ABSTRACT

TETTEH, ISAAC KOW. Three-Dimensional Characterization of Boreal Spring-Summer Climate Variability over West Africa (1948-2006). (Under the direction of Dr. Fredrick H. M. Semazzi).

The main scientific interest is to characterize the three-dimensional boreal spring-summer climate anomaly patterns from 1948-2006 using monthly UD terrestrial precipitation, ERSST, and NCEP/NCAR reanalysis data for two major rainfall seasons, March-April-May-June (MAMJ) and June-July-August-September (JJAS) over tropical West Africa. The study is organized into two parts, which entail the use of: (i) unfiltered data for general characterization, and (ii) a 10-year low-pass-filtered data to focus on decadal/low frequency (LF) structures.

Analysis techniques involve application of EOF analysis, simultaneous heterogeneous grid point correlations, linear/partial correlations, composite and simple linear regression analyses. EOF analysis is performed on West African precipitation and global SSTs from which the leading and most relevant PCs are retained. Grid point correlations between the total precipitation time coefficients (TPTCs) and global SSTAs are computed to highlight spatial SST mode(s) associated with the precipitations. Linear/partial correlations between TPTCs and 19 well-known climatic indices are computed to highlight the most important indices associated with the temporal character of the precipitations. Composite analysis is computed based on the positive (negative) phases of the decomposed TPTCs, using vertical motion, horizontal wind, and geopotential height (GH) anomaly fields in the monsoon and midtropospheric layers, represented by 1000 hPa, 850 hPa, and 500 hPa isobaric surfaces.
Velocity potential (divergence) and streamfunction (rotational) are computed from the horizontal wind fields. The linear regression model is used to evaluate the functional relationship between the net precipitation and net vertically integrated moisture budget (NVIMB) anomalies for the two seasons over West Africa, Sahel, and GOGC, and also, test the sensitivity of the divergent circulations over these climatic zones.

The composite analyses show that the unfiltered circulations at the surface and 850 hPa levels for each of the seasons are similar and are closely related to contrasting SST patterns over the Mediterranean Sea, Atlantic and Indian Oceans and the associated horizontal winds, as well as their divergent and rotational flows. At 500 hPa, the winds are more intense and well organized. Within and between the seasons, the commonalities and disparities are highlighted on the basis of SSTAs, nature of the horizontal winds, rotational wind fields-number, intensity, location, and size of their cyclonic/anticyclonic flows, as well as centers of action of their divergent circulations. These features, which generally coincide with the GH and omega fields, together, reflect the precipitation patterns over the region. However, the MAMJ divergent circulations generally do not synchronize the omega and precipitation fields, thus, appear to be closely related to subtropical Saharan high and Saharan thermal low. The regression model reveals that whilst the other two zones are insignificant, 70% unfiltered JJAS Sahel net precipitation anomalies (NPAs) can be explained by NVIMB anomalies ($r = +0.84$), implicitly, suggesting their compatibility with the divergent circulations. The LF circulation anomalies are similar to the generalized events, suggesting that the latter are dominated by at least the first two LF modes. However, the features, which serve as the main dividers between these two and also, within and between the LF events of the two seasons relate to intensely contrasting SST patterns, which may be coupled to intense
LF atmospheric circulations, manifesting themselves especially in the rotational and divergent fields. The regression analysis also shows that 73% LF JJAS Sahel NPAs can be explained by LF NVIMB anomalies ($r = -0.85$), linking them to divergent circulations. The most outstanding conclusion is that two dominant and competing mechanisms that drive precipitation over Sahel and GOGC are momentum convergence (divergence) and horizontal advection, respectively.
Three-Dimensional Characterization of Boreal Spring-Summer Climate Variability over West Africa (1948-2006)

by
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DEDICATION

This thesis is whole-heartedly dedicated to my family, Kwame Nkrumah University of Science and Technology, and the people of Ghana for their support.
Isaac Kow Tetteh, affectionately called Paa Kow, was born in Takorase in the Eastern Region of Ghana, to Mr. Albert Tetteh, of blessed memory, and Madam Faustina Sam. He started his primary education at Urban Council Primary and Middle School, in Winneba, Central Region, and completed his G.C.E Ordinary and Advanced Level education at Winneba Secondary School (WSS). He did his post-secondary school National Service at WSS. In 1985, he gained admission to the University of Cape Coast (UCC), where he obtained his BSc (Hon) Degree in Biological Sciences and a Diploma in Education in 1989.

As a professional teacher, he taught Health Science, General Science, Integrated Science, and Biology at Accra Workers’ College, Accra Polytechnic, and Prempeh College, all in Ghana. In 1996, he gained admission to the Kwame University of Science and Technology (KNUST), Kumasi, Ghana, where he obtained his MSc Degree in Environmental Science. He worked with the Department of Theoretical and Applied Biology, KNUST, until he was awarded Government of Ghana Scholarship to pursue graduate studies in Atmospheric Science, at North Carolina State University. Isaac is married to Antonia, a lovely lady, and have three nice children; a son, Kweku, and two daughters, Esi, and Araba.
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“The mighty God omniscient one, whose ways we cannot trace. He reckons every good begun and crowns it with His grace. He is here and there and everywhere, in all the ways I have trodden. I have never passed beyond the sphere of the providence of God.”

Thank you, God, the creator and sustainer of the universe, in whom all things consist, for bringing me to this stage in my career.

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CHAPTER ONE

1. Introduction

1.1 Problem Identification and Significance of the Research

The climate of tropical West Africa, a subcontinent whose rural economy thrives on rain-fed agriculture, has received tremendous attention following the persistent and devastating drought that plagued the Sahel in the early 1970s (Folland et al., 1991; Lamb and Peppler, 1992; Nicholson and Palao, 1993; Giannini et al., 2005). Efforts, which have been made to diagnose this extreme climate variability, hinge on detection and attribution, and possibly, if the causes are anthropogenic, aim at implementation of pragmatic mitigation actions through concerted efforts that could inject new lease of hope to the people of this less-developed subcontinent. Studies show that the African climate system (ACS) is subject to large intraseasonal, inter-annual, inter-decadal, multi-decadal, and millennial variations (Nicholson, 2000; Hulme et al., 2001; Nicholson, 2001). The ACS is known to be influenced by a broad spectrum of complex interactions, which include among others, wide differences in topography, vegetation, land-sea contrasts, dynamical mechanisms, and influences of different climatic teleconnections (Janowiak, 1988; Nicholson et al., 1988; Semazzi et al., 1996; Mutai and Ward, 2000; Xoplaki et al., 2003; Delire et al., 2008) and anthropogenic activities (Charney, 1975; Paeth et al., 2009).

Two major seasons, which characterize the West African monsoon (WAM) are March-April-May-June (MAMJ) and June-July-August-September (JJAS). The MAMJ and JJAS
seasons constitute the Gulf of Guinea Coast (GOGC) and the Sahel precipitation seasons, respectively. The GOGC season strictly falls under boreal spring to early summer, whereas the Sahel season has traditionally been treated as part of boreal summer, even though technically speaking, it roughly extends into the early fall season. There has not been a universal concordance as to which part of the boreal summer the Sahel receives its maximum precipitation. Whereas others argue that the Sahel receives bulk of its precipitation in July-August-September (JAS) season (e.g., Giannini et al., 2005), others too, report that it is JJAS (e.g., Semazzi et al., 1993; Rowell et al., 1995; Joly et al., 2007). Still others limit their study strictly to June-July-August (JJA) summer season (e.g., Semazzi et al., 1993; Bell and Chelliah, 2006) even though our literature search appears that Sahel rainy season studies are dominated by JAS.

An examination of West African seasonal climate variability research shows that it is dominated by boreal summer, which constitutes the Sahel’s major precipitation period. Some of the arguments advanced are that the monsoon system is strong at this time and also, the attempts at understanding and finding lasting solutions to the precarious climate variability over the Sahel. Interestingly, the GOGC and the Sahel seasonal precipitations are known to be governed by different physics (Rowell et al., 1995; Vizy and Cook, 2001; Giannini et al. 2005; Hagos and Cook, 2007; García-Serrano et al., 2008; Polo et al, 2008) even though the two climatic zones are confined within the same subcontinent. Most of the time, the physics involved in the GOGC precipitation variability is considered in tandem with the Sahel precipitation season, apparently due to the coupled precipitation modes frequently observed
in which Sahel prevails as the dominant mode over GOGC mode during the boreal summer (Giannini et al., 2005).

To date, a comparison of the 3-dimensional (3-D) climate anomaly patterns in association with the dominant precipitation modes of the two seasons (MAMJ vs JJAS) involving June, the transitional month, has not been explored. The paucity of information on this subject matter forms the uniqueness and motivation of the current research. The relevance of this research centers on improving our understanding of climate variability of West Africa, the findings of which may be a vital resource for enhancing decision support system related to efficient allocation of resources, regional planning, economic integration and cooperation in the area of climate-health, climate-agriculture, climate-water resources, climate-energy, and resettlement over the subcontinent. It will be a valuable resource for researchers interested in modeling studies in the tropics. Also, it will be a unique contribution to the atlas of Climate Variability and Predictability (CLIVAR).

1.2 Objective(s) and Structure of the Thesis

1.2.1 Objective(s) of the Research

The fundamental goal of the research is to elucidate further, the climate variability of tropical West Africa by characterizing the 3-D tropospheric circulation anomaly patterns associated with the general (unfiltered) and decadal (low frequency; LF) components of boreal spring-summer seasons in relation to climatic teleconnectivity in the monsoon and middle layers.
1.2.2 Structure of the Thesis

The thesis is organized into six chapters:

i. Chapter one deals with the introduction

ii. Chapter two relates to data sources, methods and analysis techniques

iii. Chapter three focuses on the 3-D characterization of the general (unfiltered) MAMJ and JJAS tropospheric circulation anomaly patterns

iv. Chapter four is devoted to the 3-D characterization of the LF (decadal) components of the two seasons

v. Chapter five presents summary of the research

vi. Chapter six presents conclusions and recommendations

1.3 Literature Review

1.3.1 Techniques for Analyzing Multivariate Data in Climate Research

Analysis of multivariate data is often fraught with difficulty because of multi-dimensionality of datasets. However, readily available analysis techniques for dealing with such data are empirical orthogonal function (EOF) analysis or principal component analysis (PCA), factor analysis, canonical correlation analysis (CCA), cluster analysis, discriminant analysis, logistic regression, etc (Wilks, 2006; Johnson and Wichern, 2007). In this study, the terms EOF analysis and PCA are used synonymously. EOF/PC analysis, which is the primary analysis tool used in this study, derives its roots in the Social Sciences (Pearson,
1902), where there is evidence of its substantial applications. However, its utility in Geophysical Sciences such as Atmospheric Sciences is relatively recent. It was used for the first time in the late 1940s by Obukhov (1947), followed by Fukuoka (1951), Lorenz (1956), and Kutzbach (1967). Since then, it has gained popularity as a robust analysis tool in climate and other geophysical studies. PCA types include among others, traditional/standard/regular EOF analysis, extended EOF analysis, combined EOF analysis, functional PCA, Bayesian PCA, rotated EOF analysis, multivariate EOF analysis, cyclostationary EOF analysis, probabilistic PCA, real vector EOF analysis, and complex EOF analysis (Jolliffe, 2002; Branstator, 1987; Wang et al., 1995; Kim and Wu, 1999; Houseago-Stokes and Challenor, 2004). However, they share the basic underlying principles.

EOF/PC analysis is a vector space orthogonal linear transformation that converts a variance-covariance matrix (correlation matrix) dataset of $n \times p$ dimensions into a new coordinate system represented by a few linear combinations that explains or carries a very large proportion of variance contained in the original data. The new components, representative of the original data set with $n \times p$ dimensions are known as principal components (PCs) (Jolliffe, 2002; Wilks, 2006; Johnson and Wichern, 2007). In this case, PCA is also a dimension reduction technique in which the new coordinate system has PCs with lower dimensionality, but at the same time retains those important characteristics of the original data that contributed a greater proportion of the variance in the transformation. The first PC has the highest (maximum) variance, followed by the second, third, etc. But overall, the variance of the original data and the newly transformed PCs are conserved. The computation leads to three important products namely, the eigenvalues, eigenvectors, and
scores, the dominant modes representing the most important characteristics captured from the original data. The three products represent the variance, spatial loadings/spatial patterns (loadings), and the time series, respectively. EOF analysis has the ability to orthogonalize a matrix of vectors making the variables in the new coordinate system uncorrelated with each other in space. Thus, the multicollinearity problem observed in datasets is solved with this technique since orthonormality is achieved.

1.3.2 Significance tests of principal components

Retaining the appropriate number of PCs, which effectively summarizes the total sample variance in EOF analysis, has been approached using various selection techniques (North et al., 1982; Johnson and Wichern, 2007). The eigenvalues that are arranged in descending order are truncated at certain level to retain the largest contributors to the total variance. In this study, the truncation was achieved by test of degeneracy, which involved the rule of thumb developed by North et al. (1982), otherwise also known as the delta-test. For the eigenvalues of two adjacent EOFs to be statistically different, the necessary condition needed to be satisfied is as follows:

$$\lambda_a - \lambda_b > \lambda_a (2/N)^{1/2},$$

where $\lambda_a$ and $\lambda_b$ are the two eigenvalues, and $\lambda_a > \lambda_b$ and $N$ is the number of observations. And $\partial \lambda = \lambda (2/N)^{1/2}$ is the standard error associated with a particular eigenvalue. In other words, for $\lambda_a$ and $\lambda_b$ to be statistically separate, the distance between $\lambda_a$ and $\lambda_b$ should be greater the standard error associated with $\lambda_a$. 

6
1.3.3 Data Filtering Techniques

Just like other data, geophysical data are also contaminated by noise, which tends to adulterate data quality. Data filtering (smoothing) techniques are implemented to remove noisy signals and extract real trends and patterns from the datasets (Shumway and Stoffer, 2006). Broadly, these techniques can be categorized into two: frequency domain encoded signal and time domain encoded signal filters (Smith, 2006; Shumway and Stoffer, 2007). Generally, frequency domain filters consist of three classes, which are low-pass filters (LPFs), high-pass filters (HPFs), and band-pass filters (BPFs), and all of them have many different types. LPFs (also known as high-cut filters) extract low-frequency signals whereas HPFs (also known as low-cut filter) extract high frequency signals. BPFs are a combination of LPFs and HPFs. The definition and choice of ‘low’ and ‘high’ frequencies, relative to cutoff frequency, are set by the filter designer. For instance, Arguez et al. (2009) employed 97-point Gaussian LPF technique, or 48 consecutive passes of the 1-2-1 filter (von Storch and Zweirs, 1999) to isolate low-frequency components from their extended reconstructed SST (ERSST) anomaly series.

The moving average (running or rolling mean) is among the most popular time domain encoded signal filtering techniques in digital signal processing (DSP), because of its simplicity. It is also optimal for common tasks in the sense that it reduces noisy signals while retaining sharpest step response. Its relatives are Gaussian, Blackman, and multiple-pass moving average filters, which slightly perform better in the frequency domain, but are computationally expensive. Moving average filters are implemented by convolution and recursive algorithms. Implementation by convolution entails averaging a number of points
from the input signal to produce each point in the output signal. The general equation for calculating this type of filter, which only utilizes points on one side of the output sample being calculated, is as follows:

\[ y[i] = \frac{1}{M} \sum_{j=0}^{M-1} x[i + j] \quad \text{Equation 1.1} \]

where

\[ x[\ ] = \text{the input signal} \]

\[ y[\ ] = \text{the output signal} \]

\[ M = \text{the number of points used in the moving average} \]

Alternatively, the group of points from the input signal can be averaged symmetrically around the output point to achieve a two-sided smoothing. In this case, Equation 1.1 is modified to:

\[ y[i] = \frac{1}{M} \sum_{j=-\lfloor (M-1)/2 \rfloor}^{\lfloor (M-1)/2 \rfloor} x[i + j] \quad \text{Equation 1.2} \]

The recursive solution uses the outcome of a previously calculated value. In other words, it uses two sources of data to calculate each point in the output (from the input and previously calculated points from the output). This algorithm can be expressed in the form of an equation as follows:

\[ y[i] = y[i-1] + x[i + p] - x[i-q] \quad \text{Equation 1.3} \]

where:

\[ p = (M-1)/2 \]

\[ q = p + 1 \]
In this equation,

\[ x[ ] = \text{the input signal} \]

\[ y[ ] = \text{the output signal} \]

\[ M = \text{the number of points in the moving average} \]

The recursive fashion is more efficient than the former, in terms of computational efficiency. The details of these two algorithms are fully described by Smith (2006).

Applications of moving average filters can be found in Nicholson (1980), Semazzi et al. (1996), Chelliah and Bell (2004) and Giannini et al. (2005).

1.3.4 West African Climate variability and atmospheric circulation

Numerous studies show that the climate over West Africa has a lot of unique features. The annual rainfall is almost constant along each latitude, but a sharp drop is experienced from the south to the north with a gradient of 1 mm/km, from about 1500 mm near the coast at 5°N to about 100 mm along the border with the Sahara Desert at about 20°N (Eltahir and Gong, 1996). The major rainy season occurs in the boreal spring to early summer (MAMJ) for the GOGC, and during the summer (JJAS), for the Sahel zone. Several studies have shown that Western African rainfall (WAR) is driven by tropical Atlantic sea surface temperature anomalies (SSTAs) (Lamb, 1978; Lough, 1986). Interannual variability of WAR especially over the Sahel has been documented very well. (e.g., Nicholson and Palao, 1993; Nicholson et al., 1996). Apart from the role of tropical SST in influencing WAR, other factors such as ENSO and La Niña (Semazzi et al., 1988; Wolter, 1989;
Hastenrath, 1990; Moron and Ward, 1998), soil moisture, evaporation, and albedo (Yeh et al., 1984) are known to play significant role in the climate of the subregion.

