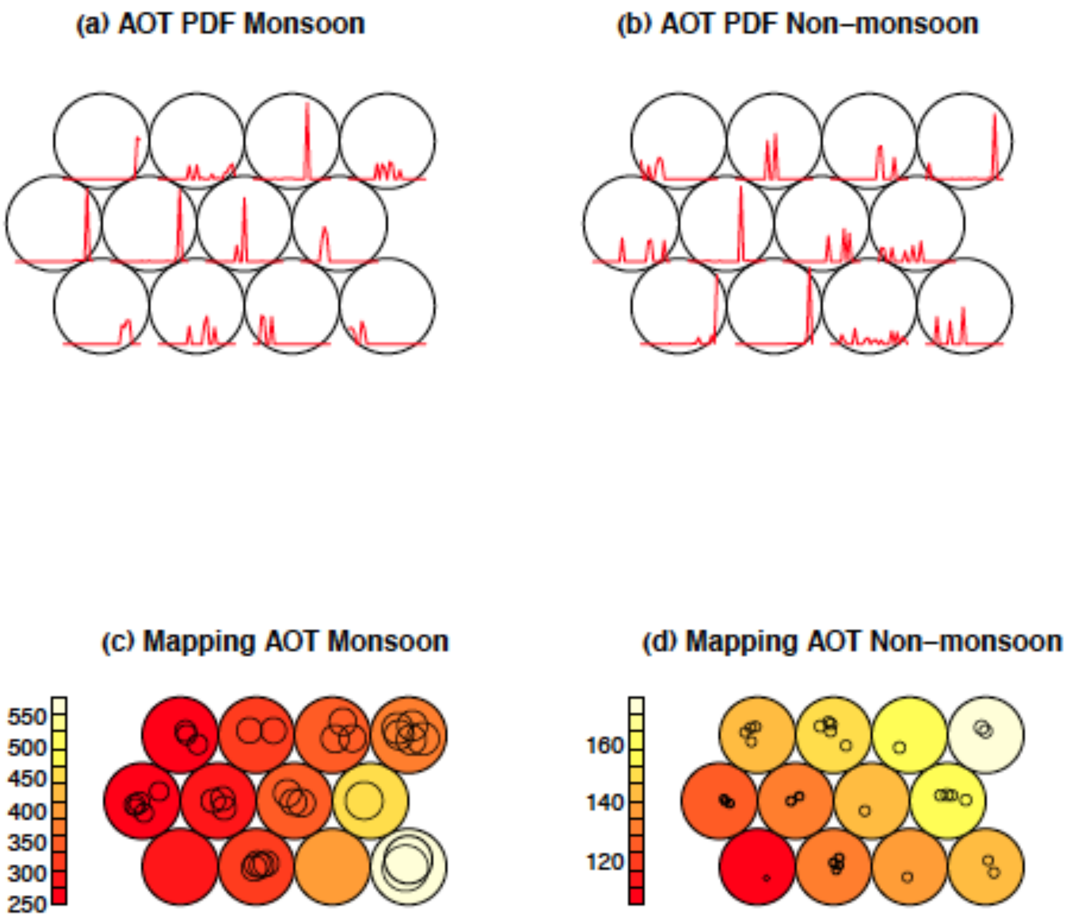

Fig. 5.3: Showing the probability density function (PDF) for AOT during monsoon (a) and non-monsoon (b) seasons. The bottom plots **c** and **d** shows mapping plots for the predictability of AOT during monsoon (c) and non-monsoon (d) seasons. The diameter of the rings in the bottom plots indicates the predictive quality of the variable under consideration – AOT in this case.

With the SOM count and iteration quality plots (Fig. 5.2), we have shown that the SOM segment plots that were used in determining the dominant controlling variable were indeed from best quality SOM segment plots. In order to compare the distribution of AOT concentrations across each of the SOM segment plots during the monsoon and non-monsoon seasons, the probability density function (PDF) plots (Fig. 5.3) are presented. The AOT mapping plots, which also depict the predictability of AOT across each of the SOM quality plots are as well presented in Fig. 5.3. The AOT PDF plots (Fig. 5.3 a and b) reveal higher AOT concentrations across the region during the non-monsoon season than monsoon season as expected. Also with Fig. 5.3, we determine the predictive influence of AOT on each of the SOM quality plots. This is done relative to the ring diameter of the predictive variable as shown in Fig. 5.3 c and d). The wider the ring diameter, the higher the predictive influence from the variable under consideration. The results (Fig. 5.3 c and d) show that AOT has generally higher predictive influence for both high and low quality SOM plots during the monsoon and non-monsoon seasons. These results suggest that although soil moisture has the dominant controlling influence on atmospheric interactions across the SWA region, as discusses earlier, AOT exerts the greater predictive influence during the monsoon rather than during the non-monsoon season. In order words, with the same concentration of AOT in the atmosphere, we expect greater predictive influence during monsoon season than during non-monsoon season.

In spite that we are dealing with a mostly complex, nonlinear, non-discrete, multidimensional and multi-scale research problem. We have used the linear correlation results as shown in Figs. 5.4 a and b to complement the SOM results. This is justified because we cannot rule out some linearity in the interaction processes between aerosols-land-atmosphere and meso-scale convective systems across the region as shown in Fig. 2.2. Hence, the percentage correlation results presented in Figs. 5.4 a and b are used to quantify and further investigate the strength of the interactions between the identified controlling variables during the seasons and across the study region, assuming linearity.

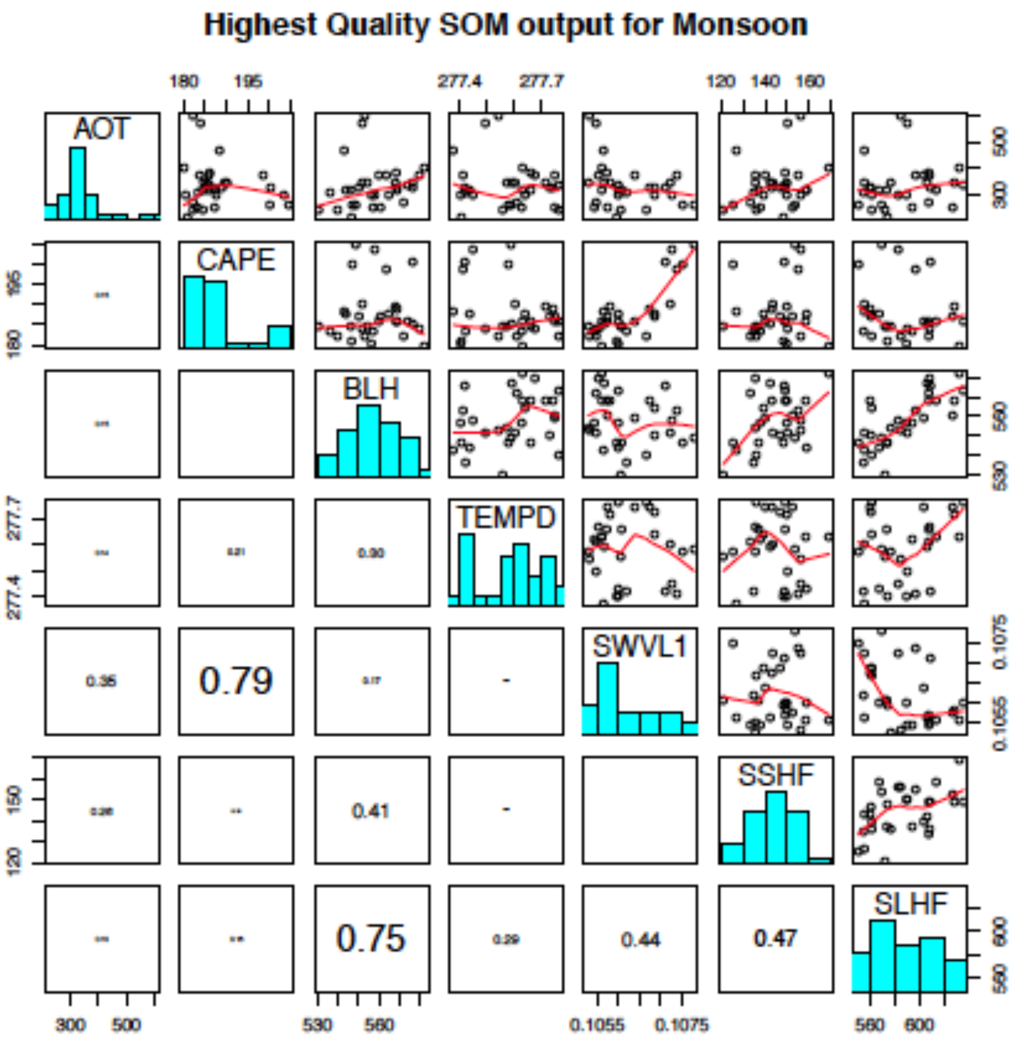

Fig. 5.4a: Showing the percentage correlation between the variables for the monsoon season. The correlation between the dominant controlling variables are discussed as shown in Fig. 5.1.

The results (Fig. 5.4 a) shows that soil moisture was about 79% correlated with CAPE and about 36% correlated with AOT during monsoon season. However, during the non-monsoon season (Fig. 5.4 b), soil moisture was about 67% correlated with CAPE and about 23% correlated with AOT. This suggests that even as soil moisture has the greatest controlling influence amongst the other variables during both seasons (as earlier discussed), soil moisture is also shown to correlate more with CAPE than AOT during monsoon than during the non-monsoon season. CAPE is a major convective initiation driving variable across the study region.

