Assessment of Long-term Spatio-temporal Rainfall Variability over Ghana using Wavelet Analysis

by

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BSc. (Meteorology and Climate Science)

A Thesis Submitted to the Deparment of Physics,

Kwame Nkrumah University of Science and Technology, in

partial fulfillment of the requirements for the degree

of

MASTER OF PHILOSOPHY

(Meteorology and Climate Science)

College of Science

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May 2016

Declaration

I hereby declare that this thesis is my own work towards the MPhil and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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Student Name & ID	Signature	Date

Certified by:

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Supervisor(s) Name	Signature	Date

Certified by:

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Head of Department	Signature	Date

Dedicated to my parents

Rev. and Mrs. Baidu.

Abstract

Rainfall variability has serious implications on food security and livelihood in West Africa since it modulates the socio-economic activities in the sub region. The interannual, inter-seasonal and inter-decadal rainfall variability in rainfall over Ghana has been studied and their periodicities analysed using wavelet analysis. A rainfall time series from 1901 - 2010 from GPCC was used in this analysis. It was observed that, high cumulative rainfall amounts ranging from 900 - 1900 mm are recorded over the entire nation per year with very high rainfall amounts between 1500 - 1900 mm recorded at the south-western part of the country and low rainfall amounts (900 - 1200 mm) recorded in the Savannah and east coast of the country. In general a decreasing trend is observed for the inter-annual rainfall over all the agro-ecological zones except for the coastal zone where a slight rise in trend of 0.1600 mm per year is seen. The seasonal trend analysis reveals a significant decreasing trend at 99% confidence level in all the agro-ecological zones except for the Savannah during the DJF season indicating an intensification of the Harmattan. The Coastal zone records lowest mean rainfall values for all the seasons with the highest of about 150 mm recorded in MAM. The Forest zone on the other hand records very high rainfall values for all the seasons with the highest of about 200 mm recorded in JJA followed by about 170 mm in MAM. The Transition zone however records almost similar rainfall values (varying between 120 and 170 mm) for all the seasons except for DJF where a lower mean value of about 50 mm is recorded. On inter-decadal time scale, below normal rainfall values is observed between the 1901 - 1920 and 1980 - 2010 periods

for all the agro-ecological zones except for the Savannah which shows above normal rainfall values within the 1901 - 1940 period. These variabilities confirm the effects of strong El Niño and La Niña episodes on the region. The wavelet analysis also revealed a strong annual periodicity over all the agro-ecological zones except for the Coastal and Forest zones where the annual periodicity is accompanied by 4 - 8 months signal. The results of both the 5 year moving average and the inter-decadal anomaly confirm that rainfall amount is significantly decreasing even in the transition zone which is the food hub of the country. This will likely have negative consequences on agricultural practices, water resource management and food security.

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Acknowledgments

My greatest appreciation goes to God for His faithfulness, grace and love that has kept me through this period of studies. I am so grateful for my life and His assistance through the successful completion of this work.

I am also grateful to Dr Leonard K. Amekudzi, my supervisor for his patience, love, encouragement and support throughout this entire time. Your constructive criticism and selfless devotion through the reading of this script is highly appreciated. I am also thankful to you for introducing me the the linux file system, the FORTRAN programming language and other skills which have been to my advantage today.

To Dr. Kwesi Preko, I say I am very thankful for your encouragement and inspiration. You have always been there for me in both good and tough times.

I am also grateful to all lecturers and staff members in the Department of Physics especially Dr. Emmanuel Quansah, Dr. Michael E. Donkor, Dr. Thomson Annor and Mr. Charles Yorke for your inputs especially for introducing me to Matlab and other data analysis tools like the Climate Data Operator (CDO) and NetCDF Operators (NCO). Mr. Aryee Jeffrey, Dr. Ernest Ohene Asare, Mr. Addi Martin, Miss Winifred A. Ayinpogbilla and all other postgraduate students of the Meteorology and Climate Science Unit, I say a big thank you to you all for introducing and assisting me through the use of other data analysis tools such as the Grid Analysis and Display System (GrADS) and the gnuplot.

A big thank you to Dr. Christopher Torrence, Exelis Visual Information Solutions, National Center for Atmospheric Research, University of Colorado Boulder and Prof.

Celso A. G. Santos, Universidade Federal da Paraiba, PB - Brasil, for their time, patience, inputs and ultimately for making the Wavelet Analysis Script available for me. I will forever be grateful.