Climate variability or change over West Africa has provoked a lot of interesting studies since the Sahel experienced drought in the 1970s. Observational and theoretical studies have been used to find answers to the drought issue. Nicholson (1989) has presented a lot of hypotheses and views from diverse literature on the causes of the drought. One of her hypotheses suggests that the drought conditions in West Africa are triggered by anomalous large-scale forcing and then sustained by local feedbacks that involve land surface processes. Other views center on the anomalous large-scale patterns of atmospheric circulation and/or global patterns of SST distribution (e.g., Kidson, 1977; Folland et al., 1986) One of the well-known hypotheses set forth is the classic paper of Charney (1975), who explained the drought by relating the regional circulation to the vegetation dynamics of the Sahara Desert. Charney hypothesized that alterations in surface albedo due to overgrazing may have been the cause of the drought in the early 1970s, during which the ITCZ experienced a southward displacement. It also suggested a vital role played by vegetation in the dynamics of Sahel rainfall. By this hypothesis, it was implied that the rainfall-producing circulation over this region is sensitive to changes in the state of vegetation at the border with the Sahara. The weakness of Charney’s mechanism is that it fails to recognize that vegetative cover lacks sufficient memory to transport information between successive years because the existence of vegetation by itself is tied to the seasonal of rainfall cycle (Tucker et al., 1991). Yeh et al. (1984) have also investigated the role of soil moisture, evaporation, and albedo in the
WACS, using modeling studies. Other studies have focused on the effect of soil moisture on the circulation and rainfall, using modeling studies (Walker and Rowntree, 1977).

Attempts have been made using observations of atmospheric variables such as rainfall, temperature, and humidity to suggest that West African climate can be approximated by zonally symmetrical description. The dynamical theories of thermally direct, zonally symmetrical circulations in the tropical atmosphere (Held and Hou, 1980; Lindzen and Hou, 1991; Plumb and Hou, 1992; Emmanuel et al., 1992) have been used to expound our knowledge of climate variability over West Africa. The thermal wind relation in a zonally symmetrical circulation is described by the following equation:

\[ \frac{\partial u}{\partial p} = \frac{1}{f} \frac{\partial \alpha}{\partial y} \]  

Equation 1.4

where \( u \) is the zonal wind, \( p \) is the pressure, \( f \) is the Coriolis parameter, \( \alpha \) is the specific volume, and \( y \) is the distance in the meridional direction. A moist zonally symmetric atmospheric model coupled with a simple land surface scheme was developed to investigate the role of vegetation in the dynamics of WAMs (Zheng and Eltahir, 1998).

Numerous studies have investigated the atmospheric circulation patterns in WACS on interannual time scales. Dry years have been linked to a weaker tropical easterly jet (TEJ) and a weaker low-level southwesterly monsoon flow, a stronger African easterly jet of the Northern Hemisphere (AEJ-N), increased geopotential height of the 700 hPa surface, increased vertical shear (i.e., enhanced horizontal temperature gradients), reduced southward extension of upper-level easterlies, and the virtual disappearance of the 850 hPa trough over West Africa (Kidson, 1977; Kanamitsu and Krishnamurti, 1978; Folland et al., 1986;
Fontaine et al., 1995). Also, vertical alignments of the AEJ-N and TEJ axes enhance a weak rainbelt and widespread drought (Nicholson, 2008). Though most studies converge on these points, the role of Hadley circulation (e.g., Kanamitsu and Krishnamurti 1978; Fontaine et al., 1995; Long et al., 2000) and ITCZ (e.g., Lamb, 1978a,b; Nicholson, 1981; Citeau et al., 1989) in modulating dry years, are conflicting. Also, the specific ways in which such factors as AEJ and TEJ, the ICTZ, and moisture flux influence rainfall variability are not adequately understood, even though probable link to wave activity has been suggested (Grist and Nicholson, 2001). In spite of divergent views on the factors that affect the rainfall variability, the most consistently divider between dry and wet years is related to the strength of the AEJ. The seasonal excursions of the AEJ and TEJ associated with rainfall-atmospheric circulations have been studied (e.g., Grist and Nicholson, 2001; Nicholson and Grist, 2003; Gu and Adler, 2004; Nicholson, 2008). On intraseasonal time scales, the Madden-Julian oscillation (MJO) (Matthews, 2004) and two intraseasonal timescales, 10–25 and 25–60 days (Sultan et al., 2003), have also been found to modulate rainfall and convection over West Africa.
CHAPTER TWO

2. Data and Methods

2.1 Data Sources and Description

The climate state variables used for the present study are specific humidity, geopotential height (GH), sea surface temperature (SST), rainfall, and zonal, meridional, and vertical wind velocities. These, together with most of the teleconnection indices used for the current study, were extracted from different sources.

2.1.1 NCEP-NCAR Reanalysis 1 Data

The specific humidity, GH, zonal, meridional, and vertical (omega) winds used were obtained from National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP-NCAR) reanalysis data (Kalnay et al., 1996). The data were used to show tropospheric circulation anomaly patterns associated with the two major seasons, MAMJ and JJAS over the West Africa. The NCEP/NCAR reanalysis data, which are a combination of observations and model results are generated by reanalyzing historical data using state-of-the-art data assimilation model. The credibility of the data centers on its relative consistency in the provision of atmospheric data, which are based on static data assimilation scheme, the use of many observational data (capturing broad spectrum of spatial patterns), and employment of data analysis tools that are global in extent (Drobot et al., 2006). The input data, assimilation scheme and model are described in Kalnay et al. (1996).
Also, data quality has been discussed in numerous studies (Kalnay et al., 1996; Serreze et al., 1998; Serreze and Hurst, 2000; Serreze et al., 2003).

The data are provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, and are available at [http://www.cdc.noaa.gov/cdc/reanalysis/](http://www.cdc.noaa.gov/cdc/reanalysis/). The datasets have a spatial coverage of 2.5° latitude x 2.5° longitude global grid (144x73), and ranges from 90N - 90S, 0E - 357.5E. The temporal coverage is monthly, spanning January 1948 to present. The GH(Z; m), zonal (u-wind; m/s), and meridional (v-wind; m/s) data are available at 17 pressures levels (hPa)): 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10. However, vertical velocity (Pa/s) and specific humidity (g/kg) are available at 12 (1000-100 hPa) and eight (1000-300 hPa) pressure levels, respectively.

### 2.1.2 Precipitation data

The University of Delaware (UD) global monthly total gridded terrestrial precipitation data (Version 1.01) in mm/month, spanning January 1900 to December 2006 were used (Willmott and Robeson, 1995). This data set compared very well with CRU terrestrial precipitation data when an initial EOF analysis was applied to both datasets over the West African subcontinent to study the spatio-temporal patterns associated with them to assess their compatibility. The two datasets matched very well. However, the CRU dataset was excluded from the full-scale analysis since it does not extend beyond 2002. The UD dataset measured in mm/month, has a spatial coverage of 0.5° latitude x 0.5° longitude global grid (720 x 360) ranging from 89.75N - 89.75S, 0.25E - 359.75E, and is available at [http://climate.geog.udel.edu/~climate/html_pages/download.html#P2007](http://climate.geog.udel.edu/~climate/html_pages/download.html#P2007).
2.1.3 Sea surface temperature data

Improved extended reconstructed sea surface temperature (ERSST) (Smith and Reynolds, 2004) data were used. The data are provided by the United States National Oceanic and Atmospheric Administration (NOAA)/OAR/ESRL PSD, Boulder, Colorado, USA, and are available at http://www.cdc.noaa.gov/. The ERSST dataset was constructed using the most recently available International Comprehensive Ocean-Atmosphere Data Set (ICOADS) data and improved statistical methods that allow stable reconstruction using sparse data. The temporal resolution of the data is monthly and spans January 1854 to present, whereas the spatial resolution is 2.0° latitude x 2.0° longitude global grid (89 x 180) and covers 88.0N - 88.0S, 0.0E - 358.0E. The data are measured in °C.

2.1.4 Teleconnection Indices

Teleconnection indices of interest are Nino 4, Nino 3.4, Nino 1+2, Oceanic Nino Index (ONI), Multivariate ENSO Index (MEI), Bivariate ENSO time series (BEST), Tropical North Atlantic (TNA), Tropical South Atlantic (TSA), Atlantic Meridional Mode (AMM), Tropical Atlantic Dipole Mode (TADM), Atlantic Multidecadal Oscillation (AMO), Southern Oscillation Index (SOI), Atlantic Tripole (AT) SST EOF 1, and Atlantic Meridional Mode (AMM). These were extracted from Climate Prediction Center (CPC), Frontier Research Center for Global Change (FGCGC), and NOAA websites. Apart from these, the following indices were constructed using ERSST data; Indian Ocean Spring-Summer Dipole (IOSSD) and global SST EOFs.
2.2 Methods

2.2.1 Analysis Domain and Time Scales

Even though the NCEP-NCAR reanalysis data are available from 1948 to present, the current study focuses on 1948-2006 yielding 59 years of continuous data for the two seasons (MAMJ and JJAS) of interest, since the UD precipitation has not been updated beyond 2006. Precipitation over the continent was confined to 20° W-20° E, 4° N and 20°N, which roughly circumscribes the subcontinental boundaries of West Africa. The spatial domain for the other variables utilizes global datasets, which were subset where necessary, and tailored to address specific objectives. Inclusion of global datasets hinges on improving our understanding on the role of teleconnection on the global environmental change or variability over West Africa.

2.2.2 Analysis Techniques

The approach adopted in this section is two-fold: i. the first involves analysis and 3-D general (unfiltered) characterization of climate anomaly patterns of MAMJ and JJAS seasons, and ii. isolation, analysis and characterization of decadal (LF) modes from the raw data of the two seasons.

2.2.2.1 EOF Analysis and Significance Test

EOF analysis (Wilks 2006; Hannachi et al., 2007; Johnson and Wichern, 2007) was applied to decompose the unfiltered precipitation and global SST fields to extract spatially
coherent patterns together with their time coefficients and variances. North et al.’s (1982) delta-test was applied to the observational data consisting of 708 months (59 years), to retain the eigenvalues that were statistically nondegenerate. The anomalies for all the data were also generated by subtracting the monthly climatology over the entire period from each grid point value to be used for composite and grid point correlation analyses.

A 10-year low-pass moving average filter algorithm scheme was implemented on all anomaly fields to remove the influence of interannual variability due to ENSO and the tropical western Pacific to emphasize certain informational components contained in LF (decadal) component (Giannini et al., 2005). This yielded 50 years of filtered/smoothed data (1948-1997), with a loss of 9 years information, the price paid for filtering the data. The low-pass filtered precipitation and global SST anomalies were similarly submitted to the EOF routine (Arguez et al., 2009) and the nondegenerate eigenvalues were retained. Both the unfiltered and filtered statistically separate global SST EOF PC time series were used as teleconnection indices. Where relevant, the leading PC time series of both the filtered and unfiltered were detrended using regression techniques (Shumway and Stoffer, 2006).

2.2.2.2 Construction of IOSSD Index

The Indian Ocean Dipole (IOD) mode, based on the traditional definition, which is the difference of SST anomaly (SSTA) between the Western Tropical Indian Ocean (WTIO; 50 E - 70 E, 10 S - 10 N) and Southeastern Tropical Indian Ocean (SETIO; 90E - 110 E, 10 S - Equator) (Saji et al., 1999), was applied to generate similar indices separately for MAMJ and JJAS seasons.
Mathematically, IOD = WTIO - SETIO… ………………………Equation 2.1

The SSTs over these two domains were submitted to EOF analysis routine. The first PC of the WTIO and SETIO in MAMJ season accounted for 86.49% and 88.16% of the unfiltered total variances, respectively. Their corresponding variances in JJAS were 80.07% and 81.86%, respectively. On this basis, the first PCs were used for the construction of the IOSSD for the two seasons.

2.2.2.3 Correlation Analyses

The linear relationships between the total dominant unfiltered rainfall PC time coefficients and the teleconnection indices were computed (Rowell et al., 1995; Ward, 1998; Giannini et al., 2005). The correlational findings were complemented by partial/semi-partial correlation analysis (Ward, 1998; Helsel and Hirsch, 1992; Sheskin, 2004), where necessary, to isolate the most important climatic indices from a pool of competing indices that are linked to the precipitation modes. Heterogeneous grid point correlations between global SST anomaly (SSTA) fields and the total rainfall EOF time coefficients were also computed (Semazzi et al., 1996; Ward, 1998; García-Serrano et al., 2008; Polo et al., 2008) to capture local and remote spatial teleconnectivity. Similar analyses were done for the LF components using the LF global SST and precipitation EOF indices.

2.2.2.4 Composite Analyses

To understand the tropospheric circulation anomaly patterns associated with the positive (negative) events of the filtered (unfiltered) dominant precipitation modes of the
two seasons, composite analysis was applied using the projection method (Arguez et al., 2009). The precipitation total PC time series of the unfiltered (filtered) were decomposed into positive and negative components at thresholds greater and less than ±1.0 standard deviation from the mean for the positive and negative phases, respectively. This was done to increase the sensitivity of the analysis. The enhanced EOF time coefficients were composited with the SST, horizontal/vertical winds and GH anomaly fields, projected on the monsoon layer (at surface and 850 hPa) and the middle layer (at 500 hPa) pressure levels. The composite analyses were limited to the domain bordered by 50°W-90°E, and 40°S-40°N, which captures the entire African continent and tropical Atlantic and Indian Oceans. However, the composites with vertical velocity (omega) were limited to the West African region.

2.2.2.5 Velocity potential and streamfunction anomaly analysis

From the horizontal winds and precipitation composites, the velocity potential and streamfunction and their associated anomaly wind fields namely, divergent (irrotational) and non-divergent (rotational) (Mancuso, 1967; Krishnamurti, 1971) were computed using the following equation:

\[ V = \nabla \psi + \nabla \phi = \hat{k} \times \nabla \psi + \nabla \phi \]

...............Equation 2.2

where, \( \hat{k}, \psi, \phi, \nabla \), and \( \nabla \) represent the vertical unit direction vector, streamfunction, velocity potential, curl and del (divergence) operators, respectively. The computation was similarly confined to 50°W-90°E and 40°S-40°N for the two seasons, at the three levels, for the filtered and unfiltered events.
2.2.2.6 Moisture budget anomaly analysis

2.2.2.6.1 Atmospheric vapor budget anomaly analysis

The atmospheric vapor budget (AVB) equation (Peixoto and Oort, 1992) can be written as:

\[ \frac{\partial W}{\partial t} = -D(\vec{Q}) + E - P \]  

Equation 2.3

where,

\[ \frac{\partial W}{\partial t} = \text{time rate of change of total precipitable water in column } W \]

\[ D(\vec{Q}) = \nabla \cdot (\vec{Q}) \], flux divergence

\[ E = \text{evaporation,} \]
\[ P = \text{precipitation} \]

The vertically integrated horizontal water vapor flux is also given by:

\[ \vec{Q} = \int_{p_t}^{p_s} \frac{1}{g} \nabla q dp \]  

Equation 2.4,

where,

\[ \vec{Q} = \text{horizontal water vapor flux (vector) obtained from zonal and meridional fluxes} \]
\[ p_s = \text{surface pressure (Nm}^{-2}\text{)} \]
\[ p_t = \text{pressure at the top layers (Nm}^{-2}\text{)} \]
\[ g = \text{gravitational acceleration (ms}^{-2}\text{)} \]
\( \vec{V} = \) horizontal velocity vector (ms\(^{-1}\))

\( q = \) mass mixing ratio of water vapor/specific humidity (gKg\(^{-1}\))

\( dp = \) pressure difference between the surface and top layer (Nm\(^{-2}\))

The equations for zonal and meridional fluxes and their transient eddies are given in Peixoto and Oort (1992) and Long et al. (2000). Over long term, \( \frac{\partial W}{\partial t} \) is negligible, and therefore, Equation 2.3 becomes:

\[
D(\bar{Q}) = E - P \quad \text{or} \quad D(\bar{Q}) = P - E \quad \ldots \ldots \ldots \ldots \quad \text{Equation 2.5,}
\]

which is a direct estimate of the (P, E) budget.

To compute the vertically integrated moisture budget anomalies on the basis of the positive (negative) precipitation events, specific humidity and horizontal wind anomalies from the 1000-500 hPa, which constitute six isobaric surfaces, were first composited with the enhanced positive (negative) precipitation time coefficients. Equation 2.5 was then applied for the computation of the moisture budget anomalies over three distinct spatial domains indicated as follows:

i. West Africa: 20° W-25°E, 4°N-20°N

ii. Sahel: 20° W-25°E, 10°N-20°N

iii. GOG (including Soudan): 13°W-25°E, 4°N-10°N
2.2.2.6.2 Regression model for the analysis of net precipitation and moisture budget anomalies

The precipitation and vertically integrated moisture budget anomalies over the three domains were summed up separately for each of these anomalies over all the grid boxes for the positive (negative) events to generate net/cumulative totals representative of each of the dominant modes over the three domains. A simple regression model was then formulated to analyze net precipitation anomalies as a function of net vertically integrated moisture budget (NVIMB) anomalies over each domain for the two seasons. The model was also used to test the sensitivity of their divergent fields.
CHAPTER THREE

3.0 Results and Discussion: Generalized (unfiltered) Structures

This chapter presents a detailed description of the 3-D characterization of the general (unfiltered) MAMJ and JJAS climate anomaly patterns over West Africa. It will focus specifically on results and discussion of EOF analysis of West African precipitation and global SSTs, and correlation, composite, velocity potential, streamfunction, and moisture budget analyses and their climatic teleconnectivity over the monsoon and middle layer.