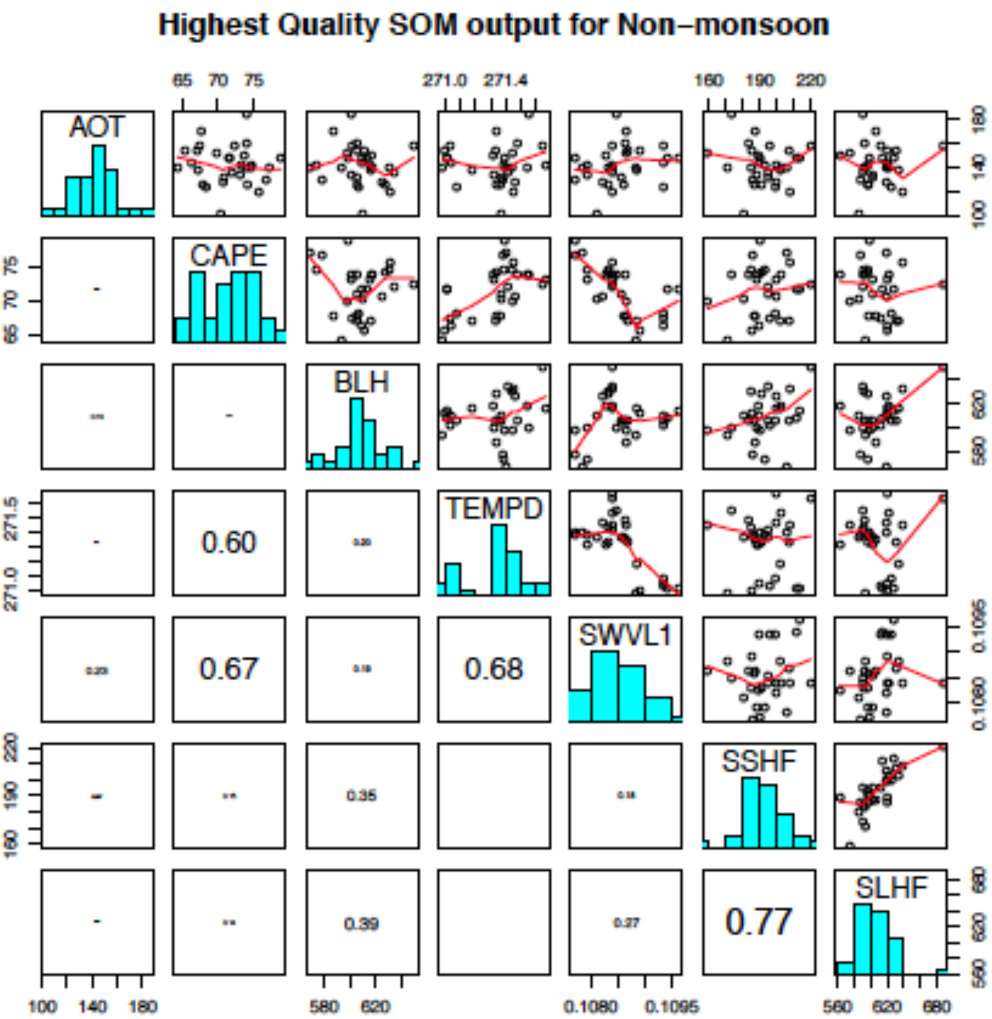

Fig. 5.4b: As in Fig. 5.4a but during non-monsoon season

Thus, we conclude that as soil moisture has higher controlling potential than AOT on convective activities during monsoon than non-monsoon seasons. We also found from Figs. 5.4 a and b that SSHF was about 47% and 77% correlated with SLHF during monsoon season and non-monsoon seasons respectively. This suggests that stronger coupling exists between the surface specific heat flux and the surface latent heat flux during non-monsoon season than monsoon season.

5.3 Interactions and feedback during Monsoon and Non-monsoon at maximum AOT

In order to investigate whether the dominant controlling variable changes at maximum AOT concentrations during monsoon and non-monsoon seasons, we selected the highest AOT threshold data subset (i.e. AOT values more than the median value of 320 μm) and generated SOM plots on the new data subset. Our results are presented in Figs. 5.5 to 5.7. We found that using maximum AOT subset, aerosols and soil moisture shows competing controlling influence during monsoon more than during the non-monsoon seasons (see Fig. 5.5). As explained with Fig. 5.1, our result here was obtained by matching the quality SOM plots (Figs. 5.5 c and d) with the SOM segment plots (Figs. 5.5 a and b). The yellowish segment plots were selected as the best quality SOM plots and from the best quality SOM plots, we selected the widest radii variable from within the best quality SOM segment plot as the dominant controlling variable.

Similar to our findings without using maximum AOT subset, the results here show that AOT has higher predictable influence during the monsoon rather than the non-monsoon season (Fig 5.6). The SOM PDF plots (Figs. 5.6 a and b) also shows aerosols with almost the same density distribution across the region during the monsoon and non-monsoon seasons. We also found the correlation between CAPE and soil moisture to be about 78% during monsoon and about 65% during non-monsoon season (Fig. 5.7). With the high AOT predictable influence and high soil moisture correlation with CAPE during the monsoon seasons, we are convinced that aerosols and soil moisture highly controls atmospheric interactions during monsoon than non-monsoon season.

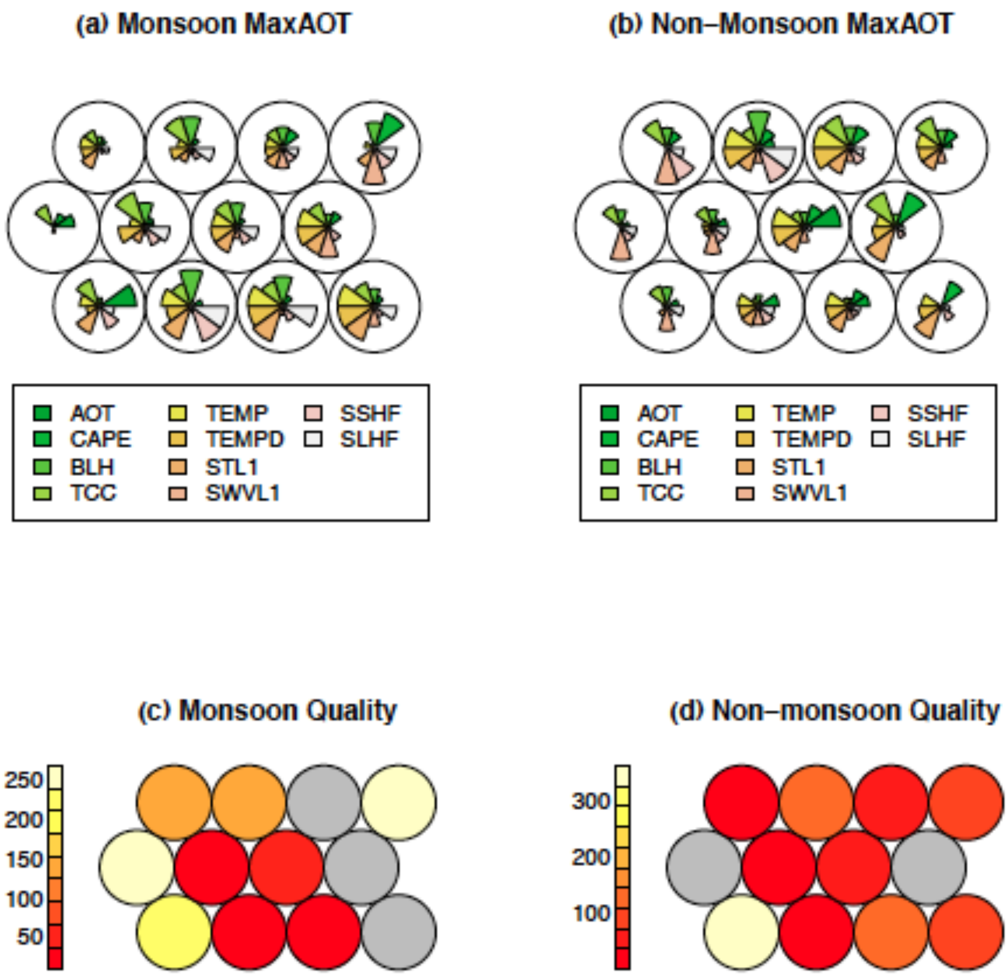

Fig. 5.5: As in Fig. 5.1 but using the maximum AOT as subset data threshold

Higher CAPE suggests higher convective activities, and as our result shows that soil moisture controls CAPE and AOT enhances predictability, we can conclude that both AOT and soil moisture significantly controls atmospheric interactions during monsoon seasons under the maximum AOT data threshold.

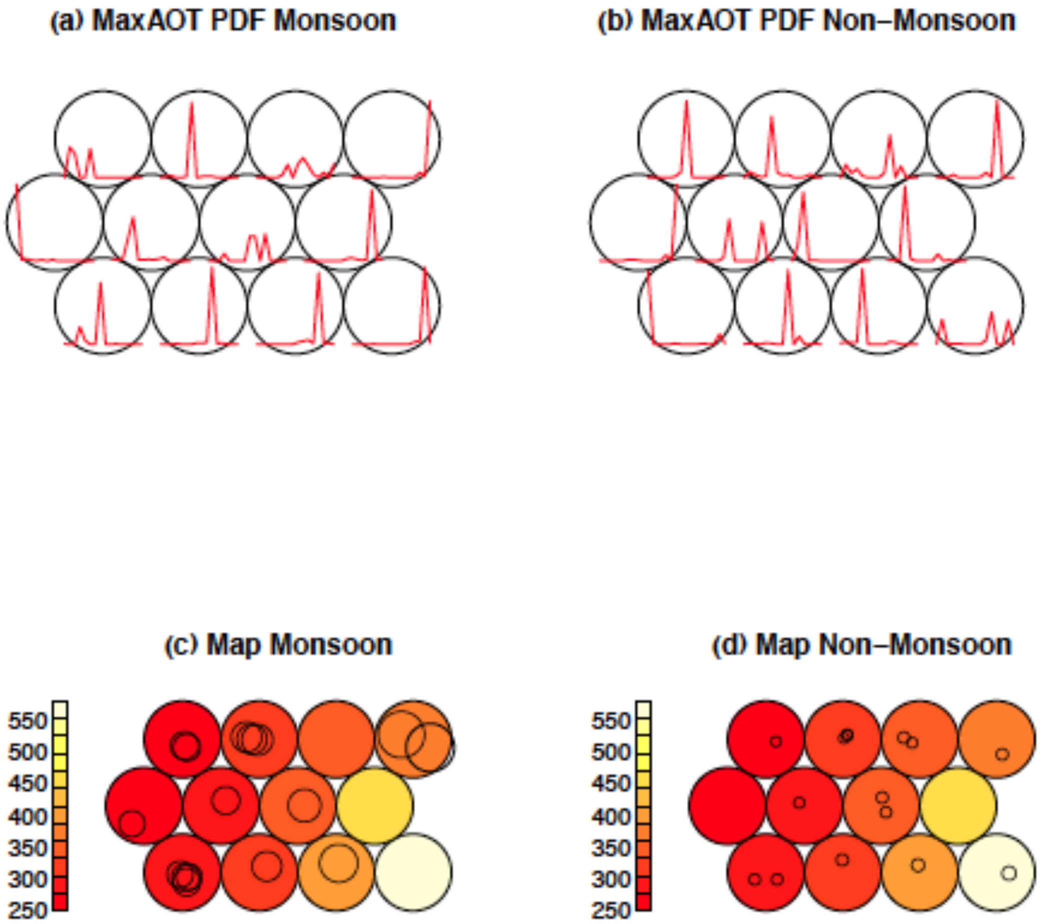

Fig. 5.6: As in Fig. 5.3 but using maximum AOT as subset data threshold

The results of percentage correlation between the identified controlling variables are as presented in Figs. 5.7 a and b. The results indicate that SSHF and SLHF are about 50% correlated during monsoon and about 75% correlated during the non-monsoon

(Figs. 5.7 a and b). The explanation for this is that during monsoon season when available soil moisture is high, the surface sensible heat flux is largely uncorrelated with the surface latent heat flux since there is more available surface moisture to be converted by latent heat – i.e. higher evaporation and evapotranspiration. However, because of the relatively dry surface conditions during the non-monsoon season, there is a relatively higher correlation between the SLHF and SSHF.