Finally, this work could not have been completed without the financial and moral support of my relatives, especially my parents, Rev. and Mrs. Baidu. I say a big thank you to you.

CHAPTER 1

Introduction

1.1 Research Background

Rainfall Variability in West Africa has serious implication on food production and livelihood as it modulates the socio-economic activities of the subregion. In general, rainfall in the region is mostly influenced by the migration of the Inter-Tropical Discontinuity (ITD). The ITD oscillates south to north and back and so modulates the pressure system of the West African Monsoon (Amekudzi et al., 2015; Sylla et al., 2011; Mounier et al., 2008; Nicholson and Grist, 2001; Wallace and Hobbs, 2006; Salby, 1996). Southwesterly winds dominates the region south of the ITD. This carries moisture from the Atlantic Ocean onto the region. On the contrary, North East trade winds which is a dry continental wind dominates the region North of the ITD. The north-south oscillation of the ITD modulates the influence of the two prevailing wind directions over the region. A single wet season is thus experienced in the Savannah and Sahel Zones of West Africa between April to October when the ITD moves to its Northern position. The southern part of the country on the other hand experiences two wet seasons: the first one which is the major wet season from March to July and the minor wet season from September to November (Owusu and Klutse, 2013; Nkrumah et al., 2014; Manzanas et al., 2014; Amekudzi et al., 2015). In addition to the variability in the position of the ITD, local convective activities which results from the vegetation type and topography plays a critical role in the spatio-temporal rainfall variability (Houze, 2012; Amekudzi et al., 2015). For instance, strong convective activities are experienced at the windward side of the Togo-Akwapim ranges in the Forest Zone of Ghana (Amekudzi et al., 2015). According to Houze (2012), when a moisture containing air parcel encounters a mountain, the air becomes unstable which could result in rainfall if the physical conditions such as the strength of the cross-barrier part of the airflow aloft, the height of the terrain barrier and the degree of thermodynamic stability are suitable. Other atmospheric feedback mechanisms like the dynamic stability, the sea surface temperature (SST), the land surface feedback and transient tropical wave influence could account for the intra-seasonal and inter-annual variability of rainfall in the West Africa (Hall and Peyrillé, 2006).

The annual rainfall in Ghana varies highly on inter-annual and inter-decadal time scales making it difficult to identify long term trends (McSweeney et al., 2010). Moreover periods of decreasing rainfall annual totals was observed together with a shifting regime from the early 1970s which is now trying to recover (Paeth and Hense, 2004; Owusu et al., 2008).

According to Neilsen et al. (2001) climate variability and change have impact on the crop-water-supply-demand relationship. This means that, crop yields are directly affected by rainfall variability. The dependence of agricultural systems on the highly variable weather conditions accounts to a greater extent, for the apparent perennial instabilities seen in the output of agricultural products which threatens food security within the West African subregion.

In the forth assessment report of the Inter-governmental Panel on Climate Change (IPCC), an intensification in the frequency of extreme rainfall events during the present century due to climate variability and change was predicted (Pachauri et al., 2007).

These changes in climatic patterns will have direct impact on the onset, duration and cessation which will affect crop production (Amekudzi et al., 2015). Assessing the impact of climate variability in the various agro-ecological zones in Ghana will enhance livelihood and food security in the country which is the focus of the present study.

1.2 Problem Statement

Understanding rainfall variability has been a major challenge to agricultural production, transportation, hydro-electricity generation and water resource management. There has been hash economic and social conditions faced in many places in Ghana due to consistent rainfall variability (Manzanas et al., 2014). However previous studies have focused on the Sahel and less studies have been done over the humid zone of West Africa. This is the reason for the general consensus of the downward rainfall trend in the West African sub region over the last few decades. This generalization may not be useful for realistic socio-economic planning since different rainfall mechanisms exist in the humid zone and the drier Sahel. The former region has a bi-modal rainfall pattern while the latter has a single rainfall peak (in summer). Other studies have also reviewed a high rainfall amount over Ghana in the 1960s and early 1970s which decreased in the late 1970s and early 1980s, resulting in the overall decreasing trend in the period between 1960 and 2008 (Amekudzi et al., 2015; Manzanas et al., 2014).

The sustainability of rain-fed agriculture is threatened if the consequences of climate change and variability are not considered in our current developmental agenda and frameworks. The anticipated increase in population by the year 2050 is also a concern for food security and the preservation of natural resources Neng et al. (2002), and thus, the need to investigate the irregularities in the rainfall over West Africa. This study therefore seek to contribute to this climate variability and change research by investigating the rainfall variability over the agro-ecological zones of Ghana.