3.1 EOF Analysis and West African precipitation-global SST covariability

EOF analysis was performed on the unfiltered precipitation and SST fields to put emphasis on spatially coherent patterns of variability and their associated temporal properties (coefficient time series) as well as their eigenvalues (variances) attributed to the eigenvectors. Linear/partial (semi-partial) and grid point correlations were computed to isolate important climatic modes that link to West African precipitation.

3.1.1 MAMJ and JJAS West African precipitation variability

Figure 1 presents the scree plots and the percent variances associated with the MAMJ and JJAS precipitation PCs. In both seasons, the first four PCs were statistically separate according to North et al.’s (1982) delta-test. The percent unfiltered total variance explained
by the leading four PCs of MAMJ and JJAS seasons are 45.22% and 54.70%, respectively, and the contributions of the individual PCs are shown in Table 1. Four departure patterns are characteristic of each of the two seasons. Isolation of distinct spatial patterns over West Africa has been found to differ from a number of authors. This is partly due to differences in analysis techniques applied, the use of seasonal or annual data, definitions of rainy seasons, data sources, domain of interest, etc (Rowell et al., 1995). Different rainfall departure patterns over the continent of Africa using different techniques have well been documented (e.g., Nicholson, 1980; Nicholson, 1986; Janowiak, 1988). It is therefore not unusual to discover four anomaly patterns in association with boreal spring-summer rainfall in the tropical West Africa in the current study.

The spatial characters of the precipitation anomalies of the two seasons and their corresponding time coefficients associated with the four most dominant PCs are presented in Figs. 2 and 3. The MAMJ precipitation EOF 1 mode explained 26.41% of the unfiltered total variance. A visual inspection of the EOF 1 eigenvectors depicts more or less ubiquitous positive weights over the region, which are reminiscent of a monopole or non-dipole structure (Fig. 2a), and appear to be dominated by Sahel. A monopole spatial structure similar to the MAMJ precipitation EOF1 spatial mode was found over tropical North Africa by Nicholson and Grist (2001) and Nicholson (2007) during boreal rainy season. The time coefficients of the MAMJ precipitation EOF 1 (Fig. 2e) are dominated by interannual-like oscillations. Further, it is argued here that even though it does not typically rain over the Sahel in March-May (MAM), the transitional month, June, which commences and ends the major rainy season of the Sahel and GOGC, respectively, is fully captured by the EOF
Figure 1. Percent variance associated with the unfiltered eigenvalues of boreal spring-summer West African precipitation.

Table 1. The first four dominant unfiltered MAMJ/JJAS West African rainfall PCs

<table>
<thead>
<tr>
<th>Seasons</th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAMJ</td>
<td>26.1</td>
<td>8.31</td>
<td>5.82</td>
<td>4.68</td>
<td>45.22</td>
</tr>
<tr>
<td>JJAS</td>
<td>36.0</td>
<td>9.56</td>
<td>5.45</td>
<td>3.65</td>
<td>54.7</td>
</tr>
</tbody>
</table>

analysis. The June precipitation, a striking over feature over the Sahel during the GOGC MAMJ season, is a manifestation of intraseasonal latitudinal monsoon shift (monsoon jump) from 5°N to 10°N (Hagos and Cook, 2007), signifying the onset of the Sahelian rainy season. The MAMJ precipitation EOF 2 (Fig. 2b) is characterized by positive departure patterns weighted heavily over the GOGC, which show anti-phase variations with the Sahelian anomalies. Its time coefficients portray decadal variability (Fig. 2f). This mode is the well-known GOGC rainfall reported in previous studies (e.g., Vizy and Cook, 2001; Gu, 2004; Hagos and Cook, 2007). Another striking feature is that a visual integration of EOF 1 with EOF 2 loadings is also, a manifestation of intraseasonal rainfall variability.
Figure 2. Unfiltered spatial patterns and their corresponding time coefficients of MAMJ rainfall during boreal spring-summer West African season.
Figure 3. As in Fig. 2, except for JJAS season.
in response to evolution of SSTA patterns.

The MAMJ EOF 3 spatial mode is characterized by three departure patterns: the centers of actions are located over central part of West Africa, in which negative anomalies are flanked by positive anomalies centered over Western Sahel and eastern part of West Africa (Fig. 2c). The time coefficients (Fig. 2g) associated by this mode demonstrate interannual variability. The MAMJ EOF 4 spatial mode (Fig. 2d) also displays the three basic anomaly patterns just like the EOF 3 (Fig. 2c), with more positively weighted anomalies centered over the Western Sahel and a dipolar structure over eastern part of West Africa. On the basis of the spatial coverage, the Western Sahel anomaly patterns (Figs. 2c and d) are herein classified as Western Sahel Anomaly Type1 (smaller) and Anomaly Type 2 (bigger), respectively. The time coefficients of the EOF 4 mode are also characterized by interannual variability. The time coefficients of the four MAMJ precipitation modes correlated poorly with the Senegal rainfall index constructed by Fall et al. (2006). It was also noticed that the anomaly patterns of boreal spring, March-April-May (MAM) were distinct from the MAMJ season, suggesting that the transitional month (June) plays a critical role in GOGC major precipitation season.

In contrast, the JJAS precipitation EOF 1 spatial pattern (Fig. 3a) is the well-known Sahel mode/continental mode (SM/CM; Ward, 1998; Giannini et al., 2005; Polo et al., 2008), depicting dipole-like structure, in which positively weighted loadings centered over the Sahel and negative loadings or precipitation deficits over the GOGC zone. The temporal character of the SM depicts decadal/interdecadal oscillations (Fig.3e). In relating the spatio-temporal characteristics of the SM in the current study to previous studies done for JJAS (Joly et al.,
over tropical West Africa, there is an indication of strong harmony between the JJAS and JAS seasons. To substantiate this for the UD precipitation data, EOF analysis was performed for JAS season too. The results reveal a perfect harmony between JJAS and JAS precipitation structures. All these analyses highlight the well-known Sahel decadal/interdecadal precipitation trends, which portray above-normal precipitation in the 1950s to late 1960s, followed by below-normal precipitation in the early 1970s, reaching its epoch in mid-1980s, culminating in the persistent and precarious drought (Folland et al., 1991; Lamb and Peppler, 1992; Nicholson and Palao, 1993; Giannini et al., 2005), which has seen some sign of recovery recently. The JJAS EOF 2 spatial mode (Fig. 3b) depicts the spatial structure characteristic of the GOGCM during the JAS season when this humid zone receives relatively low precipitation (Giannini et al., 2005). Its temporal structures show interannual oscillations. In contrast to the MAMJ EOF 3 and 4 loadings (Figs. 2c, d), the JJAS EOF 3 and 4 modes identified four main anomaly patterns (Figs. 3c, d). Their corresponding temporal structures are dominated by interannual variability (Figs. 3g, h). The anomaly patterns of EOF 3 show an approximately quasi-axisymmetric configuration about Soudanian climatic zone (Fig. 3c). The eastern and western parts of Sahel and GOGC, respectively, both positively weighted, show out-of-phase connection with Western Sahel and eastern GOGC, which are negatively weighted. Geometrically, the western and eastern parts of Sahel, which are out-of-phase, are closely, the rotated images of the out-of-phase western and eastern GOGC anomalies. In Fig. 3d, the negatively weighted Western Sahel of the EOF 4 mode is out-of-phase with respect to the positively weighted eastern part of West Africa. On the basis
of the Western Sahel anomalies (Fig. 3c, d), they are also herein distinguished as Anomaly Type 3 and Anomaly 4, respectively, even though they are very similar in spatial coverage. Types 3 and 4 are in opposition to Types 1 and 2 of MAMJ anomaly patterns described earlier on. Linear/partial correlation analysis pinpoints a strong connectivity between Fall et al.’s (2006) Senegal rainfall index and the first two leading JJAS UD West African precipitation EOF modes. Even though Fall et al. (2006) have documented that the Senegal rainfall index is rather connected to CMAP West Africa EOF 2, relegating the traditional and leading West African EOF 1 policy index, their assertion is further investigated in our elaborate 3-D anomalous circulation features depicted in section 3.2.

### 3.1.2 MAMJ and JJAS global SST variability

The percent variances explained by the PCs of the MAMJ and JJAS global SSTs are shown in Fig. 4. On the basis of North et al.’s (1982) delta-test, seven and four PCs for MAMJ and JJAS, respectively, were statistically separate. These accounted for

![Figure 4](attachment:figure4.png)

*Figure 4. As in Fig. 1, except for global SSTs.*
Table 2. As in Table 1, except for global SST PCs.

<table>
<thead>
<tr>
<th>Seasons</th>
<th>PC1</th>
<th>PC 2</th>
<th>PC 3</th>
<th>PC4</th>
<th>PC5</th>
<th>PC6</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAMJ</td>
<td>20.73</td>
<td>11.02</td>
<td>7.79</td>
<td>6.25</td>
<td>5.10</td>
<td>3.85</td>
<td>54.74</td>
</tr>
<tr>
<td>JJAS</td>
<td>17.08</td>
<td>10.85</td>
<td>7.33</td>
<td>4.42</td>
<td>-</td>
<td>-</td>
<td>39.68</td>
</tr>
</tbody>
</table>

54.74% and 39.68%, respectively, of the unfiltered total variances. The contributions of the individual PCs are displayed in Table 2. To match the precipitation modes in order to facilitate comparison of the two seasons, the seven degenerate MAMJ global SST PCs were deliberately truncated to retain the first four, which explained 45.79% of the unfiltered total variance.

The eigenvectors (EOFs) and their time coefficients associated with the two seasons are presented in Figs. 5 and 6. The EOF 1 eigenvectors of MAMJ and JJAS, which explained 20.73% and 17.08% of their respective unfiltered total variances, are characterized by high positive weights over the global oceans, with the former season more pronounced than the latter (Figs. 5a and 6a). Their time coefficients, which show upward linear trends, are indicative of global warming signature (Ward, 1998; Folland et al., 1991). The eigenvectors of MAMJ global SST EOF 2, which accounted for 11.02 % of the unfiltered total variance, depict the well-known ENSO mode (Fig. 5b,f) with its characteristic interannual oscillations (Folland et al., 1991; Ward, 1998). The global SST eigenvectors of JJAS EOF 2 explained 10.85% of the unfiltered total variance and their spatio-temporal structures (Figs. 6b,f) are similar to the MAMJ EOF 2 features.
Figure 5. As in Fig. 2, except for MAMJ global SSTs.
Figure 6. As in Fig. 2, except for JJAS global SSTs.
The MAMJ and JJAS global SST EOF 3 eigenvectors (Figs. 5c and 6c) explained 7.79% and 7.33%, respectively, of their unfiltered total variances, and their time coefficients are dominated by interannual/decadal-like oscillations. In the case of global SST EOF 4, the unfiltered percent variances attributed to the eigenvectors of the MAMJ and JJAS seasons are 6.25% and 4.42%, respectively. The maximum centers of action of their anomaly patterns are depicted by high positive weights located over the tropical Atlantic and North Atlantic Oceans, eastern and western Pacific Oceans, which are in opposition to the negative weights over the south Pacific (Figs. 5d and 6d). Their time coefficients display decadal-like oscillations. Both the eigenvectors of these two modes of the two seasons show coherent patterns, which are reminiscent of the interhemispheric SST asymmetry found in previous studies (e.g., Lough, 1986; Folland et al., 1991; Ward, 1998).

3.1.3 MAMJ/JJAS West Africa rainfall and MAMJ/JJAS global SST relationships

The associations between local/remote oceanic anomalies and tropical African rainfall variability on different time scales have been investigated by different authors (e.g., Lamb 1978a,b; Lough, 1986; Folland et al., 1986; Semazzi et al., 1996; Polo et al., 2008). Here, the results from simultaneous linear and partial/semi-partial correlations, heterogeneous grid point correlations, and inputs from the EOF analyses are used to understand the co-variability of time-evolving leading NH spring-summer global SST-WAM precipitation anomalies.

Tables 3 and 4 show the linear correlations between total precipitation time coefficients and 19 climatic indices during the two seasons. In Table 3 it is observed that MAMJ West African precipitation EOF 1 time coefficients are related to two candidates; one local and one
Table 3. Correlation between unfiltered West African MAMJ precipitation total time coefficients and climate indices. Bold-faced figures indicate statistical significance at 95% confidence level. Numbers in parenthesis are correlations with detrended SST EOF 1 time coefficients.

<table>
<thead>
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large-scale, which are TADM (r=+0.31) and global SST EOF 3 (r=−0.33) index, respectively. A partial correlation analysis between the global SST EOF 3 and MAMJ precipitation EOF 1 time coefficients, removing the influence of TADM, and also between MAMJ precipitation EOF 1 time coefficients and TADM, removing the influence of global SST EOF 3, show that the associations of the two oceanic indices with the precipitation mode 1 are not statistically different from one another. The role of TADM, a dominant climatic signal characterized by contrasting SSTAs between the tropical North and South
Table 4. As in Table 3, except for JJAS.

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Atlantic Oceans, in modulating West African precipitation has been documented (Lamb, 1978; Folland et al., 1986; Xie et al., 2005). The positive (negative) events of the TADM are usually accompanied by precipitation enhancement (suppression) over West Africa (Lamb, 1978; Folland et al., 1986). The warm phase of the TADM is inversely related to local sea-level pressure and vertical wind shear (Gray, 1984; Knaff, 1997), which are also related to above normal precipitation. The cooling (warming) global SST EOF 3 events are associated with above (below) normal precipitation over West Africa. The simultaneous heterogeneous grid point correlation between unfiltered MAMJ global SSTAs and the EOF 1
total precipitation time coefficients (Fig. 7a) shows that the precipitation mode 1 is associated to a large extent with cold (warm) SSTAs of the Equatorial mode (EM)/ Atlantic Nino and southwestern Atlantic mode, and warm (cold) SSTAs of the North Atlantic Ocean. The primary and secondary candidates connected to the MAMJ precipitation EOF 2 mode are the global SST EOF 1 index (r=-0.51) and IOSSD (r=-0.55)(Table 3), respectively, which suggest that their cooling (warming) events coincide with above (below) average precipitation over West Africa. The grid point correlation (Fig. 7b) captures the basin-wide SSTA patterns in this regard. In the case of MAMJ precipitation EOF 3, it seen from Table 3 to be connected to global SST EOF 2 (r=-0.28), which reflects an ENSO mode (Fig. 5b). The cooling (warming) ENSO events, which are closely related to reduced (increased) vertical wind shear, coincide with precipitation surplus (deficit) over the region. On the other hand, the grid point correlation links the precipitation mode to the warming (cooling) events of TNA mode (Fig. 7c). Even though the MAMJ precipitation EOF 4 time coefficients do not appear to be connected to any of the indices (Table 3), the grid point correlation captures the EM/southeastern Atlantic and northwestern Pacific modes, where cooling (warming) events lead to above (below) normal precipitation. As a whole, the detrended global SST EOF 1 time coefficients exhibited poor association with MAMJ West African precipitation EOF modes (Table 3).

On the contrary, the modes associated with the unfiltered JJAS West African precipitation appear to be connected to several candidates (Table 4). Partial/semi-partial correlational findings reveal three important candidates, namely, MEI, IOSSD, and global
a. Correlation between unfiltered WA Mar-Jun precip. EOF 1 time series and unfiltered Mar-Jun global SST anomalies

b. Correlation between unfiltered WA Mar-Jun precip. EOF 2 time series and unfiltered Mar-Jun global SST anomalies
c. Correlation between unfiltered WA Mar-Jun precip. EOF 3 time series and unfiltered Mar-Jun global SST anomalies
d. Correlation between unfiltered WA Mar-Jun precip. EOF 4 time series and unfiltered Mar-Jun global SST anomalies

Figure 7. Simultaneous heterogeneous grid point correlation between unfiltered MAMJ global SSTAs and West African precipitation total time coefficients. Significant areas at 95% conf. level using t-test are shaded.
a. Correlation between unfiltered WA Jun-Sep precip. EOF 1 time series and unfiltered Jun-Sep global SST anomalies

b. Correlation between unfiltered WA Jun-Sep precip. EOF 2 time series and unfiltered Jun-Sep global SST anomalies

c. Correlation between unfiltered WA Jun-Sep precip. EOF 3 time series and unfiltered Jun-Sep global SST anomalies

d. Correlation between unfiltered WA Jun-Sep precip. EOF 4 time series and global SST anomalies

Figure 8. As in Fig. 7, except for JJAS.
SST EOF 3 index, which are associated with the SM/CM. These three climatic indices, well represented in the grid point correlation (Fig. 8a), suggest that cooling (warming) of the tropical western Pacific, tropical Atlantic (eastern, southwestern and southeastern), and Indian Ocean leads to above (below) normal precipitation over the Sahel (Ward, 1998; Semazzi et al. 1988; Giannini et al., 2005; Polo et al., 2008, García-Serrano et al., 2008). On the contrary, as seen in Fig. 8a, warming (cooling) of the Mediterranean Sea enhances (suppresses) precipitation over Sahel, which corroborates the findings of previous studies (Folland et al., 1996; Ward, 1998; Polo et al., 2008, García-Serrano et al., 2008). These authors pinpoint the role of moisture advection from the warm Mediterranean Sea SSTAs into the Sahelian zone in enhancing pluviogenesis. The JJAS precipitation spatial mode 2 (GOGCM), which is reminiscent of the JAS GOGCM of Ward (1998) and Giannini et al. (2005), anticorrelated with TADM (r= -0.37 ) (Table 4). This negative correlation coefficient signifies the importance and presence of the equatorial cold tongue complex (CTC) during JJAS Sahelian rainy season that is associated with precipitation minimum over the humid GOGC (Vizy and Cook, 2001, Gu and Alder, 2004; Giannini et al., 2005). This TADM mode is fully captured in the grid point correlation (Fig. 8b). Also, remote links in Fig. 8b suggest that cooling (warming) in the Indian, tropical western Pacific and southwestern Atlantic Oceans suppresses (enhances) JJAS GOGC precipitation during the Sahelian rainy season of the boreal summer. However, the JJAS precipitation EOF 3 time coefficients demonstrate a positive association with global SST EOF 1 (r= 0.49) (Table 4), wherein warm (cold) SST events coincide with precipitation enhancement (suppression) over
the region, which is reflected in the grid point correlation (Fig. 8c). Finally, the JJAS precipitation EOF 4 is seen to be connected to global SST EOF 3 index \((r = 0.33)\), whose spatial structure is characterized by interhemispheric asymmetry in SST pattern of opposite signs, which is well represented in Fig. 8d. Here, positive (negative) phase is associated with enhanced (suppressed) precipitation over the eastern part of West Africa and the opposite effect over Western Sahel (Fig. 3d). As in the case of the MAMJ season, weak correlations were observed between the detrended global SST time coefficients and the precipitation modes (Table 4).