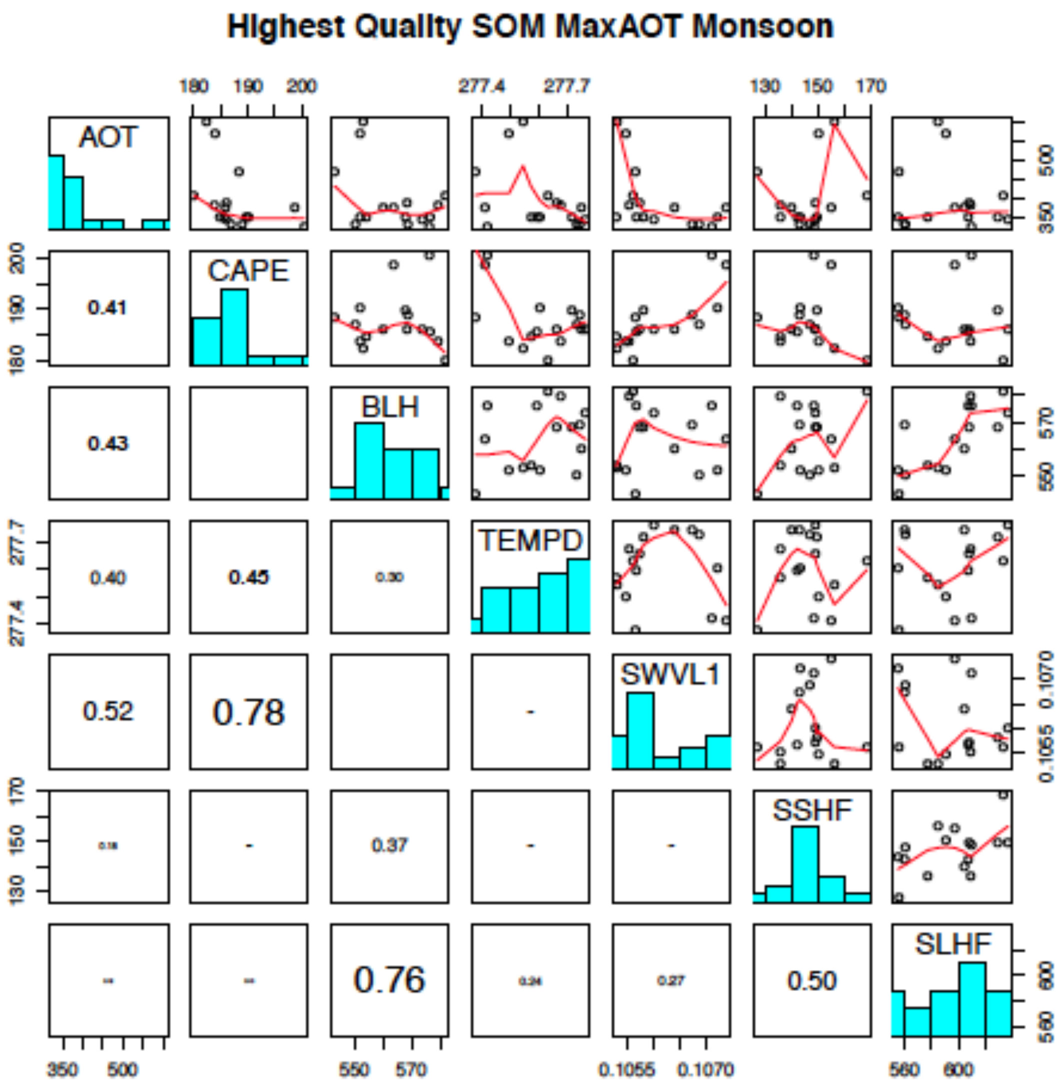

Fig. 5.7a: As in Fig. 5.4a but using the maximum AOT threshold as data subset

Thus, with maximum aerosol concentrations across the region, there appear to be a projected interaction between SSHF and SLHF during monsoon seasons than during the non-monsoon season. This suggests that high aerosols concentrations across the region significantly elevate the interactions between the surface heat fluxes than the rest of the other variables. This is a very crucial result since aerosol concentrations are technically higher during non-monsoon seasons due to the outbreak of mineral dust from the Sahara desert across the region during the non-monsoon season.

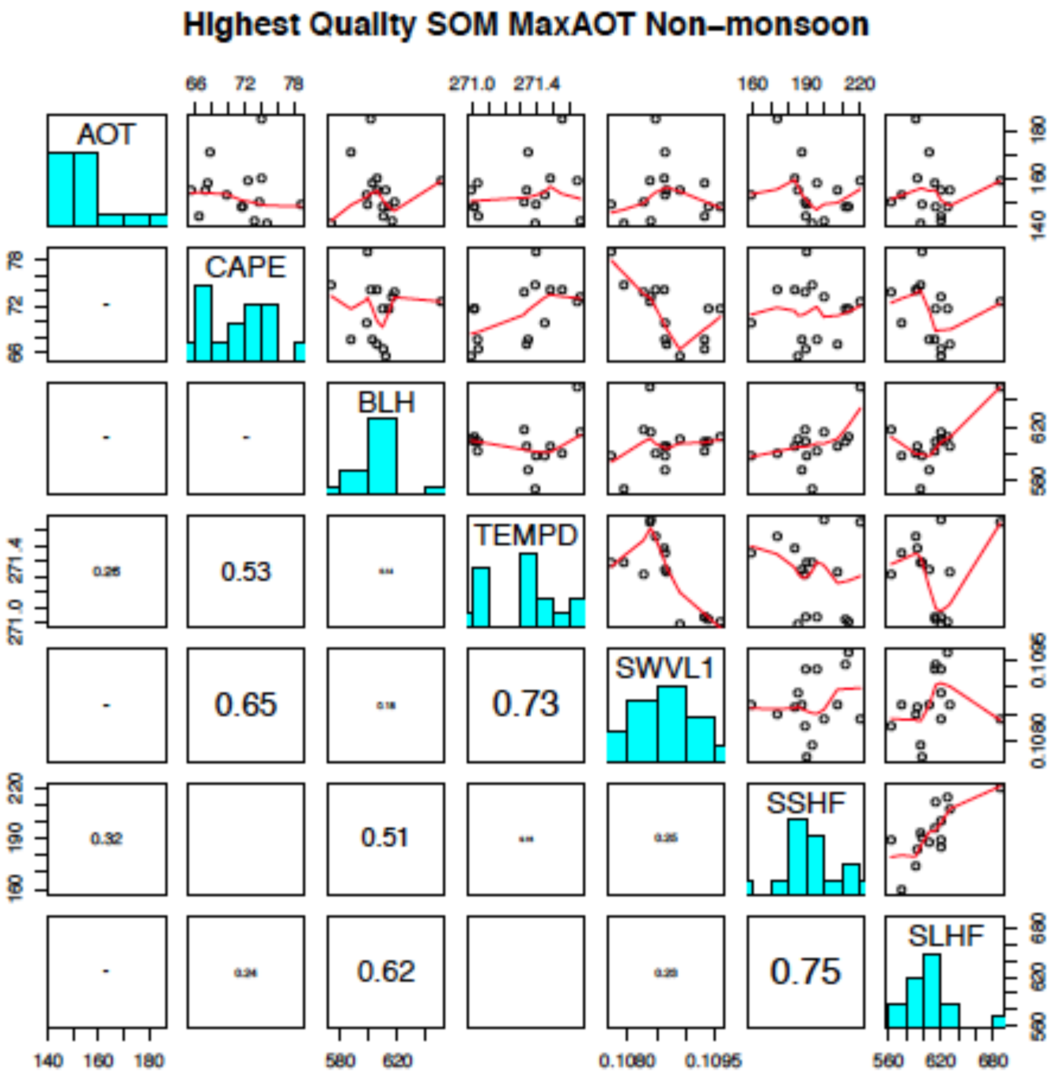

Fig. 5.7b: As in Fig. 5.4b but using the maximum AOT threshold as data subset

Meaning that a little influx of aerosols will significantly alter atmospheric interactions during monsoon season as opposed to during the non-monsoon season.

5.4 Interactions and feedback during Monsoon and Non-monsoon at minimum AOT

Similar to the data subset selection process described in section 5.3, SOM plots (Fig 5.8) were generated for the minimum AOT threshold (i.e. the AOT values less than the median value of 320 μm) values for both monsoon and non-monsoon seasons.

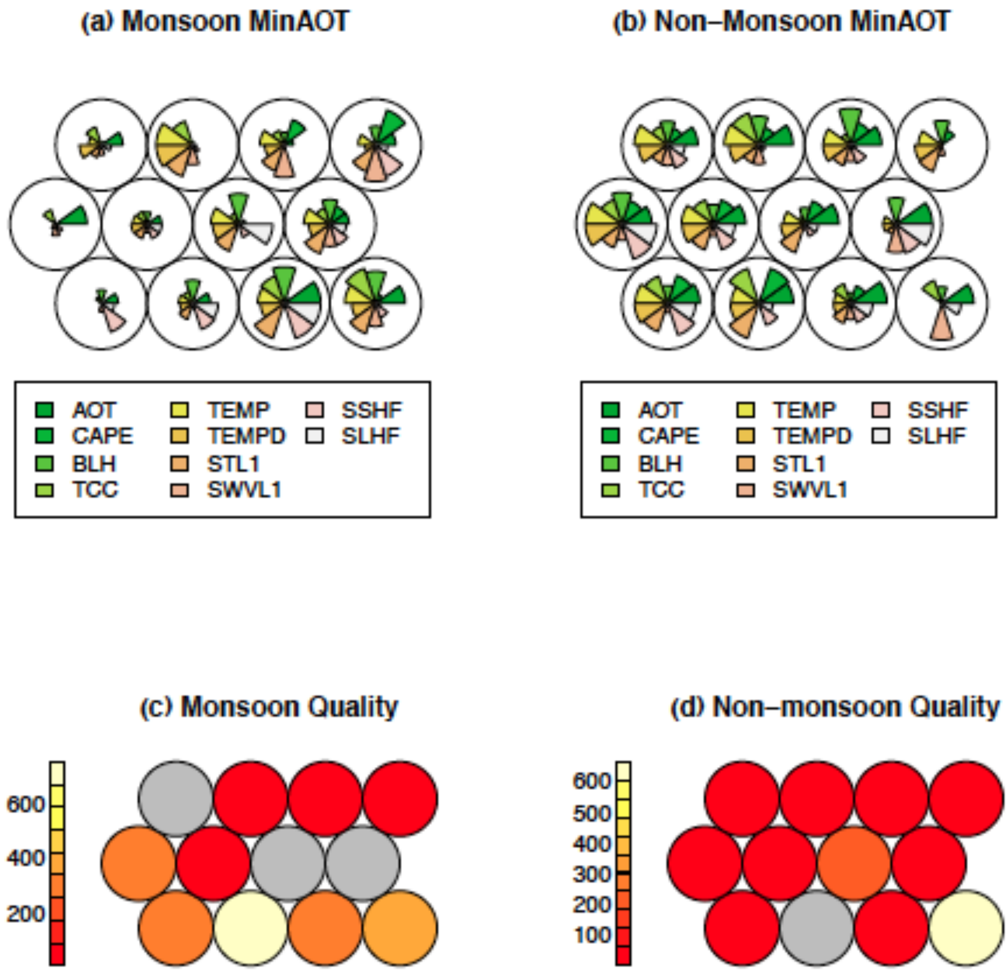

Fig. 5.8: As in Fig. 5.1 but using the minimum AOT as subset data threshold

Our results show soil moisture (the mean soil moisture value was about 0.2 kg m^{-3}) as the dominant controlling variable with its greatest controlling influence occurring during the non-monsoon season (Figs. 5.8) (as explained before, the variable with the widest radii within the highest quality SOM segment plot has the greatest controlling influence within that particular SOM segment plot). This is similar to what we found without using the threshold datasets – soil moisture predominantly controlling atmospheric interactions far more than AOT.