3.2 Boreal Spring-Summer Tropospheric Circulation over West Africa

This section focuses on the generalized (unfiltered) 3-D anomalous circulation patterns associated with the monsoon and middle layers during boreal spring-summer WAM represented by three isobaric surfaces, namely, the surface (1000 hPa), 850 hPa, and 500 hPa, where atmospheric moisture is relatively abundant as compared with other higher levels. In order to understand the physical relationships between WAM and SSTA patterns, composite analysis was applied to provide an insight for a description of the circulation regimes on the basis of the positive (negative) events associated with the precipitation modes. The description of the tropospheric circulation will be confined to the domain circumscribed by 50°W-90°E (lon), 40°S-40°N (lat), which captures the whole of African continent, the Indian Ocean and most parts of the tropical Atlantic.
3.2.1 Unfiltered surface circulation mechanism

The climate anomaly patterns of the two seasons computed are presented in Figs. 9 and 10. For the sake of convenience, all the positive (negative) events associated with the WAM circulation of the MAMJ and JJAS seasons, will hereafter be donated by the suffices pos# and neg#, where “#” denotes the precipitation time coefficients e.g.,1, 2, 3, etc.

The key anomalous circulation features associated with MAMJ pos1 (Fig. 9a) may be described as the involvement of moisture supply created by contrasting SSTA patterns in the tropical Atlantic Ocean and the Mediterranean Sea, large-scale low-level cross-equatorial moisture flux convergence, and low-level cyclonic flows. Specifically, the mechanism leading to the ubiquitous positive rainfall anomalies over West Africa entails the interactions between anomalously strong surface winds driven by southwesterly basic-state flows, TNA meridional SST gradient, TADM, moderately warm Mediterranean Sea SSTAAs, a moderately developed CTC in the tropical eastern Atlantic, whose evolution (formation, development and damping) is ascribed to the Angola/Benguela upwelling region located in the southeastern Atlantic Ocean (Folland et al., 1996; Ward, 1998; Polo et al. 2008) and low-level cyclonic flow over West Africa, generated by diabatic heating, culminating in enhanced convection over West African region (Vizy and Cook, 2001; Gu and Alder, 2004; Xie et al., 2005; Polo et al., 2008). The key circulation features of the JJAS pos1 events (Fig. 10a) are similar to the MAMJ pos1 counterparts. However, the former differs from the latter in displaying an advanced form of CTC in the tropical equatorial Atlantic/southeastern Atlantic accompanied by high pressure that transports moisture deep into the Sahel, supplemented by
moisture advection from warmer Mediterranean SSTAs, a weakening of the meridional tropical North Atlantic (TNA) SST gradient, and more intense surface winds, which consist of southerwesterlies and westerlies, depriving the humid GOGC of substantial precipitation (Giannini et al., 2005). The wetness of the Sahel during the JJAS season is also found to coincide with colder Indian Ocean SSTAs, which corroborates the grid point correlation analysis (Fig. 8a), and previous studies (Folland et al., 1996; Semazzi and Sud, 1996; Ward, 1998; Polo et al. 2008). The MAMJ neg1 and JJAS neg1 (Figs. 9e and 10e) events are the antitheses of their respective positive events. The precipitation deficits in both cases are characterized by obliteration of the CTC, negative moisture advection and momentum transport from land into the Atlantic Ocean, warmer Indian Ocean SSTAs, reversal of surface winds and anticyclonic flows.

The salient anomalous circulation features of the MAMJ pos2 events (Fig. 9b) are depicted by an absence or a weak form of CTC in the Gulf of Guinea (GOG) accompanied by high evaporation, and strong low-level southwesterlies from the Atlantic accompanied by horizontal moisture advection over the GOGC, culminating in its anomalous wetness. The above-normal GOGC precipitation is also found to have coincided with low-level cyclonic perturbations generated from anomalous West African heat lows, a well-developed CTC in the southern Atlantic and Indian Oceans. On the other hand, the JJAS pos2 events, which are typically the GOGM during the Sahelian rainy season (Giannini et al., 2005), is characterized by a warm phase of the CTC, accompanied by less moisture derived from evaporation from eastern Atlantic, which is subsequently advected into the humid coast. This explains why low precipitation is observed over the GOGC during the boreal summer.
Figure 9. Unfiltered tropospheric anomaly composites associated with positive (negative) events of MAMJ WAM at the surface level. Positive (negative) numbers denote positive (negative) phases of the decomposed precipitation time coefficients.
Figure 10. As in Fig. 9, except for JJAS at the surface level.
It was also noticed that the precipitation anomalies of the JJAS pos2 events were also associated with a well-developed CTC in southwestern Atlantic and Indian Oceans. Figure 9f shows that the MAMJ neg2 events are associated with complete obliteration of the CTC and general warming of the Atlantic and Indian Oceans. Other features include negative moisture advection, typically, soil moisture, from land to ocean. The partially wet Sahel could be due to moisture advection from the Mediterranean Sea as has been reported by others (Folland et al., 1996; Ward, 1998; Polo et al. 2008). In contrast, the JJAS neg2 events (Fig. 10f) are characterized by a well-developed CTC in the tropical eastern Atlantic, suppressing the development of rain bands over the GOGC. The CTC is also accompanied by southeasterlies, which divert moisture from the GOG into the TNA Ocean. The decay of the TNA meridional SST gradient is associated with northward moisture advection away from the Sahel by strong recurring subtropical westerlies. The development of a weak Indian Ocean dipole-like and warm monopole-like Mediterranean Sea SST patterns may be associated with complete dryness over the Sahel.

During the MAMJ pos3 events (Fig. 9c), the key climate anomaly patterns depict a virtual decay of the TNA meridional SST gradient leading to warm SSTA_s, a decay of the CTC, and negative moisture advection from land into the Atlantic Ocean. The precipitation anomaly patterns coincide with two subtropical cyclonic flows in the southwestern Atlantic and South Indian Oceans. On the other hand, Fig. 10c shows that the JJAS pos3 events are characterized by complete obliteration of CTC, accompanied by moisture convergence over the tropical eastern Atlantic. A warm TNA SSTA pattern is associated with the deprivation
of precipitation over Western Sahel. Also, the precipitation patterns over the region coincide with cyclonic flows in the South Atlantic and southern Indian Ocean, and warm Mediterranean Sea SST patterns.

As shown in Fig. 9g, the MAMJ neg3 events are closely associated with general warming of the Indian Ocean, cold Mediterranean SSTAs, obliteration of the CTC, accompanied by low-level equatorial easterlies propagating into the Atlantic, and reversal of the TNA meridional SST gradient as compared to MAMJ pos1 and pos3 cases. During the JJAS neg3 events (Fig. 10g), the salient features observed are cold SSTAs in the Atlantic and Indian Oceans, a well-developed CTC in the tropical equatorial eastern Atlantic and southwestern Atlantic, accompanied by moisture divergence centered over the eastern Atlantic. It appears that the weak pressure system associated with the basic-state flow of the CTC resulted in the generation of weak moist cross-equatorial monsoon flow preventing deep moisture transport into the continental interior, leading to sparse distribution of rainfall over the Sahel. It is observed that weak horizontal moisture advection renders the GOGC also relatively dry.

It is observed from Fig. 9d that the circulation anomalies of the MAMJ pos4 events feature equatorial and South Atlantic CTCs and dipolar Mediterranean Sea, tropical eastern Atlantic and Indian Ocean SST patterns. It also appears that the equatorial CTC initiates a low-level circulation that shunts moisture into the TNA Ocean, and further southwards. The equatorial shunting system may have been potentiated by a similar system in the South Atlantic, which coincides with asymmetric precipitation anomalies over the Sahel, leaving the GOGC virtually dry. The rainfall deficit over the GOGC is aggravated by moisture
advection from land into eastern equatorial Atlantic, which enters the equatorial shunting system, sustaining a secondary circulation, which may be described as vicious cycle of GOGC precipitation deficit. In the case of the JJAS pos4 events (Fig. 10d), the anomalous circulation coincides with warm Indian Ocean SST, TNA SST gradient and cold Mediterranean SST patterns. Other features include weak CTC and moisture convergence over TNA Ocean. The MAMJ neg4 events (Fig. 9h) reveal damping of the CTC and a deepening of the TNA meridional SSTA gradient. The associated atmospheric features are low-level North Africa cyclonic perturbations, which may be associated with subtropical Saharan lows. On the contrary, the JJAS neg4 events (Fig. 10h) highlight general warm SSTA patterns, and regional-scale low-level anticyclonic flows, which are associated with the observed precipitation anomaly patterns.

3.2.2 Unfiltered atmospheric circulation anomalies at 850 hPa

At 850 hPa, the atmospheric circulation patterns associated with positive (negative) events of unfiltered MAMJ and unfiltered JJAS are similar to their respective surface counterparts. This may be due to the fact that both levels, which are part of the monsoon layer, are associated with similar land-ocean-atmosphere interactions.

3.2.3 Unfiltered Atmospheric circulation anomalies at 500 hPa

At 500 hPa, the generalized MAMJ and JJAS events are characterized by intense and well-organized midtrosospherhic winds and tropical/subtropical cyclones, which have different locations. This level is also acknowledged as the level of maximum vertical ascent
(Gu and Adlder, 2004) and also close to the location of the 600 hPa African Easterly Jet-N (AEJ-N) over West Africa (Nicholson and Grist, 2003; Chen, 2003, 2005).

The MAMJ and JJAS events are presented in Figs. 11 and 12. Generally, the events are characterized by strong east-west (west-east) mid-level subtropical/tropical and equatorial winds. An examination of these events show that the two seasons differ essentially with respect to the direction and intensity of wind propagation, and the size, spatial patterns and centers of actions of their rotational winds. Here, the MAMJ pos1 and JJAS pos1 events and their corresponding negative events are used for illustration. The MAMJ pos1 events (Fig. 11a) depict eastward propagating midtropicospheric subtropical northwesterlies and southwesterlies over the Sahara Desert, and southwestern parts of Africa and Indian Ocean, respectively. The West African region is dominated by strong equatorial westerlies. The westerlies and easterlies may be associated with Kelvin and Rossby wave perturbations, respectively. Other important features include subtropical/ tropical cyclonic and anticyclonic systems, which are associated with above-normal precipitation over the West African region. One of such cyclonic flows is centered over West Africa subcontinent, and also a subtropical North Atlantic high. The JJAS pos1 events (Fig. 12a) depict strong westward (eastward) propagating winds. Rossby wave-like perturbations, which are associated with westward propagating winds, have been suggested as the cause of Saharan desertification (Rodwell and Hoskins, 1996). The pluvial Sahelian zone appears to be connected to the large-scale cyclonic circulation over West Africa. During the MAMJ neg1 events (Fig. 11e), drought over West Africa, is connected to intense cyclonic and anticyclonic flows located over tropical northern Africa and Saudi Arabia, respectively. The role of the Saudi Arabian high in
Figure 11. As in Fig. 9, except for MAMJ 500 hPa.
Figure 12. As in Fig. 9, except for JJAS 500 hPa.
modulating African and Asian monsoon systems has been reported by (Chen, 2003, 2005). The dryness observed in the JJAS neg1 events (Fig. 12e) coincides with the subtropical North Atlantic cyclone and west-east (east-west) equatorial, tropical and subtropical winds. The other MAMJ and JJAS events are resolved and highlighted in the divergent and rotational wind composites in the next section.

3.2.4 Unfiltered vertical velocity, velocity potential and divergent anomalies

Vertical motion (omega) is integral part of atmospheric divergence (outflow) and convergence (inflow) fields (Wang, 20042; Chen, 2005). It has been suggested that in an effort to better understand vertical motion and divergent circulation, these two fields need to be treated simultaneously (Hastenrath, 2001). In this section, anomalous divergent circulation at the surface and 500 hPa will be related to the 500 hPa vertical motion field for the two seasons, the 500 hPa level being representative of the midtroposphere.

The positive and negative events associated with the anomalous divergent circulations and vertical motions for the two seasons are shown in Figs. 13-18. Divergent circulation is based on the principle that low (high) velocity potentials are associated with divergence (convergence) (Gu and Adler, 2004). Figure 13a indicates that the middle (surface) level divergence (convergence) of the MAMJ pos1 is located roughly over Libya between latitude 20°-30°N of northern Africa (Figs. 13a, 15a). The associated vertical motions of the MAMJ pos1 events reveal relatively weak anomalous ascent and descent, located over the Sahel and the GOGC, respectively (Fig. 17a), and do not appear to show any coincidence with the
divergent circulation centers of actions, neither do they coincide with the MAMJ precipitation EOF 1 spatial field. However, the MAMJ pos1 midtropospheric divergent center and its corresponding surface level convergence are indicative of the existence of subtropical Saharan highs and thermal (heat) lows, which are connected to boreal summer tropical WAM (Chen, 2003, 2005). In contrast, the anomalous middle (surface) level divergence (convergence) of the JJAS pos1 events is centered over the Sahel (Figs. 14a, 16a), whose anomalous ascent (descent) (Fig. 18a) is centered over the Sahel (GOGC), and thus, shows consistency with the JJAS divergent circulation field and the JJAS SM/CM. During the MAMJ neg1 events, the middle (surface) level convergence (divergence) is centered over Chad-Sudan region (Figs. 13e, 15e), a shift from the Libya center of the MAMJ pos1. However, the vertical motion field (Fig. 17e), which is dominated by anomalous subsidence, coincides with precipitation deficit observed in Fig. 9e. An examination of the JJAS neg1 events indicate that the anomalous surface level divergent field is overlain by middle level convergence centered over the Sahel (Figs. 14e and 16e). These fields are associated with strong anomalous subsidence and weak ascent over the Sahel and GOG, respectively, which are also in coherence with JJAS neg1 precipitation field described earlier on.

The anomalous divergent circulation associated with MAMJ pos2 events indicate that the middle level divergence is centered over West Africa (Fig. 13b) and the surface level convergence is centered over Sahel (Fig. 15b), which shows coincidence with the maximum ascent (Fig. 17b). These fields however, fail to synchronize fully with the MAMJ precipitation mode 2 field (GOGCM). The anomalous divergent circulation and vertical motion of JJAS pos2 events (Figs. 14b and 18b), which are quite similar to the JJAS pos1
events also fail to coincide well with the GOGCM pattern during the Sahelian rainy season. Similarly, the anomalous divergent circulations of the MAMJ neg2 events, together with the anomalous vertical motion are also spatially incoherent with the MAMJ precipitation neg2 field (Fig. 9f), where literally, the region is characterized by anomalous subsidence. An interesting observation lies with the centers of action of the JJAS neg2 anomalous divergent circulation (Figs. 14f and 16f), the negative phase of the GOGCM of the Sahel rainy season. The middle (surface) level convergence (divergence) centers are roughly, the mirror or rotated image of the MAMJ pos1 centers. This relationship suggests that the JJAS neg2 is inversely related to the subtropical Saharan high and thermal (heat) low (Chen, 2003, 2005). It can therefore be concluded that MAMJ pos1 and JJAS neg2 show direct and indirect relationships, respectively, with the subtropical Saharan high and thermal (heat) low, where direct relationship implies above normal precipitation (Fig. 9a) and indirect relationship implies precipitation deficit, especially, over the GOGC (Fig. 10f). The vertical motion (Fig.18f) associated with the JJAS neg2 divergent circulation depicts anomalous subsidence over the region, which is fairly consistent with its corresponding precipitation deficit, especially over the GOGC.