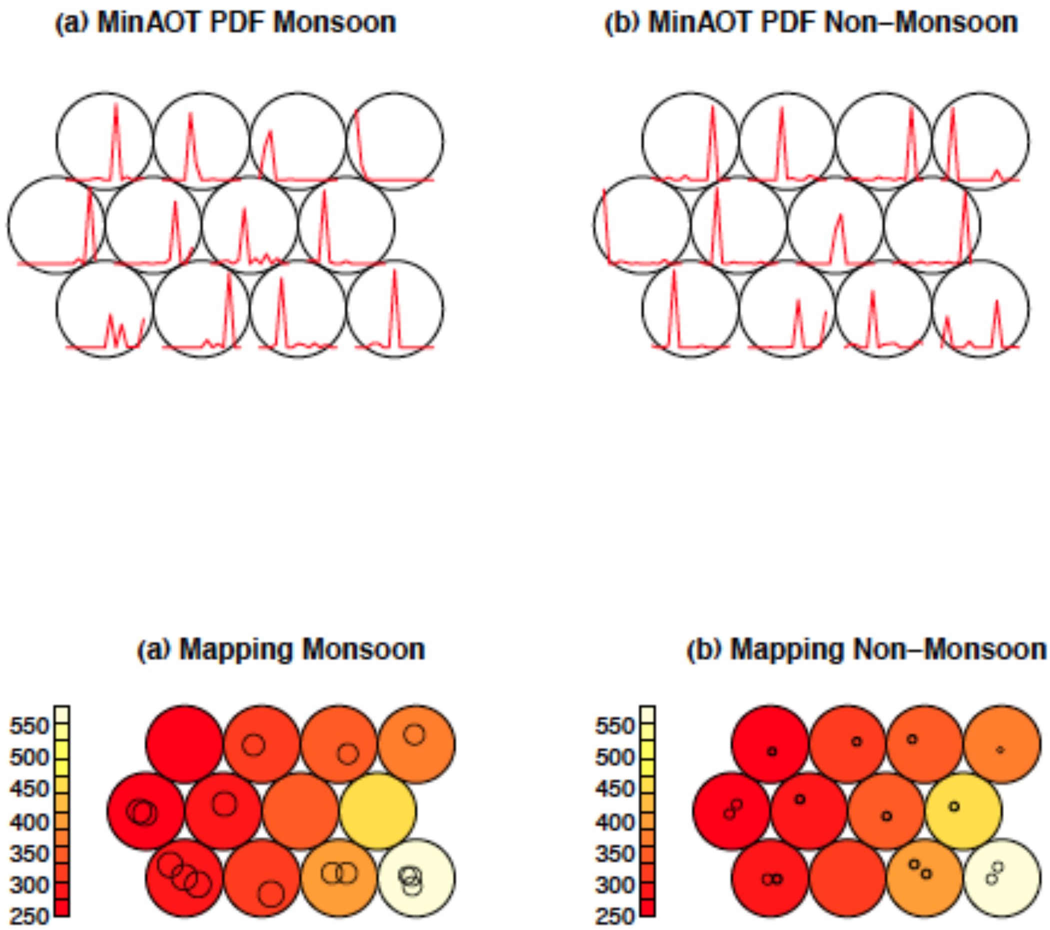

Fig. 5.9: As in Fig. 5.3 but using the minimum AOT as subset data threshold

We also see that the AOT has its greatest predictive influence during the monsoon season than non-monsoon season (Fig. 5.9) but with less intensity (as seen from the ring radii diameter in Figs. 5.9) when compared with that of the maximum AOT data threshold condition. The AOT distribution density also shows greater influence during the monsoon than non-monsoon season.

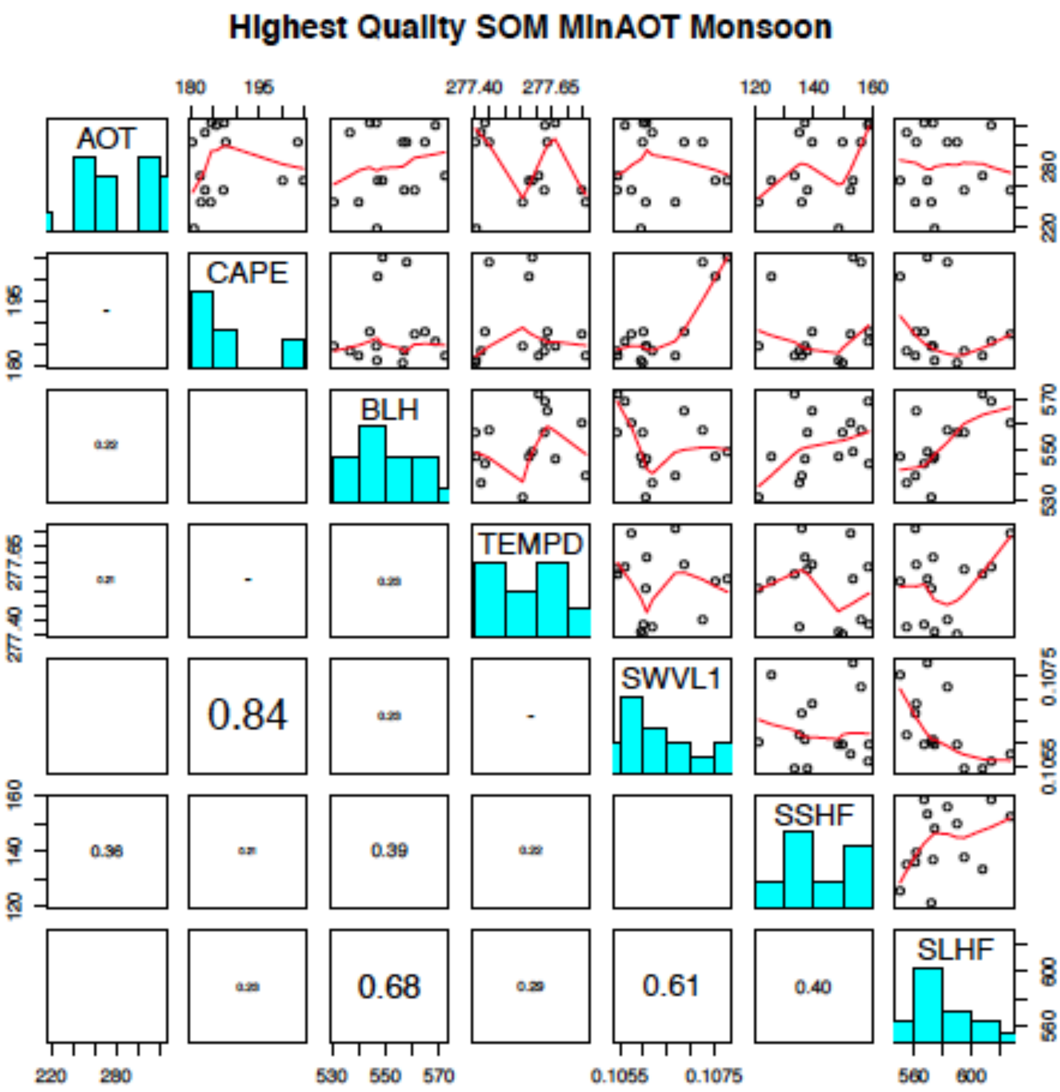

Fig. 5.10a: As in Fig. 5.4a but using the minimum AOT as subset data threshold

Results (Figs. 5.10 a and b) also show stronger correlation between SSHF and SLHF during non-monsoon than the monsoon season, suggesting that with minimum AOT data threshold, the fluxes are independent of AOT.

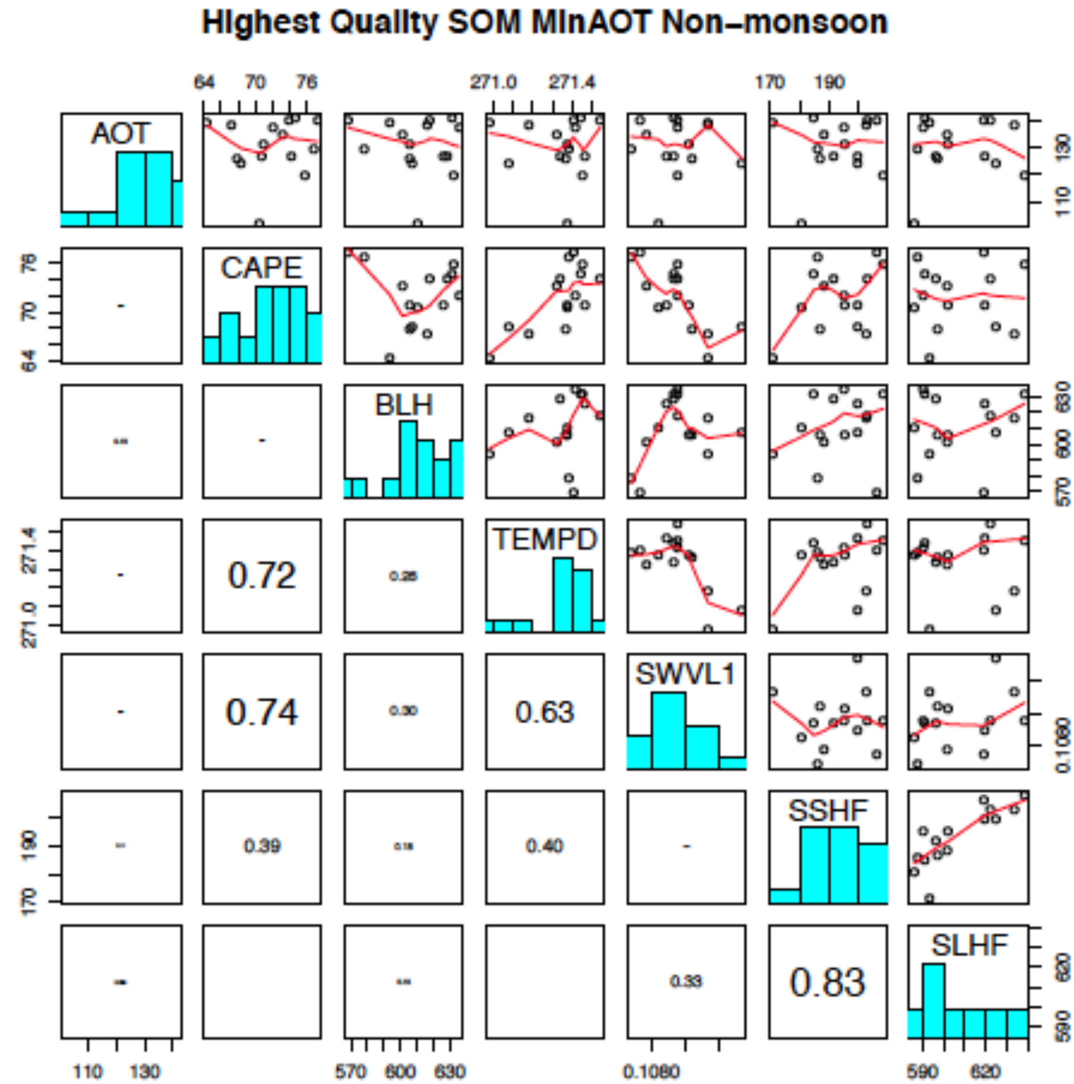

Fig. 5.10b: As in Fig. 5.4b but using the minimum AOT as subset data threshold

5.5 Interactions and feedback during Monsoon and Non-monsoon at maximum soil moisture

SOM plots for maximum soil moisture data subset (i.e. at maximum soil moisture greater than the mean value of 0.2 m^3/m^3) are presented in Fig. 5.11. Results show that AOT and soil moisture are at equilibrium as the dominant controlling variables during the monsoon season. But during the non-monsoon season, AOT was shown as the dominant controlling variable (Figs. 5.11 to 5.13) (again, we used the widest radii variable within the best quality SOM segment plot as the dominant controlling variable).