The midtropospheric anomalous divergent circulation shows the MAMJ pos3 events are characterized by middle (surface) level divergence (convergence) centered over the Sahel (Figs. 13c and 15c), whose vertical ascent is confined mostly to the Soudano-Guinea transitional zone (Fig. 17c). Outside this zone, is essentially, the presence of vertical descent. The vertical motion, by virtue of its coincidence with the divergent circulation, reasonably captures the precipitation anomaly patterns of the MAMJ pos3 events. The action centers of
the divergent circulations are also indicative of the presence of Sahelian highs and thermal (heat) lows in modulating boreal spring to early summer WAM. The JJAS pos3 midtropospheric divergent circulation anomalies are similar to the MAMJ pos3, in which the JJAS pos3 events portray middle (surface) level convergence (divergence) over West Africa (Sahel) (Figs. 14c and 16c), with centers of maximum ascent (descent) over GOGC (eastern part of Sahel) (Fig. 18c). The similarity in their divergent circulations is a manifestation of intraseasonal variability of anomalous West African lows and highs. The GOGC pattern in the JJAS pos3 precipitation field (Fig. 10c) exhibits the most consistent relationship with the 500hPa JJAS upward motion anomalies. In the MAMJ neg3 midtropospheric divergent circulation, middle level convergence is centered over the Sahel (Fig. 13g), with the corresponding surface level divergence centered over the tropical northwestern Africa (Fig. 15g). Here too, the divergent circulation of MAMJ neg3 is the mirror or rotated image of JJAS pos3, suggestive of an inverse relationship of the former with West African lows and highs. In the MAMJ neg3, weak anomalous ascent is observed over Western Sahel and western GOGC, and strong anomalous subsidence over eastern part of West Africa (Fig. 17g). The JJAS neg3 midtropospheric anomalous divergent circulation also reveals interesting features characteristic of tropical African midtropospheric circulation during the NH summer. Figures 14g and 16g show that the middle (surface) level divergence (convergence) is located roughly over subtropical North Africa. These fields, which are also a reflection of the existence of Saharan highs and heat (thermal) lows, play significant roles in WAM variability (Chen, 2003, 2005). Unlike the MAMJ pos1, a positive connection of the precipitation anomaly fields of JJAS neg3 to these highs and lows appears to be weak as can
Figure 13. As in Fig. 9, except for 500 hPa unfiltered MAMJ velocity potential, divergent winds, and precip. anomaly composites. Velocity potential (m²/s), horizontal wind vectors (m/s); contour interval x10⁶.
Figure 14. As in Fig. 9, except for 500 hPa unfiltered JJAS velocity potential, divergent winds, and precip. anomaly composites. Velocity potential (m²/s), horizontal wind vectors (m/s); contour interval x10⁶.
Figure 15. As in Fig. 9, except for unfiltered MAMJ velocity potential, divergent winds, and precip. anomaly composites at the surface level. Velocity potential (m$^2$/s), horizontal wind vectors (m/s); contour interval x10$^6$. 
Figure 16. As in Fig. 9, except for unfiltered JJAS velocity potential, divergent winds, and precip. anomaly composites at the surface level. Velocity potential (m^2/s), horizontal wind vectors (m/s); contour interval x10^6.
Figure 17. As in Fig. 9, except for 500 hPa unfiltered MAMJ vertical vel. and precip. anomaly composites. Contour interval x 10^6 Pa/s.
Figure 18. As in Fig. 9, except for 500 hPa unfiltered JJAS vertical velocity and precip. anomaly composites. Contour interval x 10^6 Pa/s.
inferred from Figs. 9a and 10g. Figure 18g shows that the anomalous vertical ascent, located on the mid-Sahel stretching to the maximum center in the eastern GOGC, is roughly flanked to the north and south by subsidence.

The study shows that even though MAMJ pos4 anomalous divergent circulation of the subcontinent is the antithesis of MAMJ neg4, it is however, structurally similar to the MAMJ neg3 events (Figs. 13d, 15d vs 13g, 15g). In addition to this, the MAMJ pos4 midtropospheric convergent center is similar to JJAS pos3 counterparts, both of which coincide with anomalous anticyclonic flows over the Sahel shown in the streamfunction composite analysis in the next section. The anomalous vertical motion associated with the MAMJ pos4 midtroposphere are characterized by weak ascent and strong decent over Western Sahel and eastern part of the subcontinent, respectively (Fig. 17d). Also, the MAMJ neg4 midtropospheric divergent circulation anomalies are similar to MAMJ pos2 events (Fig. 13b, h). The middle level divergence anomalies of these two events, which are all located over tropical northwestern Africa, are manifestations of their proximities to the 600 hPa African easterly jet (AEJ-N) (Nicholson and Grist, 2003, Chen, 2003, 2005), an anticyclonic system, which is associated with the WAM variability. However, the corresponding surface level convergence fields of MAMJ neg4 and MAMJ pos 2 differ essentially, with respect to their centers of action, which are Libya (North Africa) and Sahel, respectively (Figs. 15b, h). The anomalous vertical motion associated with the MAMJ neg4 midtropospheric divergent circulation shows weak subsidence and ascent over Western Sahel and eastern part of the subcontinent, respectively (Fig. 15h). Figures 14d and 16d show that the JJAS pos4
midtropospheric middle level convergence and its corresponding surface level divergence are located over tropical West Africa, and coincide with strong subsidence almost over the whole of West African region (Fig. 18d). The JJAS neg4 divergent circulation, even though it depicts antithetic relationship with its corresponding pos4 events, both have similar vertical motion anomalies (Fig. 18 h).

3.2.5 Unfiltered geopotential, streamfunction and rotational wind circulation anomalies

This section provides a comparative description of the anomalous generalized (unfiltered) circulation patterns of the streamfunctions and their associated rotational winds in relation to anomalous 500 hPa GH and horizontal wind vectors. In the monsoon layer, however, only rotational wind circulation will be highlighted.

3.2.5.1 Unfiltered streamfunction and rotational winds circulation: surface and 850 hPa

The positive (negative) events of the unfiltered anomalous streamfunctions and their associated rotational winds at the surface for the two seasons are shown in Figs.19-20. The results for all the events show that positive (negative) streamfunction anomalies are associated with anticyclonic (cyclonic) perturbations in the Northern Hemisphere (NH). In the Southern Hemisphere (SH) the sign is reversed. All the positive (negative) events associated with the unfiltered MAMJ streamfunctions are characterized by cyclonic (anticyclonic) flows (Fig. 19), which do not necessary apply for the JJAS season (Fig. 20).
Figure 19. As in Fig. 9, except for unfiltered MAMJ streamfunction (m²/s), rot. winds, and precip. anomalies at the surface level. Contour interval x10⁶.
Figure 20. As in Fig. 19, except for unfiltered JJAS streamfunction, rot winds winds, and precip. anomalies at the surface level. Contour interval x10^6.
The MAMJ pos1 (Fig. 19a) shows a cyclonic flow over North Africa, which is generated from Saharan thermal low and tropical Rossby waves. Other rotational flows include subtropical North and South Atlantic highs. These features coincide with the ubiquitous positive precipitation anomalies over the West African region during the MAMJ pos1 events.

In the JJAS pos1 events (Fig. 20a), large-scale cyclonic anomalies are observed centered over the NH tropical Africa traversing east to west in the latitudinal band between 10°N and 30°N, extending into the eastern TNA Ocean. This cyclone, which appears to have developed from intense Rossby waves (Vizy and Cook, 2001) suggests a strong NH summer time monsoon flow accompanying an anomalously wet Sahelian season shown in Fig. 3a. The formation of an anomalous cyclone (0°-10°S, 40°E-60°E) and a juxtaposed cyclonic/anticyclonic flow located between 10°N-10°S, 60°E-90°E could also be linked to dipolar precipitation pattern over West Africa, wherein the humid GOGC receives relatively minimal precipitation during the pluvial phase of the Sahelian season (Giannini et al., 2005).

During the MAMJ neg1 events (Fig. 19e), a well-developed anticyclonic flow is centered over Libya (North Africa), which coincides with the MAMJ pos1 and neg1 divergent center. Another feature noticed is a juxtaposition of a cyclone/anticyclone located between 10°N-10°S, 60°E-90°E. These rotational flows, which are connected to intense surface level divergence (Fig. 15e), coincide with expulsion of moisture from the land to the ocean leading to enhanced drought in the region. The JJAS neg1 events (Fig. 20e) are characterized by highly developed anticyclonic perturbations over central North Africa, close to the Sahel, and also, in the eastern tropical Atlantic. Others include a subtropical anticyclonic centered over North Atlantic Ocean, and other anticyclonic flows located in Angola, southwestern tropical
Indian Ocean below the Greater Horn of Africa (GHA), and a juxtaposed cyclone/anticyclone located between 10°N-10°S, 60°E-90°E. The rotational flows coincide with the negative moisture advection over the subcontinent, leading to dryness.

A close examination of all the other events of the unfiltered MAMJ and JJAS streamfunction circulation anomalies (Figs.19b-h, 20b-h) reveal that the key commonalities and differences stem from the location, intensity, frequency, and orientation of cyclonic/anticyclonic perturbations, and with their interactions with other features on the surface level, precipitation is either enhanced or suppressed over the region. It is also worth mentioning that all the key characteristic features of the positive (negative) events are similar to the 850 hPa level.

### 3.2.5.2 Unfiltered geopotential height, streamfunction and rotational winds anomalies: 500 hPa

The unfiltered 500 hPa midtropospheric streamfunction and rotational wind circulation anomalies for the two seasons are presented in this section alongside the 500 hPa GH and horizontal wind vectors (Figs.21-24). During the MAMJ pos1 events, positive GH anomalies (Fig. 21a) are centered over the mid-Sahel and extend into the eastern North Atlantic, the sub-tropics and the seaboard off northwestern Sahara. They also occur over southwestern subtropical Atlantic Ocean. On the other hand, negative GH anomalies in Fig. 21a are centered over the continent including the rest of the GOGC and Sahel, and most parts of the
two oceans. The positive and negative centers of the GH anomalies over tropical West Africa coincide with positive phase of MAMJ precipitation spatial mode one.

In association with the GH anomalies are subtropical northwesterlies (NH), subtropical westerlies (SH) and strong equatorial easterlies. Other key features are cyclonic and anticyclonic circulation anomalies, which are resolved better in the streamfunction and rotational wind analysis (Fig. 23a). The streamfunction analysis shows distinct cyclonic and anticyclonic systems over NH Africa. The cyclonic flows consist of a subtropical cyclone centered over North Africa, extending into the Mediterranean Sea. Others are centered over central equatorial Africa projecting over the GOG, and between 0° and 10°N over the TNA Ocean. The anticyclonic flow is a large-scale tropical high confined to between 10°-20°N latitudinal band of the entire Sahel belt, traversing east to west, projecting over the TNA Ocean. These rotational flows coincide with the MAMJ precipitation pos1 events. The JJAS pos1 events depict a wide-scale negative GH anomalies (Fig. 22a), in which over tropical West Africa, the center of action is located over the Sahel, and connects to the positive precipitation anomalies over this climatic zone. The negative GH anomalies are associated with subtropical easterlies (NH), subtropical westerlies (SH), equatorial westerlies, a well-developed cyclonic circulation (Fig. 24a) revealed by the streamfunction analysis.

This anomalous cyclonic flow, occupying the same region of as the anticyclone of the MAMJ pos1 events, is observed to be associated with the JJAS Sahelian precipitation. A close examination of all of the other events for both seasons suggests that the precipitation anomalies observed are closely associated with the sign of the GH field, where positive (negative) anomalies often coincide with below (above) normal precipitation.
Figure 21. As in Fig. 9, except for 500 hPa unfiltered MAMJ geopot. hgt (m), horizontal wind vectors (m/s), and precip. anomaly composites. Contour interval x 10^6.
Figure 22. As in Fig. 9, except for 500 hPa unfiltered JJAS geopot. hgt (m), horizontal wind vectors (m/s), and precip. anomaly composites. Contour x 10^6.
Fig. 23. As in Fig. 9, except for 500 hPa unfiltered MAMJ streamfunction (m²/s) and rot. winds, and precip. anomaly composites. Contour interval x 10⁶.
Figure 24. As in Fig. 9, except for 500 hPa JJAS streamfunction (m^2/s), rot. winds, and precip. anomaly composites. Contour interval x 10^6.
Others include the frequency, size, location, intensity of tropical/subtropical cyclones (anticyclones), and the strength of the westerlies, and easterlies.

3.2.6 Unfiltered net moisture budget and precipitation anomalies

This section briefly presents the findings of the linear regression model used to investigate the functional relationship between the NVIMB and the net precipitation anomalies.

![Graphs of regression analysis](image_url)

Figure 25. Regression of unfiltered net precipitation and vertically integrated moisture budget anomalies.
anomaly fields, and also the sensitivity of the divergent fields in relation to the precipitation fields during the two seasons for the three climatic zones - West Africa, Sahel, and GOGC. The results are presented in Fig. 25. It is observed that all of the zones depict statistical insignificance during the MAMJ season, suggesting that there are unobservable or latent factors in the divergent fields, which are linked to the WAM. However, 70% JJAS Sahelian precipitation can be explained by NVIMB anomalies ($r = +0.84$), which suggests the presence of stronger monsoon system during boreal summer, closely linked to the divergent fields (Chen, 2003, 2005).
CHAPTER FOUR

4.0 Results and Discussion: Low Frequency Structures

This chapter also provides a detailed description on the 3-D climate anomaly patterns associated with the LF precipitation modes during boreal spring-summer seasons over West Africa. The same presentation sequence used in the generalized (unfiltered) characterization in the previous chapter will be adopted here.

4.1 EOF analysis of low frequency precipitation and global SSTs

4.1.1 Low frequency West African seasonal precipitations

The scree plots showing the PCs associated with the LF precipitation during the boreal spring-summer West African precipitation are displayed in Fig. 26. For the LF MAMJ precipitation, five PCs passed North et al.’s (1982) delta-test, whereas the LF JJAS precipitation registered three. The LF MAMJ and LF JJAS precipitations accounted for 84.5% and 83.0% of the 10-year running mean low-pass (LP)-filtered total variances, respectively, of which their individual contributions are depicted in Table 5. As expected, the LP-filtered variances of the two seasons are substantially higher than the unfiltered variances (Chelliah and Bell, 2004). In keeping with the criteria established previously, three leading LF MAMJ precipitation modes, which explained 73% of the LP-filtered total variance, were retained so that the number of PCs of the two seasons could match.
Table 5. As in Table 1, except for LF dominant PCs of WAM precipitation

<table>
<thead>
<tr>
<th>Seasons</th>
<th>PC 1</th>
<th>PC 2</th>
<th>PC 3</th>
<th>PC 4</th>
<th>PC 5</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>JJAS</td>
<td>64.1</td>
<td>12.76</td>
<td>6.10</td>
<td>-</td>
<td>-</td>
<td>83.0</td>
</tr>
</tbody>
</table>

The spatial modes and their time coefficients of the LF MAMJ and LF JJAS are presented in Figs. 27 and 28. The EOF 1 loadings (eigenvectors) of the LF MAMJ precipitation anomalies (Fig. 27a) depict a large-scale spatial coherence, in which the sign of the anomalies is positive over most of the region, and is reminiscent of the unfiltered counterpart in Fig. 2a. This suggests that the unfiltered appears to be dominated by LF components. The time coefficients associated with this mode (Fig. 27d) depict interdecadal variability, which are reminiscent of the LF Sahel mode computed by other researchers (Rowell et al., 1995; Ward,
The EOF 2 and 3 loadings (eigenvectors) of the LF MAMJ precipitations (Fig. 27b,c) displayed complex, variegated anomaly configurations. The two modes were then subjected to varimax rotation to make their fields more physical. However, no significant differences were noted between the rotated and unrotated solutions. The original modes were retained for discussion. Just like the time coefficients of the EOF 1 loadings, the EOF 2 and 3 also depict interdecadal variability (Fig. 27e,f). The EOF 1 loadings (eigenvectors) of the LF JJAS precipitation (Fig. 28a) here too, are reminiscent of the generalized (unfiltered) loading patterns (Fig.3a), which also suggest that the unfiltered appears to be dominated by LF components. The time coefficients of the LF JJAS precipitation (Fig. 28d) portray interdecadal LF fluctuations of Sahelian precipitation, which are consistent with previous studies done over this region (Nicholson, 1980; Nicholson and Palao, 1993; Rowell et al., 1995; Ward, 1998; Giannini et al., 2005). The EOF 2 loadings (eigenvectors) of the LF JJAS precipitation (Fig. 28b) correspond to the LF GOGCM (Ward, 1998; Giannini et al., 2005). The EOF 3 loadings (eigenvectors), just as loadings 2 and 3 of MAMJ, were similar to their corresponding rotated solutions. The original mode (the unrotated solution) was retained. Also, the time coefficients of the LF JJAS second and third loadings (Fig. 28e,f) are dominated by decadal oscillations.
Figure 27. As in Fig. 2, except for LF MAMJ WAM precipitation.
Figure 28. As in Fig. 2, except for LF JJAS WAM precipitation
4.1.2 Low frequency MAMJ/JJAS global seasonal SSTs

The LF global SST EOF analyses for the two seasons are presented in Figs 29-31 and Table 6. The percent variances explained by the PCs of the two seasons are portrayed in Fig. 29. In MAMJ, the number of PCs that were statistically separate in accordance with

![Graphs showing variance explained by different EOF modes](image)

Figure 29. As in Fig. 1, except for LF MAMJ global SSTs.