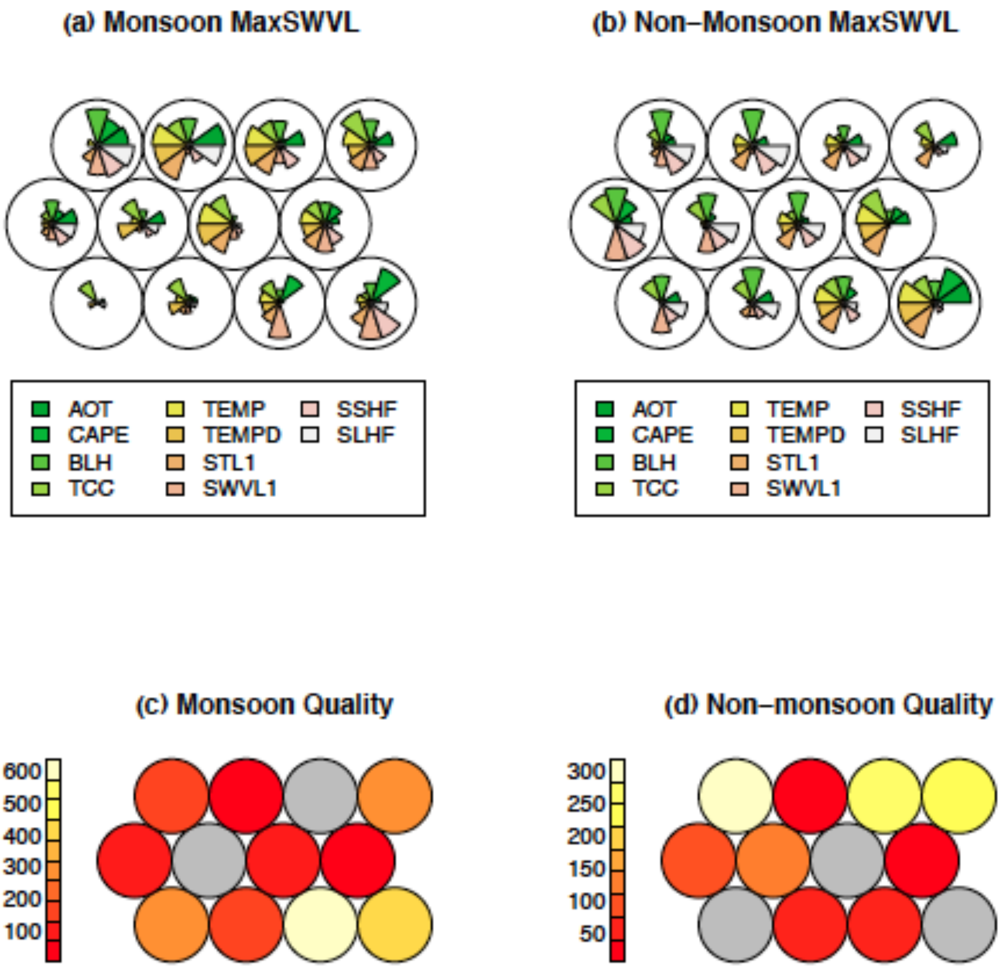

Fig. 5.11: As in Fig. 5.1 but using the maximum soil moisture as subset data threshold

Results also showed no significant seasonal difference (using the SOM predictability plots) in the predictability of soil moisture (Fig. 5.12) – since the ring diameters as shown in the predictive SOM plots (Fig. 5.12 c and d) are almost the same for the entire segment plots and for both seasons. Again, as mentioned before, we found that SSHF and SLHF are generally more closely correlated during the non-monsoon than monsoon season (Figs. 5.13 a and b).

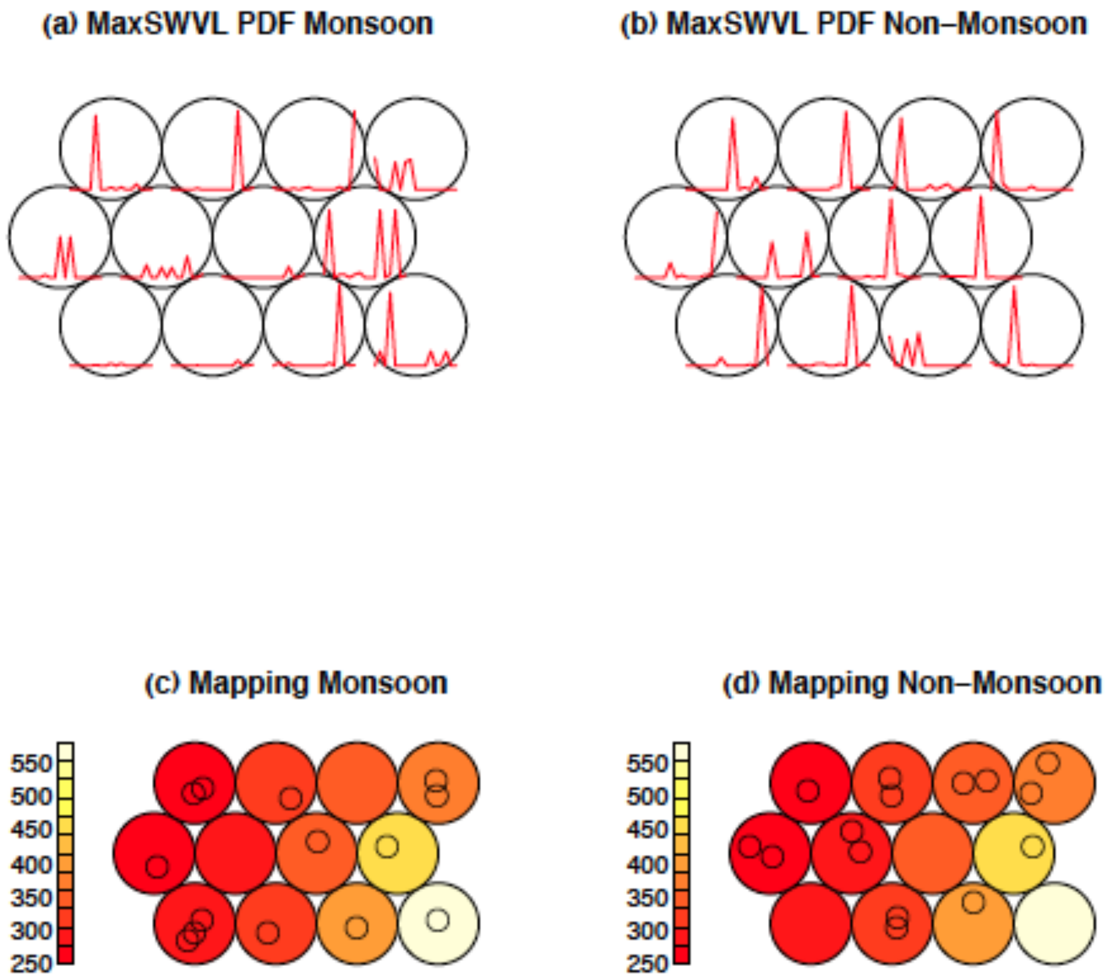

Fig. 5.12: As in Fig. 5.3 but using the maximum soil moisture as subset data threshold

The results suggest that with the data subset at maximum soil moisture threshold the controlling influence of AOT during the non-monsoon season is elevated. Meaning that with higher soil moisture during the dry season, AOT plays elevated controlling influence on atmospheric interactions across the region.