North et al’s (1982) delta-test was seven, whereas five PCs were obtained for the JJAS season. The contributions of the most dominant PCs to LP-filtered total variances shown in Table 6 summed up to 94.88 % and 91.11 % for LF MAMJ and LF JJAS, respectively. To be consistent with precipitation analysis, the first three PCs were retained whose LP-filtered total variances were 76.30 % (MAMJ) and 78.6 % (JJAS). The loadings (eigenvectors) and time coefficients of these modes are shown in Figs.30 and 31.
Table 6. As in Table 5, except for LF seasonal dominant global SST PCs

<table>
<thead>
<tr>
<th>Seasons</th>
<th>PC 1</th>
<th>PC 2</th>
<th>PC 3</th>
<th>PC 4</th>
<th>PC 5</th>
<th>PC 6</th>
<th>PC 7</th>
<th>Total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAMJ</td>
<td>48.85</td>
<td>17.47</td>
<td>9.93</td>
<td>8.14</td>
<td>5.48</td>
<td>3.37</td>
<td>1.64</td>
<td>94.88</td>
</tr>
<tr>
<td>JJAS</td>
<td>42.12</td>
<td>25.76</td>
<td>10.71</td>
<td>8.41</td>
<td>4.11</td>
<td>-</td>
<td>-</td>
<td>91.11</td>
</tr>
</tbody>
</table>

In Fig. 30a, the eigenvectors (loadings) and the time coefficients of the LF MAMJ global SST EOF 1 show a more positive linear trend, indicative of a pronounced LF global warming signature as compared to the generalized structure (Fig. 5a). It has been reported that LF global warming may be a signal in response to planet-scale LF atmospheric circulation anomalies (Branstator, 1992; Saravanan, 1998). The loadings (eigenvectors) of the LF MAMJ global SST EOF 2 (Fig. 30b) depict LF modes of the interhemispheric contrast. In the SH, it captures South Pacific, South Atlantic, and Indian Ocean modes. In the NH, it captures North Atlantic and northwestern/northeastern Pacific modes. The temporal character associated with this mode reveals opposite linear trends from 1948-1975 and 1975-1997, which mainly describe a sequence of warming and cooling events, respectively (Fig. 30e). The loadings (eigenvectors) of the LF MAMJ global SST EOF 3 (Fig. 30c), which are regional in character, may be linked to three likely candidates, which are Pacific multidecadal oscillation (PDO), Atlantic multidecadal oscillation (AMO), and Atlantic meridional mode (AMM) (Mantua, 2002). The LF global SST EOF 3 time coefficients display sinusoidal, decadal-like oscillations (Fig. 30f). An examination of the LF JJAS global SST spatio-temporal structures (Fig. 31) reveals that they are similar to the LF MAMJ counterparts.
Figure 30. As in Fig. 2, except for LF MAMJ global SST loadings and time coefficients
Figure 31. As in Fig. 2, except for LF JJAS global SST loadings and time coefficients.
4.1.3 Low frequency WAM precipitation and global SST relationships

In an effort to describe the covariability of the LF WAM precipitation modes with the LF global SST modes for the two seasons, the same techniques used in Chapter Three were applied. Tables 7 and 8 show the simultaneous correlations between the two climatic parameters. The decadal variability of the LF MAMJ WAM precipitation EOF 1 one is strongly linked to LF MAMJ global SST EOF 1 (Table 7), which appears to be one of the main factors that drives precipitation trend over the tropical West Africa. Specifically, this SST mode could be associated with the persistent precipitation deficits experienced from the mid-1960s to late 1990s that reached its epoch in the mid-1980s (Benson and Clay, 1998). This precipitation deficit has partially been attributed to anthropogenic forcing. For instance, Biasutti and Giannini’s (2006) study showed that at least 30% of the recent Sahelian rainfall deficits were externally forced. Over the same region, Caminade et al. (2006) have argued that variations in precipitation in association with global warming are characterized by

Table 7. As in Table 3, except for LF MAMJ WAM and LF MAMJ global SST linear correlations. Figures in italics are correlations from detrended SST EOF 1 time coefficients.

<table>
<thead>
<tr>
<th>Indices</th>
<th>Precip. EOF 1</th>
<th>Precip. EOF 2</th>
<th>Precip. EOF 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global SST EOF 1</td>
<td>-0.79 (0.31)</td>
<td>-0.45 (-0.70)</td>
<td>0.32 (0.07)</td>
</tr>
<tr>
<td>Global SST EOF 2</td>
<td>-0.49</td>
<td>0.42</td>
<td>-0.52</td>
</tr>
<tr>
<td>Global ST EOF 3</td>
<td>0.26</td>
<td>-0.19</td>
<td>0.11</td>
</tr>
</tbody>
</table>
precipitation increase over Sahel–Sudan accompanied by strong increase in surface evaporation, and precipitation decrease with no significant differences, along the GOGC. The simultaneous linear correlation analysis (Tables 7 and 8) and heterogeneous grid point correlations (Figs. 32a,d) depict the associations between the LF global warming signature and the two LF WAM precipitation EOF 1. They show that the connection is more pronounced for the LF MAMJ precipitation EOF 1 than the LF JJAS EOF 1 counterpart. However, their connectivity with the detrended global SST EOF 1 time series reversed the sign and strength of their associations. Partial correlation analysis revealed that the LF MAMJ precipitation EOF 2 is associated with LF MAMJ global SST modes 1 and 2. It has a negative (positive) but relatively weaker linear correlations with the LF MAMJ global SST EOF 1 (EOF 2). This means cooling (warming) events associated with LF MAMJ global SST EOF 1 coincides with above (below) normal precipitation over the region. However, the association with the detrended global SST EOF 1 depicts a more pronounced relationship. For the LF MAMJ global SST EOF 2, warming (cooling) events are associated with above (below) normal precipitation over the region. The grid point correlation (Fig. 32b) appears

Table 8. As in Table 3, except for LF JJAS WAM and LF JJAS global SST linear correlations. Figures in italics are correlations from detrended SST EOF 1 time coefficients.

<table>
<thead>
<tr>
<th>Indices</th>
<th>Precip. EOF 1</th>
<th>Precip. EOF 2</th>
<th>Precip. EOF 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global SST EOF 1</td>
<td>-0.61 (0.47)</td>
<td>-0.57 (-0.62)</td>
<td>-0.53 (-0.33)</td>
</tr>
<tr>
<td>Global SST EOF 2</td>
<td>-0.73</td>
<td>0.17</td>
<td>0.59</td>
</tr>
<tr>
<td>Global SST EOF 3</td>
<td>0.20</td>
<td>-0.43</td>
<td>0.07</td>
</tr>
</tbody>
</table>
a. Correlation of filtered Mar-Jun precipitation EOF 1 time series with global SST

d. Correlation of filtered Jun-Sep precipitation EOF 1 time series with global SST

b. Correlation of filtered Mar-Jun precipitation EOF 2 time series with global SST
e. Correlation of filtered Jun-Sep precipitation EOF 2 time series with global SST

c. Correlation of filtered Mar-Jun precipitation EOF 3 time series with global SST
f. Correlation of filtered Jun-Sep precipitation EOF 3 time series with global SST

Fig. 32. As in Fig. 7, except for LF MAMJ and JJAS.
to be in harmony with the LF MAMJ global SST EOF 1 index. The LF MAMJ WAM EOF 3 is statistically connected to LF MAMJ global SST EOF 2, where cooling (warming) coincides with enhancement (inhibition) of convection in the rainbelt. However, the grid point correlation (Fig. 32c) positively connects the LF MAMJ WAM EOF 3 to LF MAMJ global SST EOF 1, the global warming signature, which is the secondary candidate captured by the linear correlation analysis (Table 7). On the contrary, the LF JJAS WAM precipitation modes display different associations with LF JJAS global SST modes. It is seen from Table 8 that the LF JJAS WAM precipitation EOF 1 is strongly connected to LF JJAS global SST EOF 2, whereas LF JJAS WAM precipitation EOF 2 is connected to LF SST EOF 1 where in both cases, cooling (warming) SST events lead to precipitation enhancement (suppression) over the region. The detrended global SST EOF 1 time series demonstrated a stronger connection with precipitation EOF 2. The LF JJAS WAM precipitation EOF 3, which shows connection with the global SST EOF 2, indicates that warming (cooling) events are associated with precipitation enhancement (inhibition) over the region. These connections are generally captured by the grid point correlation (Fig. 32d-f).

4.2 Low Frequency Boreal Spring-Summer Tropospheric Circulation over West Africa

This section is also intended to give a comparative description of the LF 3-D circulation anomaly patterns associated with the LF MAMJ and LF JJAS precipitation modes on the basis of their positive (negative) events.
4.2.1 Low frequency anomalous surface circulations

Figures 33 and 34 indicate positive (negative) events of the anomalous surface circulations associated with LF MAMJ and LF JJAS WAM precipitation modes, respectively. A comparison of LF events with the generalized (unfiltered) events shows that both have similar underlying physical mechanisms indicating that the generalized structures are dominated by LP components at least for the first two modes of both seasons. However, the unique features, which also serve as the main dividers within and between the LF MAMJ and JJAS events, relate to intensely contrasting SST patterns, which may be coupled to intense LF atmospheric circulations, manifesting themselves especially in the rotational and divergent fields, highlighted in the other sections.
Figure 33. As in Fig. 9, except for LF MAMJ circulation anomalies at the surface level.
Figure 34. As in Fig. 9, except for LF JJAS circulation anomalies at the surface level.
4.2.2 Low frequency 500 hPa anomalous circulations

The LF MAMJ pos1 events (Fig. 35a) depict anomalous mid-level equatorial westerlies, tropical easterlies, and cyclonic flow over Chad. The LF MAMJ neg1 events (Fig. 35d) show reversal of winds in addition to two well-developed cyclonic perturbations centered over the Sahel and TNA Ocean. The rest of the LF MAMJ events are basically differentiated on the basis of intensity, frequency, orientation, size, and centers of action of cyclonic and anticyclonic circulations as seen in Figs. 35b-f, as with the study of Zarrin et al. (2009). The LF JJAS events (Fig. 36a-f) also depict similar circulation anomalies with respect to mid-level equatorial westerlies/easterlies, tropical westerlies/easterlies, but differ with regard to the number of cyclonic and anticyclonic flows. These features coincide with the observed precipitation patterns for the two seasons over the region.
a. Filtered Mar-Jun precip., SST, and 500 hPa winds anomaly composites (+1)

b. Filtered Mar-Jun precip., SST, and 500 hPa winds anomaly composites (+2)

c. Filtered Mar-Jun precip., SST, and 500 hPa winds anomaly composites (+3)

d. Filtered Mar-Jun precip., SST, and 500 hPa winds anomaly composites (-1)

e. Filtered Mar-Jun precip., SST, and 500 hPa winds anomaly composites (-2)

f. Filtered Mar-Jun precip., SST, and 500 hPa winds anomaly composites (-3)

Figure 35. As in Fig. 9, except for LF MAMJ circulation anomalies at 500 hPa.
Figure 36. As in Fig. 9, except for LF JJAS circulation anomalies at 500 hPa.
4.2.3 Low frequency vertical velocity, velocity potential and divergent anomalies

This section describes the surface and mid-level (500 hPa) velocity potential and divergent wind anomalies in relation to 500 hPa vertical velocity anomalies for the two seasons. At 500 hPa, the center of mid-level divergence associated with the LF MAMJ pos1 events is located over the West African region (Fig. 37a). The corresponding surface level convergence is centered over the Sahel (10°-20°N). The surface level convergence suggests positive rainfall anomalies dominated by Sahel. The anomalous upward motion associated with the positive precipitation anomalies and the divergent circulation is observed in the eastern part of Sahel, West Africa (Fig. 41a). The central GOGC is characterized by strong vertical ascent flanked to the east and west by weak descent. During the LF MAMJ neg1 events, mid-level convergence is centered over Chad-Libya (Fig. 37d), with its corresponding surface level divergence centered over the Sahel (Fig. 39d). Accompanying these events, is the virtual absence of ascending motion (Fig. 41d), which coincides with the precipitation deficit (Fig. 33d). The center of action of the middle (surface) level divergence (convergence) of LF MAMJ pos2 events is located over North Africa (Figs. 37b, 39b), which do not coincide with the GOGC precipitation. This divergent circulation over North Africa is not sufficient enough to generate precipitation over this arid region. The propagation of Rossby wave train over this region has been suggested as the cause of this aridity (Rodwell and Hoskins, 1996). However, the divergent circulation is a manifestation of the connection of LF subtropical Saharan high with the GOGC precipitation. Therefore, the GOGC
Figure 37. As in Fig. 9, except for 500 hPa LF MAMJ velocity potential, divergent winds, and precip. anomaly composites. Velocity potential (m²/s). Horizontal wind vectors (m/s). Contour interval x 10⁶.
Figure 38. As in Fig. 9, except for LF 500 JJAS velocity potential, divergent winds, and precip. anomaly composites. Velocity potential (m$^2$/s). Horizontal wind vectors (m/s). Contour interval $\times 10^6$. 

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Figure 39. As in Fig. 9, except for LF MAMJ velocity potential, divergent winds, and precip. anomaly composites at the surface level.
Figure 40. As in Fig. 9, except for LF JJAS velocity potential, divergent winds, and precip. anomaly composites at the surface level. Velocity potential (m²/s). Horizontal wind vectors (m/s). Contour interval x 10⁶.
Figure 41. As in Fig. 9, except 500 hPa LF MAMJ vertical velocity and precip. anomaly composites. Contour interval x $10^6$ Pa/s.
Figure 42. As in Fig. 9, except for 500 hPa LF JJAS vertical velocity and precip. anomaly composites. Contour interval x 10^6 Pa/s.
precipitation seems to be driven mainly by horizontal moisture advection from the adjacent ocean. Strong ascending motion is observed over the GOGC during this season (Fig. 41b). The LF MAMJ neg2 events show middle (surface) level convergence (divergence) over West Africa (Western Sahara) (Figs. 37e, and 39e). The associated vertical motion (Fig. 41e) is consistent with the divergent circulation, in which anomalous weak (strong) ascent (descent) is located over Western Sahel (GOGC). During the LF MAMJ pos3 events, the center of action of the middle (surface) level convergence (divergence) is located over central North Africa (Figs.37c and 39c), whose corresponding 500hPa vertical velocity are predominantly positive anomalies (Fig. 41c) indicative of precipitation deficit over the West African region. The LF MAMJ neg3 events are characterized by middle (surface) level convergence (divergence) centered over West Africa (Sahel) (Figs. 37f and 39f), which coincide with anomalous sinking motion and dryness over the region (Fig. 41f).

The anomalous divergent circulations of LF JJAS pos1 and neg1 events (Figs. 38a, 40a and 38d, 40d) strongly resemble the LF MAMJ pos1 and neg1 cases. However, they differ from the MAMJ events with respect to intensity and location of their associated vertical motions. During the LF JJAS pos1 events, maximum anomalous ascent is located over the Sahel, and tends to coincide with the observed positive precipitation anomalies whereas the GOGC registers anomalous descent associated with precipitation deficit (Fig. 42a). This asymmetric circulation anomaly creates a LF quasi-dipolar spatial structure over the region. The LF JJAS neg1 events (Figs. 38d, 40d, 42d) are antithetical to their positive events, marked by pronounced drought over the region (Fig. 34d). The centers of action of the

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middle (surface) level divergence (convergence) of the LF JJAS pos2 events (Figs. 38b, 40b), which are the LF GOGC events during the Sahelian rainy season, closely resemble the pos1 events. However, the low level convergence has two centers; one located over Western Sahel and another in North Africa located between 20°-30°N. Even though anomalous ascent covers almost the entire region (Fig. 42b), the surface level convergence centers, which are far removed from the GOGC suggest that surface level moisture convergence may be a prerequisite (a necessary condition) but not a sufficient condition for pluviogenesis to be initiated over this zone. This further suggests that the LF GOGC precipitation is essentially driven by LF anomalous horizontal moisture advection. It also suggests that the LF JJAS pos2 events are connected to West African and Saharan heat (thermal) lows. The LF JJAS neg2 events (Figs. 38e, 40e), are the reverse of the pos2 events, with strong anomalous descent over the Sahel and weak ascent over the GOGC (Fig. 42e). In LF JJAS pos3 events, middle (surface) level convergence (divergence) is centered over Sahel (Figs. 38c, 40c). In association with these events are anomalous descent (Fig. 42c), a manifestation of precipitation deficit over the region. The LF JJAS neg3 events (Figs. 38f, 40f) are very similar to the pos3 counterparts. Also, the anomalous descents associated with the neg3 (Fig. 42f) are very similar to that of pos3 and neg1, but the opposite of pos1 (Figs. 42c vs 42d vs 42a), wherein the neg3, pos3, and neg1 are all characterized by pronounced drought.
4.2.4  Low frequency geopotential height, streamfunction and rotational wind circulation anomalies

4.2.4.1  Low frequency geopotential height anomalies at 500 hPa

Figures 43 and 44 show the LF composite analysis of GH and horizontal wind anomalies at 500 hPa associated with the positive (negative) events of MAMJ and JJAS precipitation modes, respectively. In both cases, pos1-2 and neg1-2 events are associated with negative and positive GH anomalies, respectively, which coincide with the ascent and subsidence at 500 hPa over the region (Figs. 41a,b and 42a,b). All the other LF events of the two seasons show that positive (negative) GH anomalies are generally, associated with subsident (upward motion) movements over the region. There are no striking differences in the GH anomaly fields associated with the two seasons over the region. The GH anomalies compare well with the 850 hPa ones, except that at 500 hPa the associated winds are more intense and at that level, moisture is very minimal. The LF rotational winds associated with the GH anomalies are resolved in the streamfunction analysis in the next section.