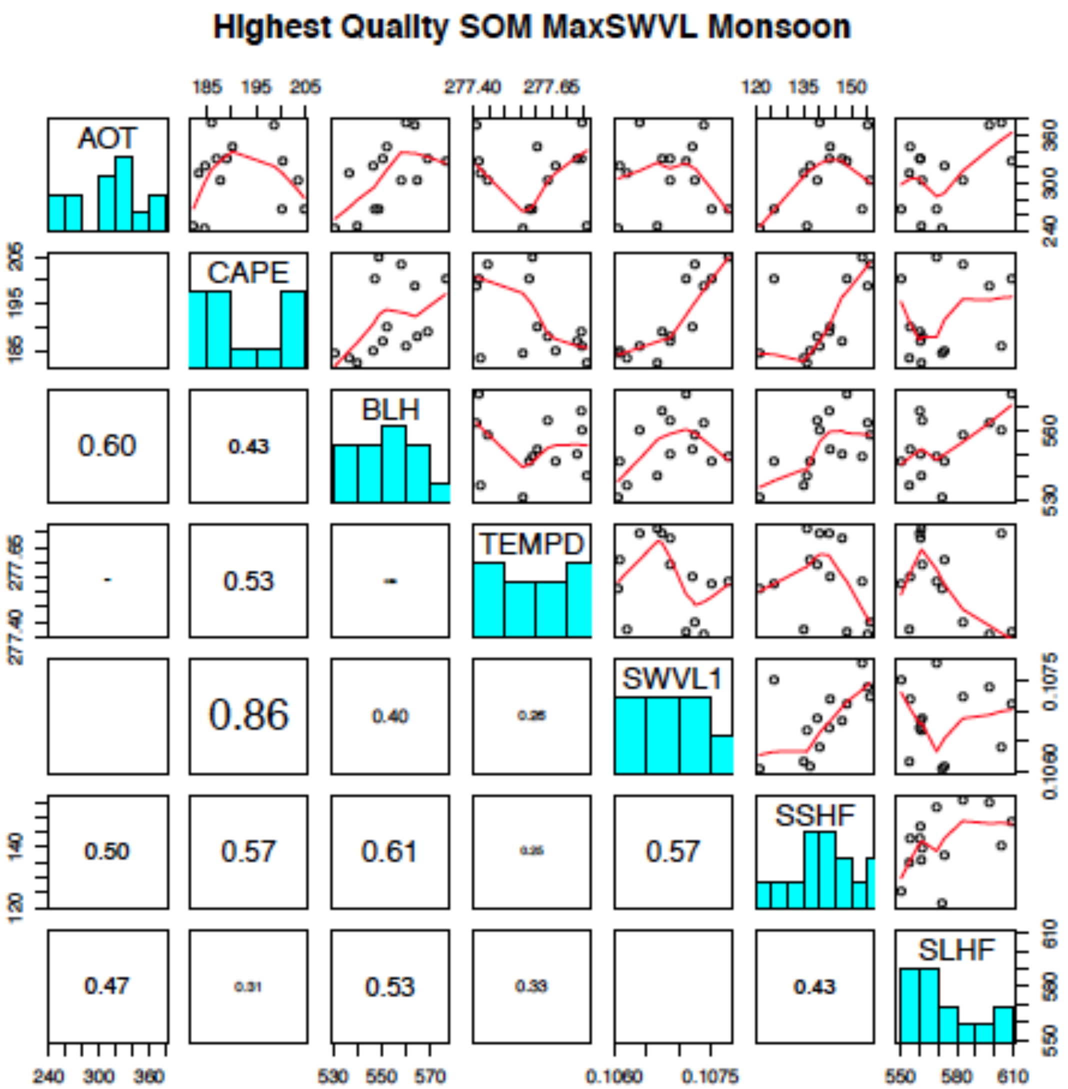

Fig. 5.13a: As in Fig. 5.4a but using the maximum soil moisture as subset data threshold

This is in agreement with the findings by Rosenfeld et al. (2008) and Li et al. (2011), which argued that as AOT suppresses warm precipitation, they also induces more cloud particles thereby initiating the release of more latent heat and consequently invigorates convection.

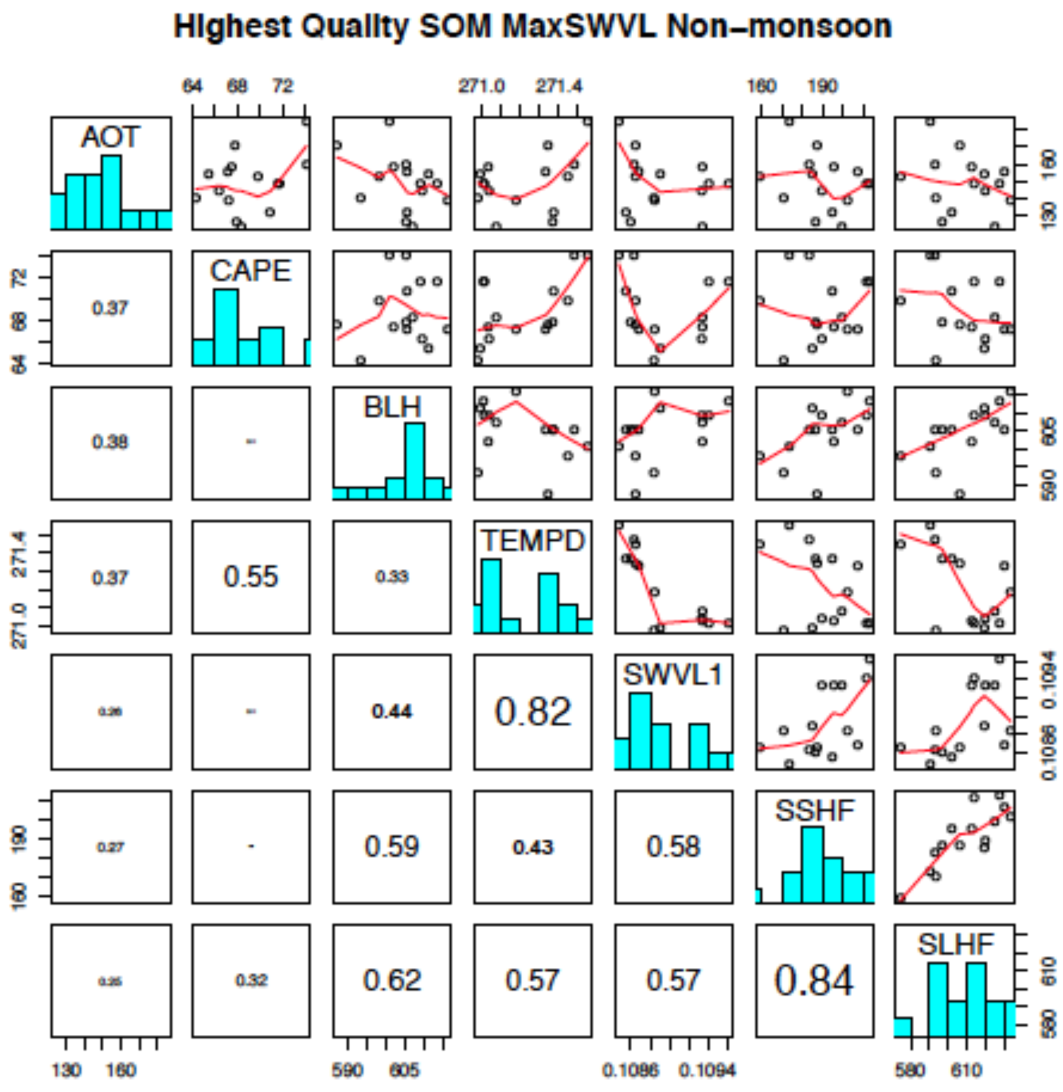

Fig. 5.13b: As in Fig. 5.4b but using the maximum soil moisture as subset data threshold

5.6 Interactions and feedback during Monsoon and Non-monsoon at minimum soil moisture

SOM plots for minimum soil moisture data subset (i.e. at soil moisture values less than the mean soil moisture value of 0.2 m^3/m^3) are presented in Fig. 5.14. From the results we found no particular dominant controlling variable during monsoon season. However, during non-monsoon season, soil moisture was shown as the dominant controlling variable (Figs. 5.14 a and b).

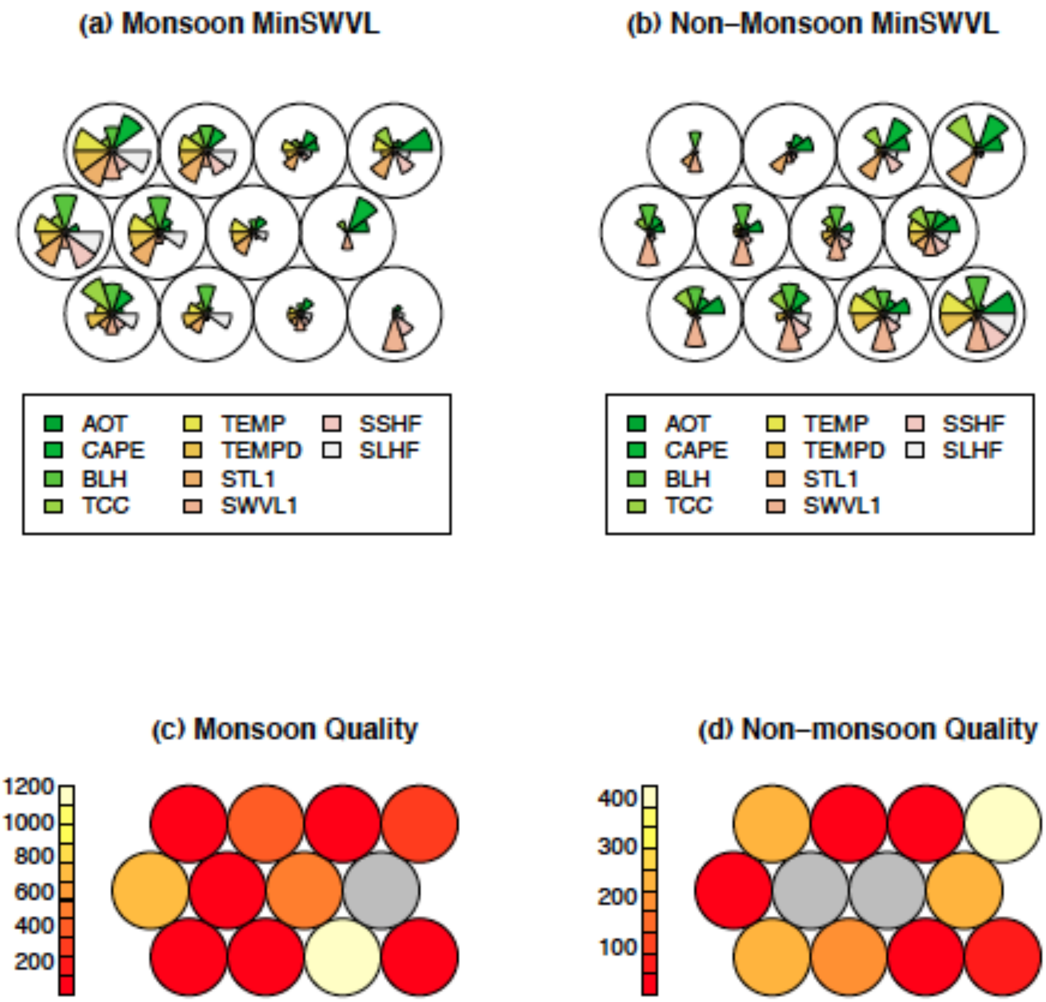

Fig. 5.14: As in Fig. 5.11 but using the minimum soil moisture as subset data threshold

To investigate the predictive influence of soil moisture during both seasons, we used the results as presented in Fig. 5.15. Again, we found that soil moisture remains the most controlling variable especially for both seasons, using the minimum soil moisture data threshold. The ring diameter of the predictive mapping plots for soil moisture for both seasons are almost the same within the best quality SOM segment plots (Fig 5.15 c and d).