4.2.4.2  Low frequency streamfunction and rotational wind anomalies at the Surface and 850 hPa

The features at the surface level will be used as a representation of the two levels since their events are similar. During the LF MAMJ pos1 events the streamfunction and
rotational wind anomalies (Fig.45a) show strong equatorial westerlies and a cyclonic perturbation centered between 10°-30°N over northwestern tropical Africa, which coincide with above-normal precipitation anomalies over the region. The neg1 events are characterized by strong equatorial easterlies and an anticyclonic flow, also centered between 10°-30°N (Fig. 45d). The LF MAMJ pos2 events depict two cyclonic circulation anomalies centers: one over the GOGC and the other, a subtropical cyclone in North Africa (Fig. 45b). These distinct features are found to be associated with the positive precipitation anomalies observed over the GOGC. The corresponding negative events depict a subtropical anticyclonic circulation (Fig.45e), which is associated with precipitation deficit over the region. The LF MAMJ pos3 and neg3 events (Figs. 45c,f) are similar, typified by strong equatorial easterlies and an anticyclone, which could be linked to sparse precipitation distribution over the region. The LF JJAS pos1-3 and neg1-3 events (Fig.46) are reminiscent of the LF MAMJ events. Here too, the chief differences relate to intensity, orientation, location, size, and frequency of the cyclonic and anticyclonic systems.
Figure 43. As in Fig. 9, except for 500 hPa LF MAMJ geopot. hgt (m), winds, and precip. anomaly composites. Horizontal wind vectors (m/s). Contour interval x 10^6.
a. Filtered Jun-Sep 500 hPa geopot. hgt, winds and precip. anomaly composites (+1)

b. Filtered Jun-Sep 500 hPa geopot. hgt, winds and precip. anomaly composites (+2)

c. Filtered Jun-Sep 500 hPa geopot. hgt, winds and precip. anomaly composites (+3)

d. Filtered Jun-Sep 500 hPa geopot. hgt, winds and precip. anomaly composites (-1)

e. Filtered Jun-Sep 500 hPa geopot. hgt, winds and precip. anomaly composites (-2)

f. Filtered Jun-Sep 500 hPa geopot. hgt, winds and precip. anomaly composites (-3)

Figure 44. As in Fig. 9, except for 500 hPa LF JJAS geopot. hgt., winds, and precip. anomaly composites. Horizontal wind vectors (m/s). Contour interval x 10^6.
Figure 45. As in Fig. 9, except for LF MAMJ streamfunction (m²/s), rot. winds, and precip. anomaly composites at the surface level. Contour interval x 10^6.
Figure 46. As in Fig. 9, except for LF JJAS streamfunction (m$^{-2}$/s), rot. winds, and precip. anomaly composites at the surface level. Contour interval x 10$^6$. 
4.2.4.3. **Low frequency streamfunction and rotational wind anomalies at 500 hPa**

Figures 47 and 48 show the LF composite analysis of the streamfunction and rotational wind anomalies at 500 hPa associated with the positive (negative) events of MAMJ and JJAS precipitation modes, respectively. As can be seen from Fig. 47a, the midtropospheric monsoon circulation associated with the LF MAMJ pos1 events is similar to the one at the surface (Fig. 45a), except that the former is characterized by a pair of cyclonic circulations centered over Eastern Sahel, specifically, over Chad-Sudan region, and a more developed structure over tropical eastern North Atlantic Ocean. When viewed together, Figs. 47a and Fig. 37a depicts a juxtaposition of the continental midtropospheric cyclonic center with the midtropospheric divergent center, which suggests that they are maintained by LF diabatic cooling (heating) (Chen, 2003, 2005). These two anomalous circulations, which are in-phase, coincide with positive rainfall anomalies over the region. Their velocity potential and streamfunction anomalies suggest the existence of spatial quadrature relationship as found in similar studies (Chen and Chen, 1997; Chen, 2003, 2005). During the LF MAMJ neg1 events, a cyclonic flow is found located over North Africa between 20°-30°N (Fig. 47d). Unlike the pos1 events, the streamfunction (rotational winds) and velocity potential (divergent) fields (Figs. 49d and 37d) depict opposite polarity and do not suggest any evidence of spatial quadrature. The out-of-phase relationship coincides with the precipitation deficit over the region.
a. Filtered Mar-Jun 500 hPa streamfunction and rot. wind anomalies (+1)

b. Filtered Mar-Jun 500 hPa streamfunction and rot. wind anomalies (+2)

c. Filtered Mar-Jun 500 hPa streamfunction and rot. wind anomalies (+3)

d. Filtered Mar-Jun 500 hPa streamfunction and rot. wind anomalies (-1)

e. Filtered Mar-Jun 500 hPa streamfunction and rot. wind anomalies (-2)

f. Filtered Mar-Jun 500 hPa streamfunction and rot. wind anomalies (-3)

Figure 47. As in Fig. 9, except for 500 hPa LF MAMJ streamfunction (m$^2$/s), rot. winds, and precip. anomaly composites. Contour interval x 10$^6$. 
Figure 48. As in Fig. 9, except for 500 hPa LF JJAS streamfunction (m$^2$/s), rot. winds, and precip. anomaly composites. Contour interval x 10$^6$. 

a. Filtered Jun-Sep 500 hPa streamfunction and rot. wind anomalies (+1)

b. Filtered Jun-Sep 500 hPa streamfunction and rot. wind anomalies (+2)

c. Filtered Jun-Sep 500 hPa streamfunction and rot. wind anomalies (+3)

d. Filtered Jun-Sep 500 hPa streamfunction and rot. wind anomalies (-1)

e. Filtered Jun-Sep 500 hPa streamfunction and rot. wind anomalies (-2)

f. Filtered Jun-Sep 500 hPa streamfunction and rot. wind anomalies (-3)
It is observed that the LF MAMJ pos2 events (Fig. 47b) are characterized by well-developed midtropospheric anomalous cyclonic and anticyclonic flows centered over central North Africa and Saudi Arabia, respectively. The anticyclonic flow coincides with Saudi Arabian convergent center, whereas the cyclonic flow lies aloft over Nigeria-Chad convergent center (Fig. 37b). These flows are associated with the positive precipitation anomalies over the GOGC. The LF MAMJ neg2 events are characterized by two distinct anomalous anticyclonic flows centered over Egypt-Libya and Nigeria-Chad (Fig. 47e). These highs may have been generated from LF Saharan and LF West African thermal (heat) lows, respectively. These spring-early summer LF monsoon circulations are associated with irregular precipitation anomaly patterns observed in Fig. 33e. These observed midtropospheric highs, together with their associated convergent center (Fig. 37e) are indicative of the presence of spatial quadrature. Chen (2005) similarly reported that the midtropospheric Saharan high, which is well depicted by 600 hPa streamfunction located over Northwest of Africa, is in spatial quadrature with the 600 hPa North African divergent center over Chad-Sudan.

The LF MAMJ pos3 events are characterized by a well-developed midtropospheric cyclone centered between 20°-30°N of North Africa and strong equatorial easterlies. This anomalous cyclonic flow generated by diabatic cooling is associated with surface level divergence (Fig. 39c), subsidence (Fig. 41c) accompanied by sensible heat loss, and positive GH anomalies (Fig. 43c), leading to precipitation deficit over the region (Fig. 33c). The salient features that characterize the LF MAMJ neg3 events are a tripod system.
of anomalous anticyclonic monsoon circulations, whose center is occupied by a cyclonic flow (Fig. 47f). This type of configuration system may be ascribed to the orographic effects, which divide the rotational flows into cyclonic/anticyclonic flows. The role of orography in generating distinct anticyclones from anticyclonic belt has been discussed by Rodwell and Hoskins (2001). Also, a subtropical cyclone is located in the eastern TNA Ocean. An examination of the corresponding continental velocity potential anomaly field shows a large-scale midlevel convergence spanning West to North Africa (Fig. 37f), which is associated with the rotational flow systems.

The monsoon system during the northern tropical summer is known be very strong (Chen, 2003, 2005). An examination of the LF JJAS events at least for pos1 and neg1 (Figs. 46a,d) is a manifestation of this peculiarity. The LF JJAS pos1 events (Fig. 48a) depict a very intense and large-scale midtropospheric anomalous tropical cyclonic circulation over the northern sector of Africa stretching into the eastern TNA Ocean. The cyclonic flows may be associated with long-term variability in the midtropospheric westerlies. They may also be related to long-term variations in diabatic heating/cooling, mid-level humidity, large-scale low-level convergence, and PDO, which has secondary signatures in the tropics (Mantua, 2002), as well as tropical meridional mode (TMM 2) (Bell and Cheliah, 2006). In the LF JJAS neg1 events (Fig. 48d), two intense anticyclonic flows are seen located over the Sahel and stretch into the eastern TNA Ocean from East Africa. In association with these flows is a cyclonic circulation centered between 20°-30°N (North Africa), and midlevel equatorial easterlies, which might be Rossby wave response to tropical monsoon heating. The LF JJAS pos2 events (Fig.48b)
lack clearly defined rotational flows over the subcontinent, but depict a midtropospheric subtropical cyclone over eastern TNA Ocean between 30°-40°N, which coincides with the GOGC precipitation. The LF JJAS neg2 events (Fig. 48e) are characterized by tropical anomalous cyclone centered between 20°-30°N, which is flanked on the west and east by two anomalous anticyclonic flows (a subtropical and a tropical). The midtropospheric subtropical high centered between 30°-40°N may be the result of LF Saharan thermal-low heating (Chen, 2003, 2005), whereas the midlevel cyclonic flow may be associated with diabatic cooling (Rodwell and Hoskins, 2001). Over the eastern TNA Ocean is a juxtaposition of cyclonic and anticyclonic flow. The association of midtropospheric anomalous easterlies with these rotational flows also coincides with positive GH anomalies (Fig. 44e), anomalous descent (Fig. 42e) and inhomogeneous precipitation anomalies over the region (Fig. 36e). The LF JJAS pos3 events (Fig.48c) are very close to the patterns of the LF JJAS neg1 events (Fig. 48d) as well as their vertical motion and GH fields (Figs. 42c,d; 44c,d). The most conspicuous difference is that the number of cyclones of the latter outnumbers the former marginally, by one. The LF JJAS neg3 events (Fig. 48f) are antithetic to JJAS pos1 events (Fig. 48a).

4.3 Low frequency anomalous net moisture budget and precipitation relationship

Figure 49 shows the net LF precipitation anomalies as a function of NVIMB anomalies over the three climatic zones (West Africa, Sahel, and GOGC). Here too, the most significant
a. Filtered WA Mar-Jun precip. as a function of vertically moisture budget

\[ Y = 2.345 \times 10^7 x - 22.36 \]
\[ R^2 = 0.1689; p = 0.42 \]

b. Filtered GOG Mar-Jun precip. as a function of vertically moisture budget

\[ Y = 2.6 \times 10^6 x - 7.95 \]
\[ R^2 = 0.50; p = 0.12 \]

c. Unfiltered Sahel Mar-Jun precip. as a function of vertically moisture budget

\[ Y = -1.6 \times 10^7 x + 6.2 \]
\[ R^2 = 0.03; p = 0.72 \]

d. Filtered WA Jun-Sep precip. as a function of vertically integrated moisture budget

\[ Y = -4.3 \times 10^7 x + 41.20 \]
\[ R^2 = 0.51; p = 0.11 \]

e. Filtered GOG Jun-Sep precip. as a function of vertically moisture budget

\[ Y = 8.1 \times 10^5 x + 1.1 \times 10^{-1} \]
\[ R^2 = 0.0; p = 0.98 \]

f. Filtered Sahel Jun-Sep precip. as a function of vertically moisture budget

\[ Y = -5.2 \times 10^7 x + 39.87 \]
\[ R^2 = 0.73; p = 0.03 \]

Figure 49. Regression of net LF precipitation and vertically integrated moisture budget anomalies.
relationship is found to exit between only net LF JJAS Sahelian precipitation and LF NVIMB anomalies. It shows that 73% variability of the net LF Sahelian precipitation anomalies can be explained by NVIMB anomalies, but with a correlation of $r = -0.85$ as opposed to a positive correlation detected in the generalized case. In other words, 73% of the net LF Sahelian precipitation can be explained by net LF vertically integrated moisture flux divergence. This relationship further shows that other factors other than atmospheric moisture may be associated with the Sahelian precipitation (Nicholson and Palao, 1993). The nonsignificant relationship between the net precipitation and NVIMB anomalies over West Africa and the GOGC suggests that anomalous divergent circulation over these zones during MAMJ and JJAS seasons do not seem to bear any visible or direct relationship their precipitation fields. They may however, affect these precipitation fields mediated through other pathways, the most plausible one being tropical Atlantic SSTs. Similarly, it can be inferred as with the generalized case that the two dominant and competing mechanisms that drive LF precipitation over Sahel and GOGC are LF momentum convergence (divergence) and horizontal advection, respectively.
CHAPTER FIVE

5.0 Summary

Attempt has been made to present diagnostic descriptions of the three-dimensional northern hemispheric spring-summer climate anomaly patterns from 1948-2006, on the basis of positive and negative events associated with the leading MAMJ and JJAS precipitation modes over tropical West Africa. Two approaches were adopted to facilitate comparative descriptions of climate variability of the two seasons.

The first approach, which entailed the general characterization, focused and highlighted the unfiltered characters of the two seasons. The second involved the isolation of the low frequency (LF) (ie, decadal) modes of all the data using a 10-year running mean low-pass filter to smooth out interannual variability due to ENSO and the tropical western Pacific Ocean. Analysis techniques involved standard EOF analyses (unrotated solutions) of West African precipitations and global SSTs for the two seasons. The unrotated solutions were supplemented by varimax rotation, where necessary, to filter out some errors in the observations in order to improve and make their fields appear more physical. Other techniques involved were the application of simple simultaneous linear correlations, partial/semipartial correlations, and simultaneous heterogeneous grid point correlations to capture the local and remote climatic candidates associated with the dominant precipitation modes of the two seasons. Composites analyses, which highlighted the tropospheric circulations, were computed from anomaly fields based on the positive (negative) events.
associated with the dominant precipitation modes. Analyses were confined to the monsoon layer (e.g., surface and 850hPa) and midtropospheric layer, represented by 500hPa, to delineate spatially coherent fields from which the circulation structures of the two seasons were compared. Secondly, atmospheric moisture, the precursor of precipitation is abundant especially, in the monsoon layer, beyond which, insignificant quantities are observed, justifying the need for us to limit our analysis to these two layers. The anomalous composite analyses focused on SST and geopotential height fields overlain by horizontal wind fields, and also, vertical motions, divergent and streamfunction circulations, all projected onto 1000 hPa, 850 hPa and 500 hPa isobaric surfaces. Our final analysis involved the formulation of a simple regression model on the basis of the positive (negative) events associated with the leading precipitation modes to establish the functional relationships between the net (cumulative) precipitation anomalies and vertically integrated moisture budget anomalies from the surface to the middle layer (i.e., 1000-500 hPa isobaric surfaces), comprising six pressure levels. Here, three climatic zones considered along the two seasons were the entire West African region, the Sahel and the GOGC. Also, this procedure was implemented to further test the sensitivity of the seasonal divergent fields. We proceed by summarizing the salient features of the general structures, followed by the LF (i.e., decadal) case.

The study has revealed that within the domain of study, four distinct precipitation modes, depicting spatially coherent departure patterns are typical of each of the seasons. The percent variances accounted by the four leading MAMJ and JJAS precipitation modes were 45.2% and 54.7%, respectively. The EOF 1 spatial patterns of MAMJ depicted more or less ubiquitous positive weights over the region, which are reminiscent of a monopole or non-
dipole structure, dominated by the Sahel pattern. The time coefficients of the MAMJ this mode depict decadal-like variability just like the well-known boreal summer Sahel mode (e.g., Rowell et al., 1995; Giannini et al., 2005). However, the MAMJ EOF 2 spatial pattern depicts two departure patterns, in which the positively weighted GOGC mode is connected to out-of-phase Sahelian precipitation anomalies. This mode is a representation of the well-known GOGC rainfall index described by previous studies. Its time coefficients portray decadal-like variability. However, a visual integration of MAMJ EOF 1 and 2 spatial patterns is a manifestation of intraseasonal rainfall variability and latitudinal monsoon jump over the Sahel in response to evolving SSTA patterns. The MAMJ spatial modes 3 and 4 identified three basic anomaly patterns. For the EOF 3, the negatively weighted anomalies centered over the central part of West Africa are flanked by positive anomalies centered on the Western Sahel and eastern part of West Africa. The associated time coefficients depict interannual rainfall variability. The MAMJ spatial mode 4 is characterized by a dipolar structure in the eastern part of West Africa and positive anomaly patterns centered over the Western Sahel. On the basis of the spatial coverage, the Western Sahel anomaly patterns of the modes 3 and 4 were distinguished as Western Sahel Anomaly Type 1 (smaller) and Type 2 (bigger), respectively. The time coefficients associated with the mode 4 also demonstrate interannual variability. The time coefficients of the four MAMJ precipitation modes correlated poorly with the Senegal rainfall index constructed by Fall et al.(2006). In contrast, the JJAS spatial mode 1 is the well-known Sahel mode/continental mode (SM/CM; Ward, 1998; Giannini et al., 2005; Polo et al., 2008). In this mode, the GOGC anomalies are characterized by negative loadings, which are consistent with previous studies (e.g., Rowell
The temporal structures associated with the SM/CM indicate the well-known decadal precipitation variability over the Sahel, which depict above-normal precipitation from the 1950s to late 1960s, followed by below-normal precipitation in the early 1970s, culminating in the persistent and precarious drought (Folland et al., 1991; Lamb and Peppler, 1992; Nicholson and Palao, 1993; Giannini et al., 2005), which has seen some signs of recovery recently. The JJAS EOF 2 mode portrays the spatial structures characteristic of the GOGC during the JJAS, when it receives relatively low precipitation (Giannini et al., 2005). Its temporal structures show decadal precipitation trend. The JJAS EOF 3 and 4 identified four anomaly patterns. The anomaly patterns of spatial mode 3 show an approximately quasi-axisymmetric configuration about Soudanian climatic zone. The western and eastern parts of Sahel, which are out-of-phase, are closely the rotated images of the western and eastern GOGC anomalies. The JJAS mode 4 shows an out-of-phase relationship between Western Sahel and eastern parts of the West Africa. Similarly, on the basis of the spatial modes 3 and 4, the Western Sahel patterns were classified as Anomaly Type 3 (bigger) and Type 4 (smaller), respectively, which are in opposition to Types 1 and 2 of MAMJ anomaly patterns. However, their time coefficients also portrayed interannual oscillations. Weak correlations were found between all the four MAMJ time coefficients and the Senegal rainfall index computed by Fall et al. (2006). On the contrary, the Senegal rainfall index was strongly connected to the first two leading JJAS precipitation time coefficients.

The EOF analysis of global SST revealed that seven and four PCs were statistically separate for MAMJ and JJAS seasons, respectively. These leading modes explained 54.74 % and 39.68 % of their total variances, respectively. However, four PCs were retained for the
MAMJ case so as to match the number of precipitation modes. Invariably, the two seasons share commonalities in their spatio-temporal structures. Their first modes highlight global warming signature, whereas their second modes are a manifestation of interannual ENSO variability, which are consistent with previous studies (Ward, 1998; Folland et al., 1991). The global SST EOF 3 and 4 modes show coherent anomaly patterns, which are reminiscent of interhemispheric contrast computed in earlier studies (Lough, 1986; Ward, 1998; Folland et al., 1991).

In an effort to understand the covariability between MAMJ/JJAS West African rainfall and their corresponding seasonal global SSTs, simultaneous linear correlation analysis was computed using the dominant precipitation time coefficients and 19 climatic indices, complemented by partial/semipartial correlation analyses and simultaneous heterogeneous grid point correlations between the precipitation total time coefficients and anomalous SST fields. The linear/partial correlation analyses show that the MAMJ precipitation EOF 1 is associated with two candidates; TADM and global SST EOF 3. However, the simultaneous grid point correlation isolated equatorial/southwestern Atlantic mode as an additional mode associated with the precipitation mode. The MAMJ precipitation EOF 2 showed significant but an anticorrelation with IOSSD$_{MAMJ}$ and global SST EOF 1 indices, of which these two candidates were well captured by the grid point correlation analysis. However, the detrended global global SST EOF 1 index showed a poor association with the MAMJ precipitation EOF 2. The MAMJ precipitation EOF 3 is associated with global SST EOF 2. The grid point correlation shows that it is also connected to the positive phase of the TADM. On the whole, the MAMJ precipitation EOF 4 time coefficients show
weak linear correlations with all the climatic indices. However, the grid point correlation isolated equatorial Atlantic/TSA mode, which inversely correlated significantly with the EOF 4 time coefficients. In the case of the JJAS, the precipitation EOF 1 mode was found to be associated with three candidates, namely, MEI, IOSSDJAS, and global SST EOF 3, which are captured by the grid point correlation. The grid point correlation also captured the connection between the precipitation mode 1 and tropical western Pacific, the equatorial mode (EM) and the South Atlantic mode, in which cooling (warming) events are indicative of above (below) normal precipitation over the Sahel. These observations corroborate the findings of previous studies (Folland et al., 1991; Ward, 1998; Polo et al., 2008). It was observed that the JJAS precipitation EOF 2 (the GOGC mode), anticorrelated with TADM. The grid point correlation revealed that the GOGC mode is also remotely linked to warming (cooling) events in the Indian Ocean, tropical western Pacific and the equatorial southwestern Atlantic, which coincide with the positive (negative) rainfall anomalies. The JJAS precipitation EOF 3 mode showed significant (insignificant) positive correlations with trended (detrended) global SST EOF 1 indices. An examination of the corresponding grid point correlation reveals that warming (cooling) events over the tropical Pacific/Atlantic and Indian Ocean are associated with above (below)-normal precipitation. Finally, the JJAS precipitation EOF 4 was found to be positively associated with global SST EOF 3 index. The grid point correlation revealed two candidates; the warming (cooling) events of South Pacific Ocean below South American continent are linked to precipitation enhancement (suppression), whereas the cooling (warming) events over TNA Ocean are also linked to precipitation enhancement (suppression).
The general 3-D anomalous tropospheric circulations of the two seasons are summarized on the basis of the positive (negative) events associated with their precipitation modes. Generally, the surface and 850 hPa circulations in monsoon layer were similar for each season, but differed significantly from their respective 500 hPa midtropospheric circulations. The salient features that characterized the positive MAMJ events involved less developed but varied cold tongue complex (CTC) (generated from a deeper thermocline and a weakened equatorial upwelling), cross-equatorial flows, large-scale southwesterly moisture flux convergence, and low-level cyclonic flow generated from diabatic heating. Another feature spotted was the presence of tropical North Atlantic (TNA) SST gradient. The interactions of these features, which were also identified in previous studies (Vizy and Cook, 2001; Gu and Adler, 2004) culminated in convection over the entire West African region. But the variations in these features determined the degree of enhanced convection to drought conditions associated with the other events. Generally, the JJAS positive events differed from the MAMJ events primarily on the basis of well-developed CTC and zone of low-level maximum convergence over the Sahel, perceivably, driven by anomalous high pressure system in the case of the Sahel mode. The other positive events associated with the JJAS season are marked by a warm phase of the CTC accompanied by evaporative heat loss and its attendant moisture transport (in the case of EOF 2, the GOGC mode), or complete obliteration of the CTC accompanied by negative moisture advection and anticyclonic flow (in the case of EOF 3) and cold SST anomalies in equatorial Atlantic (EA) and moisture convergence over tropical equatorial North Atlantic (in the case of EOF 4) leading to different anomaly patterns. In all cases as with the MAMJ events, positive rainfall anomalies
generally coincide with negative anomalous 500hPa vertical motions and 850hPa/500hPa geopotential height (GH) levels. The negative events of the two seasons are generally associated with reversal of their positive events, which show coincidence with positive anomalous subsidence at 500 hPa.

The commonalities and differences in the 500 hPa midtropospheric MAMJ and JJAS anomalous circulations hinged on the sizes, the frequencies, intensities, spatial distributions and centers of action of divergent circulations, cyclonic/anticyclonic flows, as well as GHs and the propagations of the subtropical, tropical, and equatorial westerlies and easterlies, which were found to coincide with the rainfall departure patterns over the West African region. One striking difference between the MAMJ and JJAS anomalous circulations relate to their divergent fields at the surface and 500 hPa levels. Whereas one of the most widely accepted explanation of pluviogenesis involves upper level divergence (convergence) and surface level convergence (divergence) generally, coinciding with above (below) normal precipitation (Gu and Adler, 2004) holds for JJAS, this mechanism most of the time was at variance with the precipitation fields of the MAMJ events. This was corroborated by the regression model, which revealed a poor linkage between the net precipitation and vertically integrated moisture budget anomalies for the MAMJ season over West Africa, Sahel and the GOGC. This could imply that precipitation over the GOGC is sufficiently driven by evaporation from the adjacent oceans, and moisture convergence (divergence) is an added plus. However, one striking feature found was that the 500 hPa midtropospheric anomalous divergent circulation centers associated with MAMJ positive 1 events were manifestations of their proximities to the 600 hPa midtropospheric subtropical Saharan thermal (heat) lows and
Saharan highs (Chen, 2003, 2005), which play significant roles in WAM variability. On the other hand during JJAS, Sahel showed that about 70% of its net precipitation anomalies could be explained by net vertically integrated moisture budget anomalies in JJAS, which implies the moisture divergence (convergence) is a sufficient condition to explain pluviogenesis over the Sahel. It can therefore be inferred that the two dominant and competing mechanisms that drive precipitation over Sahel and GOGC are momentum convergence (divergence) and horizontal advection, respectively.

Three PCs were retained for the LF (decadal) precipitation and global SST of the two seasons. The percent variances accounted by these PCs of the West African rainfall were 73 % and 83 % for MAMJ and JJAS, respectively. The first loadings (eigenvectors) of the LF MAMJ precipitation anomalies depicted a large-scale spatial coherence, in which the sign of the anomalies was positively weighted over most of the region. The time coefficients associated with this mode depict interdecadal variability, which is reminiscent of the LF Sahel mode computed by other researchers (Rowell et al., 1995; Ward, 1998; Giannini et al., 2005). When varimax rotation was applied to the second and third LF MAMJ precipitation fields, no significant differences in their precipitation fields were spotted for both the rotated and unrotated solutions. The original modes were then retained. The LF JJAS precipitation EOF 1 spatial patterns portrayed the well-known LF Sahel mode whose time coefficients depicted interdecadal-like variability, just like the LF MAMJ mode 1. The positively weighted LF JJAS precipitation EOF 2 spatial patterns could be described as the LF JJAS GOGC mode, whose time coefficients were similar to LF MAMJ mode 2.
Application of the varimax rotation to the LF JJAS mode 3 yielded the same results as the LF MAMJ 3 case, justifying the need to retain the original mode.

Three most dominant LF global SST PCs were also retained for both seasons to match the number of LF precipitation modes. The percent variations explained by the MAMJ and JJAS seasons were 76.30% and 78.6%, respectively. In both seasons the SST patterns were similar. The LF global SST EOF 1 spatial patterns demonstrated enhanced long-term global warming trend, whereas the second and third PCs gave signatures of LF interhemispheric contrasts (for EOF 2) and Pacific decadal oscillation (PDO)-/Atlantic multidecadal oscillation (AMO)-/Atlantic meridional mode (AMM)-like and LF Indian Ocean modes (for EOF 3). Even though PDO is primarily a pattern of Pacific climate variability over North Pacific and North America, it has been found to have secondary imprints in the tropics (Mantua, 2002). Both the AMO (Delworth and Mann, 2000) and AMM (Xie and Carton, 2004) are natural modes of variability in the tropical North Atlantic (TNA) Ocean and tropical Atlantic. The AMO is a manifestation of variability in the Atlantic Ocean’s thermohaline circulation. The AMM is a meridional mode characterized by meridional displacement of the ITCZ and attendant shifts in SST and winds.

The covariability of LF precipitation and global SST were also studied using the same techniques for the unfiltered events. Linear/partial correlation analyses showed that LF MAMJ precipitation modes 1 and 2 were associated with LF global SST EOF 1 and 2 in the following ways: (i) LF MAMJ precipitation mode 1 was linked to LF global SST EOF 1, but with positive and lower association with its corresponding detrended PC time series, (ii) LF MAMJ precipitation mode 2 was linked to two candidates; global SST EOF 1, but enhanced
by its corresponding detrended PC time series, and global SST EOF 2., and (iii) LF MAMJ precipitation mode 3 was linked to global SST EOF 2. On the contrary, the LF JJAS events revealed the following findings: (i) LF JJAS precipitation mode 1 was associated with LF global SST EOF 2, (ii) LF JJAS precipitation mode 2 was associated with LF global SST EOF 1, but enhanced by its corresponding detrended PC time series, and (iii) LF JJAS precipitation mode 3 is also connected to global SST EOF 2. Generally, the grid point correlations captured the LF global warming, PDO-like, AMO/AMM-like and Indian Ocean modes.

By visual inspection, the salient features of the LF MAMJ and JJAS low and midlevel tropospheric circulations appeared to be similar to their corresponding general (unfiltered) structures. However, isolation of LF modes captured PDO/AMO/AMM-like modes, which are known to play significant roles in climate variability in the tropics (Mann, 2000; Mantua, 2002; Xie and Carton, 2004). Some of the unique LF features associated with MAMJ and JJAS seasons, which may be linked to these LF ocean-atmosphere coupled natural modes are the large-scale cyclonic and anticyclonic anomalous flows generated from long-term anomalous diabatic heating (cooling)/ differential vertical heating, enhanced anomalous vertical motions, as well as the presence of spatial quadrature signature in the velocity potential and streamfunction anomaly fields of the midtropospheric positive 1 events. Even though the LF modes of the two seasons share some commonalities, they differed in terms of their divergent and rotational fields as was the case with the general (unfiltered) structures. Here too, unlike the LF JJAS divergent circulation fields which generally, were consistent with the precipitation fields, the MAMJ events did not seem to be so. The LF MAMJ net
budget and precipitation anomalies showed insignificant correlations for all of the three climatic zones. On the contrary, the 73% LF JJAS Sahel net precipitation anomalies were explained by net vertically integrated moisture budget anomalies, linking the precipitation anomalies to divergent circulations.
CHAPTER SIX

6. Conclusions and Recommendations

In this study, the spatio-temporal and 3-D features of northern hemispheric spring-summer climate anomaly patterns over tropical West Africa have been documented using diagnostic techniques. The study essentially builds on the concepts and principles of 2-D climate variability applied by Semazzi et al. (1993) for June-July-August (JJA) and extends the ideas on 3-D climate variability experimented by Giannini et al. (2005) for July-August-September (JAS) and García-Serrano et al. (2008) for summer-late winter over the tropics. Unlike Semazzi et al. (1993), who employed atmospheric modeling techniques only, a combination of observation cum modeling techniques was utilized by Giannini et al. (2005), whereas the current research primarily focused on empirical analysis just as García-Serrano et al.’s (2008) study. The following outstanding conclusions emerged from the current research.

First, the climate anomalies associated with JJAS and JAS seasons are exactly the same, suggesting that the definition of boreal summer Sahelian season by an investigator is a matter of choice. In contrast, the climate variability associated with MAMJ is quite distinct from JJAS and boreal spring, March-April-May (MAM) events, indicative of different underlying physical science basis. Second, the study has shown that the Senegal rainfall index computed by Fall et al. (2006) is strongly associated with JJAS West African precipitation EOF 1 and 2 computed from the University Delaware (UD) terrestrial precipitation data. This analysis was fully supported by the 3-D anomalous circulations in the
monsoon and middle layer, where it was shown that precipitation over West Africa including Senegal involved moisture convergence arising from the anomalous cross-equatorial southwesterly flows from the tropical Atlantic into the continental interior. Also, the precipitation fields synchronized the divergent, omega and geopotential height (GH) anomaly fields, reinforcing the connectivity between the Senegal precipitation zone and the two leading West African precipitation modes. On the contrary, Fall et al. (2006) have emphasized that the Senegal rainfall index is strongly related to the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) West African EOF 2, relegating the leading and traditional EOF 1 index. They further argued that the 850 hPa circulation projected on the CMAP EOF 2 for West Africa showing moisture convergence over Senegal clearly evidenced their assertion. However, their study failed to incorporate the positive and negative circulation regimes, which could have increased sensitivity of the analysis connected to the two leading modes of CMAP for West Africa. Moreover, 3-D perspective encompassing other climatic fields such as velocity potential (divergence), omega, streamfunction (rotational), and GHs, which can shed more light on West African-Senegal precipitation connectivity, was deficient in their study. Therefore, ruling out West African precipitation EOF 1, a traditional policy index and its importance to end users as far as West Africa-Senegal rainfall scenario is concerned may be quite premature, since the current study has revealed a more realistic and elaborate information. Third, the study has documented that JJAS precipitation fields generally show coincidence with the anomalous divergent circulation fields and that between 70-73% Sahelian precipitation can be explained by net vertically integrated moisture budget (NVIMB) anomalies (1000-500 hPa), suggesting that
Sahelian precipitation is implicitly and intricately connected to the divergent circulation. This is because moisture flux divergence is a direct estimate of net moisture budget (Peixoto and Oort, 1992). The MAMJ precipitation fields on the other hand, generally, were at variance with the anomalous divergent circulations, neither did their NVIMB anomalies adequately explain the observed precipitation. Literally, the centers of action of their anomalous divergent circulation fields, which failed to coincide with the precipitation fields, were mostly located roughly over subtropical North Africa, where subtropical Saharan highs and thermal lows are prevalent. These observations spontaneously became a spotlight, compelling us to address the following question: “What then is responsible for driving MAMJ and JJAS precipitations?” The answer to the question hinges on two basic competing mechanisms associated with changes in SST anomaly patterns that are linked to precipitation departure patterns over Sahel and GOGC (Vizy and Cook, 2001). An increase (decrease) in tropical Atlantic SST over the Gulf of Guinea is accompanied by an increase (decrease) in evaporation and low (high) pressure that leads to wetness (dryness) over the GOGC. In contrast, reversal of these events over the Gulf of Guinea is responsible for wetness (dryness) over the Sahel. The two factors ultimately underlying these competing mechanisms appear to be momentum convergence (divergence) and horizontal moisture advection. With reference to the 2-D study by Semazzi et al. (1993), it was concluded that stronger (weaker) moist cross-equatorial monsoon flow was responsible for precipitation enhancement (suppression) over Sahel. But in the current study, the problem has been investigated further using additional meteorological variables, which were also deficient in their model, and then extended the analysis to 3-D perspective for the two seasons. The study therefore concluded
that the factors responsible for precipitation over the Sahel and GOGC are momentum convergence (divergence) and horizontal advection, respectively. Because of these dominant factors, we have to be very cautious in defining Sahel and GOGC seasons.

In view of the above conclusions, the following recommendations are worthwhile. A combination of observation and modeling studies is crucial for elucidating the physical science basis underlying CMAP and UD precipitation fields over West Africa. Also, this conjoined approach is imperative for providing valuable insights into our understanding of the divergent circulations of the two seasons. It will be desirable to perform EOF analysis on the momentum convergence (divergence) and horizontal advection terms to understand their spatio-temporal properties. Finally, it will also be desirable to perform a more refined analysis on monthly basis to monitor the time dependence on evolution of the leading modes.
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