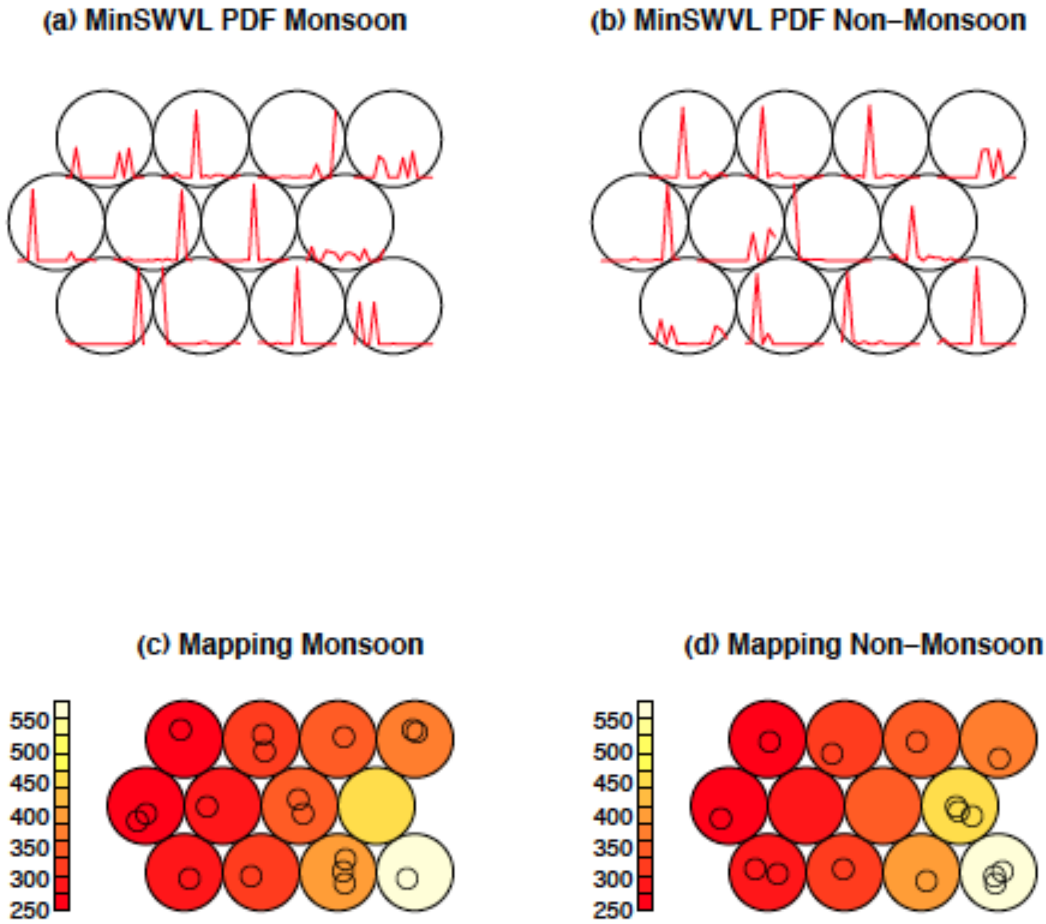

Fig. 5.15: As in Fig. 5.12 but using the minimum soil moisture as subset data threshold

Furthermore, the density plots (Fig. 5.15 a and b) also show that soil moisture has higher density distribution during the non-monsoon than monsoon season. This suggests that high soil moisture (using the minimum soil moisture threshold data) does not really alter soil moisture as the controlling variable for both seasons – we arrived at this result by matching the best quality SOM plots with the PDF plots (Fig. 5.15 a and b) and thereafter interpreting the PDF plots for the best quality SOM plots.

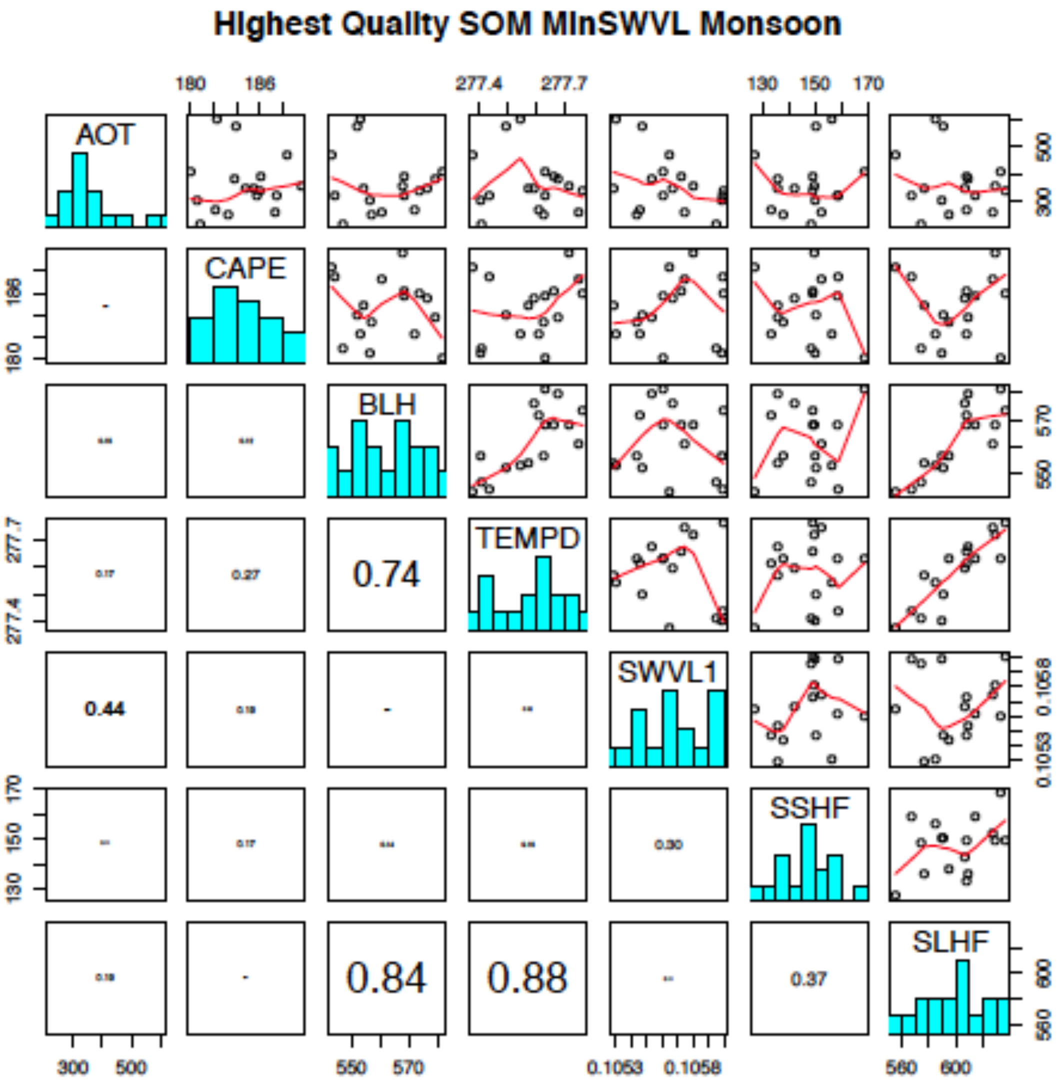

Fig. 5.16a: As in Fig. 5.13a but using the minimum soil moisture as subset data threshold

From the percent correlation plots (Figs. 5.16 a and b), our results show that CAPE, and boundary layer height (BLH) have high percent correlation with soil moisture during non-monsoon than monsoon seasons.

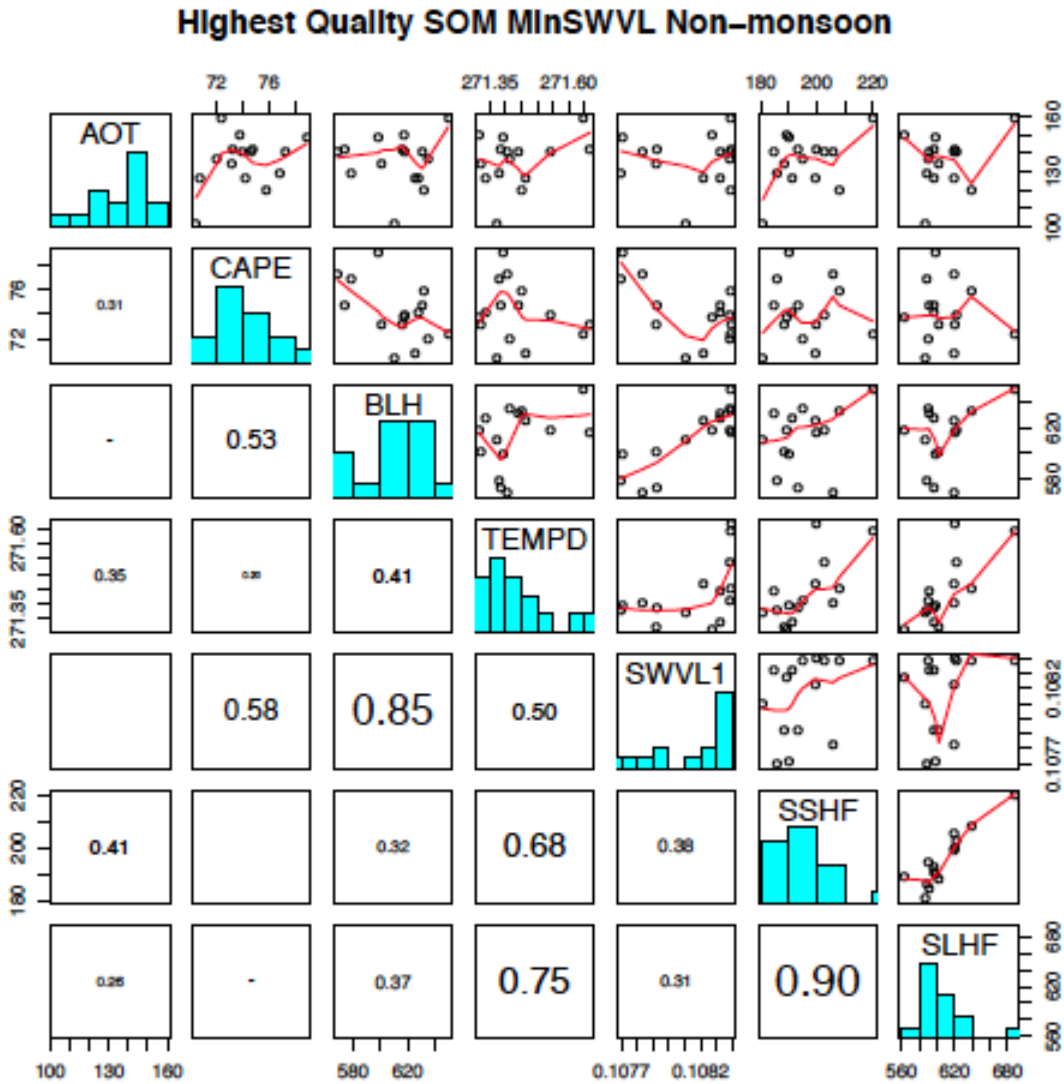

Fig. 5.16b: As in Fig. 5.13b but using the minimum soil moisture as subset data threshold

Thus, at minimum soil moisture threshold data subset, soil moisture is highly correlated with convective parameters during non-monsoon season than monsoon season – suggesting that the controlling influence of soil moisture on convective activities (under the minimum threshold data subset condition) is higher during dry season than during wet season. This means that the same increase in soil moisture volume for both seasons will show greater controlling influence on convective activities during non-monsoon than monsoon seasons. We know that soil moisture values are generally lower during non-monsoon than monsoon seasons because of the generally dry and dusty prevailing conditions.

5.7 Discussion and Summary

This work investigates the changes that occur to the controlling influence of aerosols, meso-scale convective parameters and land-surface properties on atmospheric interactions across the sub-Saharan West Africa (SWA) region during monsoon and non-monsoon seasons (see Figs. 5.1 to 5.16). Data for the month of July over the period 2002 to 2010 were used to represent monsoon season and the data for the month of November over the same nine-year period were used to represent non-monsoon season. Aerosols data were retrieved from NASA MODIS Aqua data archive and the meso-scale convection and land-surface properties data were retrieved from ERA-Interim reanalysis. From our results, we have noticed significant seasonal variability in the intensity at which aerosols, meso-scale convective parameters and land-surface properties controls atmospheric interactions. The important findings of this study are summarized in this section.

In general, our results reveal very strong seasonal influence in determining the dominant controlling variable on the interactions and changes between aerosols, meso-scale convective systems and land-surface properties across the study region. It was also shown that most of the variables generally controls atmospheric interactions mostly during the monsoon (wet) seasons than non-monsoon seasons. Although, a noticeable influence was observed during the non-monsoon season (dry), the most significant effects of aerosols and soil moisture were observed during the convective active season of the year. These results are consistent with those of Rosenfeld et al. (2008), Kim et al. (2010) and Li et al. (2011), where seasonal variations in aerosol concentrations were proven to be responsible for the enhanced circulation and precipitation, which resulted in cooling of the Sahel, and consequently resulted in shifting the peak meridional temperature gradient northward. With this type of shift, an enhanced anomalous easterly jet was found, which was associated with increased cyclonic circulation to the south consequently leading to anomalous rainfall regimes across the Sahara.

Results also show that between soil moisture and aerosols during the monsoon period, soil moisture has the highest controlling influence on atmospheric interactions across the region. This is an important finding especially regarding the understanding of the influence of soil moisture on the initiation and dissipation of meso-scale convective systems across the region. For instance, we know that increasing available surface soil moisture increases the potential for convection. And as surface soil moisture increases, sensible heat flux is reduced even though evaporation and transpiration increases. Thus, any further increase in evaporation and transpiration would enhance additional heat flux, thereby increasing available boundary layer convective energy, which thus provides favorable thermodynamic conditions for increase precipitation (Pielke et al., 2007).

We also found that even though aerosols control atmospheric interactions especially during the monsoon season, its controlling influence is not as significant as that of the soil moisture. Results further showed that soil moisture has the potential to control CAPE up to about 79% during the monsoon season and up to about 67% during the non-monsoon seasons, while AOT can control CAPE up to about 67% during monsoon and up to about 23% during the non-monsoon season. In general, SSHF and SLHF have a more controlling influence one each another during non-monsoon seasons than monsoon seasons. These results are not particularly surprising since we know that large scale agricultural-related activities across the region normally alters the land-surface physical properties, which could consequently influence the climate controlling variables (Niyogi et al., 2006; Pielke et al., 2007).

With the maximum aerosols threshold data subset, we found that soil moisture has a balanced controlling effect with aerosols on the atmospheric interactions during monsoon season but then soil moisture still show the dominant controlling influence during non-monsoon season. With the minimum aerosols threshold data subset, soil moisture still has the dominant controlling influence with its strongest influence occurring during the non-monsoon season. Maximum soil moisture data subset showed no particular variable as the dominant controlling variable during the monsoon season but AOT was found to be the most dominant variable during non-monsoon season. Finally, with minimum soil moisture data subsets, soil moisture was shown as the most dominant controlling variable with some competing influence with aerosols and total cloud cover during the non-monsoon season.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

This dissertation has studied closely the effects of aerosols and land-atmosphere interactions on meso-scale convective systems across the sub-Saharan West Africa (SWA) region. The incomplete understanding of aerosols-land-atmosphere interactions by climate scientists has been greatly implicated as one of the largest source of uncertainties in our understanding of climate systems (Marticorena et al., 2010). Despite these shortcomings, climate models remain very useful, and their products still serve as an important aid for modern day weather and climate predictions. As in this dissertation, there are several ongoing research and development efforts (for example, Kim et al., 2010; Marticorena et al., 2010; Freud & Rosenfeld, 2012; Konwar et al., 2012; Mark et al., 2012; Niu & Li, 2011) to improve our understanding of the roles of aerosols-land-atmosphere interactions on meso-scale convective systems in order to improve output results from climate models. Thus, in general, this study provides valuable contributions to climate science especially because of its contributions to improving weather and climate predictions across the SWA region.

The SWA region is known as the global hot spot for aerosols because it is bordered in the north by the Sahara desert, which is the world's largest single source of atmospheric mineral dust aerosols. The region is also known to have the highest intensity of biomass burning per square km across the globe (Niyogi et al., 2006; Ichoku et al., 2008; Huang et al., 2009). It is therefore very relevant to study the dynamics of aerosols-land-atmosphere interactions across the SWA region. Most of the rain-bearing convective weather systems across the region originate under different large-scale atmospheric conditions with different meso-scale features. The major mystery that still surrounds these convective systems is the exact mechanisms that trigger them and the mechanisms for their dissipation. This region therefore plays a very significant role in the atmospheric general circulation and in the initiation, growth and propagations of most of the major high-impact convective weather systems across the globe.

In agreement with previous findings (e.g. Rosenfeld et al., 2008; Kim et al., 2010; Marticorena et al. 2010 and Li et al., 2011), our results show that there is a very strong seasonal influence on what determines the most dominant controlling variable on the interactions between aerosols, meso-scale convective systems and land-surface properties across the study region. We have also found that these controlling variables are mostly very significant in modulating atmospheric interactions across the region during the monsoon (wet) seasons than during the non-monsoon (dry) seasons. Furthermore, we found that although there is a noticeable control by aerosols on the interactions between land-atmosphere and meso-scale convective systems, available surface soil moisture still exert the dominant control on these interactions across the region especially during the active convective period (monsoon season) of the year.

The most significant contribution to climate science especially in the study of aerosol-land-atmosphere interactions in this dissertation is our discovery of the strong seasonal control that exits in determining dominant controlling convective and land-atmosphere variables across West Africa. For the first time, we have provided aerosol-land-atmosphere interaction results with seasonal dependency as shown in Fig. 2.2. This clarifies our understanding of the seasonal control of atmospheric aerosols and land-atmosphere variables on meso-scale convective systems across the region

Another interesting accomplishment of this study was the ability to adapt the self-organizing map (SOM) methodology in investigating our problems. Though not very common in climate research, SOM has proven very useful in solving many statistical, cognitive psychology and artificial intelligence problems (Hewitson & Crane, 2002). As in this dissertation, we have for the first time, and to the best of our knowledge, used the SOM for climate research over Africa. It is our hope that following this work, African climate scientists will begin to explore the application of this highly sophisticated pattern recognition artificial intelligence method in providing answers to their research questions.

It is known that weather, climate and water-related disasters accounts for more than 90% of disasters worldwide, and the trend is growing, most probably because of the increase in population and infrastructure, and maybe because of increasing climate warming. In spite of this rising trend in weather and climate related disasters, most of the African weather centers who are supposed to issue early warnings are inadequately equipped and poorly funded. They operate with little infrastructures and poor training and research facilities. Increased financial support to develop and strengthen African weather centers, especially by way of promoting and encouraging relevant training and research, should be seen as an investment aimed at reducing the cost of disasters – human mortalities as well as infrastructural damage. African governments and other funding institutions should be encouraged to increase their contributions to the implementation of national, regional and international initiatives aimed at establishing and strengthening mechanisms that would help improve their weather forecasting capacities.

As a recommendation for future work, the next step to quantifying aerosols-land-atmosphere interactions on meso-scale convective systems across the region will include comparing our findings from this study with results from using raw station data observations instead of using the gridded ERA-Interim reanalysis and MODIS aerosol datasets – we are currently limited by the paucity and sometimes outright unavailability of these raw station datasets especially across the study region. We also hope to further investigate, in the nearest future, the effects of separating individual aerosol types (e.g. black carbon, dust, smoke, etc.) and investigating their controlling influences on the land-atmosphere interactions across the region. Another future study interest includes investigating the effects of aerosol inter-annual variability and trends on meso-scale convective systems across the region.

In conclusion, we have presented our findings here in this dissertation after closely examining aerosols-land-atmosphere interactions across the SWA region and how they affect the highly frequent and sometimes damaging meso-scale convective systems across the region. Recommendations for future work have also been discussed. These results contribute to improving our understanding of the formal representation of aerosols in climate models, which is expected to improve our predictability of these highly frequent high-impact convective systems.

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VITA

Oluseun Samuel Idowu was born in Ijebu–Ode, Ogun-State, Nigeria. He started his meteorology education as a trainee at the World Meteorological Organization (WMO) Regional Meteorological Training Centre (RMTC) in Nigeria, where he graduated with distinction. Subsequently, he secured a national scholarship to study for his BS degree in Agricultural Meteorology and Water Resources Management at the University of Agriculture Abeokuta (UNAAB), Nigeria. He finished with a First Class Honours degree, and as the best academic student of the year. He also secured sponsorship for a Postgraduate Diploma in Remote Sensing and GIS from the United Nations African Regional Centre for Space Science and Technology Education (ARCSSTEE) at the Obafemi Awolowo University Campus, Nigeria.

In 2009, Idowu completed his MS degree in Meteorology from the University of Pretoria, South Africa. He started his interdisciplinary Ph.D. studies at the University of Missouri – Kansas City in Geosciences and Statistics, beginning Fall 2008. He received the UMKC Chancellors Doctoral Fellowship (2010-2012) and successfully served as a Graduate Teaching Assistant (GTA) at UMKC and in both South Africa and Nigeria where he obtained his MS and BS degrees, respectively. Idowu has published peer reviewed scientific papers in international journals. He has also presented his research in international symposiums. Upon graduation with his Ph.D., he plans to be a mentor and a successful climate research scientist whose interests focuses on aerosols-land-atmosphere interactions and coupling, geared towards improving predictability of climate systems.

Prior to coming to the United States for PhD studies, Idowu worked at the

Nigerian Meteorological Agency (NIMET) for more than 10 years as a desk forecaster and a national TV weather presenter. While at NIMET, he successfully managed a network of over 40 weather stations in compliance with the World Meteorological Organization's (WMO) weather instrumentation, observation, coding and reporting standards. He also successfully used multiple numerical weather prediction (NWP) products to issue weather forecasts and agricultural/hydrological advisories.

Idowu also trained on the Use and Interpretation of Numerical Weather Prediction (NWP) products at the European Centre for Medium Range Weather Forecasts (ECMWF)—Reading, UK. Other training opportunities that he had completed include a workshop on Regional Weather Predictability and Modelling at the International Centre for Theoretical Physics (ICTP)—Trieste, Italy, and On-the-Job Training in NWP at the African Centre of Meteorological Application for Development (ACMAD)—Niamey, Niger Republic. He had also been invited twice to attend the NSF-funded Advanced Study Program at the National Centre for Atmospheric Research (NCAR) in Boulder, Colorado.

In recognition of his scholarly achievements, in 2009, through a grant application process, Idowu received the prestigous Phi Kappa Phi Love of Learning Award, which counted him among the top 50 graduate students in America. As a volunteer, he worked with the UMKC School of Graduate Studies to provide guidance to intending and newly employed GTAs. Part of his community service in the Kansas City area is to work as a peer mentor with high school and college age youth to achieve academic excellence and positive academic attitudes.