1.3 Justification of the Study

A number of research on rainfall have been done focusing on specific locations in Ghana, however very few studies have been conducted on the entire nation as a whole. Moreover, most of these studies used data with time scales of 30 - 60 years which is not suitable for the analysis of an inter-decadal variability. For instance, Adiku et al. (2007) used a 22 - 55 year data and focused on Accra and Tamale. Yengoh et al. (2010); Yamba (2010) used a 47 and 48 year data respectively and focused on the transition and Savannah Zones of Ghana. Owusu and Waylen (2013) used a 40 year data and concentrated on Wenchi and Friesen et al. (2002) used a 22 year period and concentrated on Northern Ghana. Manzanas et al. (2014) used 14 synoptic stations in Ghana over a period of 49 years to investigate the variability and trends in rainfall in Ghana. Furthermore, Lacombe et al. (2012) used the Re-sampling-Based Mann-Kendall Test to study the trend in a 45 year rainfall pattern in 16 stations in Ghana.

Although Owusu and Klutse (2013) studied the spatial pattern of rainfall over the entire nation Ghana using CORDEX (Coordinated Regional Climate Downscaling Experiment) only a 19 year data was used. The current study focuses on the variability of rainfall over all the agro-ecological zones in Ghana using a 110 year rainfall data from the Global Precipitation Climatology Centre (GPCC).

Moreover, a combination of time domain multivariate statistics including harmonic analysis, linear regressions, Fourier analysis and cross correlation have been applied to climate data in the tropics to determine the relationship among the climate elements (Norzaida et al., 2015; Feng et al., 2013; Fenta, 2010; Wong et al., 2009). The limitation of these methods has been the assumption of stationarity or linearity which is not satisfied by most natural phenomena (Huang et al., 1998). Therefore in the investigation of the climate variability over Ghana and its relationship with other climatic elements, the current study seeks to analyse the irregularly distributed events in time that predict non-stationary power at it various frequencies.

To accomplish this, Wavelet Analysis was used to understand the variability in the rainfall pattern from the period 1901-2010 and their trends determined using the Mann Kendall trend test for the various zones in Ghana. The Wavelet Analysis will provide the opportunity to investigate the nature of rainfall variability in the various agroecological zones and to identify periods with high levels of rainfall variability that have the potential to adversely affect crop or livestock production in the country.

1.4 Main Objective

The main objective of this study is to investigate the extent and nature of the interannual, inter-seasonal and inter-decadal rainfall variability in the various agro-ecological zones in Ghana.

1.4.1 Specific Objectives

To achieve the set goal, the following specific objectives have been set:

- Validate GPCC data with GMet gridded data.
- Investigate the inter-annual, -seasonal and -decadal variability in each of the agro-ecological zones.
- Perform trend analysis and use Mann-Kendall test to detect significant trends in each zone.
- Perform wavelet analysis for each agro-ecological zone using the wavelet analysis tool described in Torrence and Compo (1998) to identify the significant frequencies in each zone.

1.5 Organization of the thesis

The thesis is organized into five chapters, chapter one presents a general overview of the various Agro-Ecological zones of Ghana and the rainfall variability of these zones, the problem statement, the justification of the study, the objectives and the thesis structure.

The first section of Chapter two presents an overview of the Rainfall variability over West Africa. A review of various studies conducted with regards to the inter-annual, inter-decadal and seasonal variability of rainfall in Ghana, is carried out in the second and third sections of Chapter two. The fourth section highlights the various methods used in rainfall variability studies and works carried out in that light. The final session introduces the wavelet analysis and reviews the various works carried out by this method.

Chapter three focuses on the description of the study area, the source of the data and the various methods used in the study. The wavelet transform and its application to any meteorological data is also presented. The various extensions to the wavelet analysis such as the Global wavelet power spectrum and the Scaled average wavelet spectrum are also presented in this chapter.

Chapter four presents the results and its discussion. The results of the spatial variation of the multi-year mean rainfall over Ghana as well as its seasonal variability is presented and compared to that of GMet gridded data. The results of the trend analysis for the various agro-ecological zones as well as their corresponding 5 year moving averages is also presented and discussed. Finally, the output of the wavelet analysis for the agro-ecological zones is shown and discussed. This is compared with the Global wavelet power spectrum and the Scaled Average wavelet power spectrum for each zone.

Finally, the conclusions and recommendations drawn from the work are presented in chapter five.

CHAPTER 2

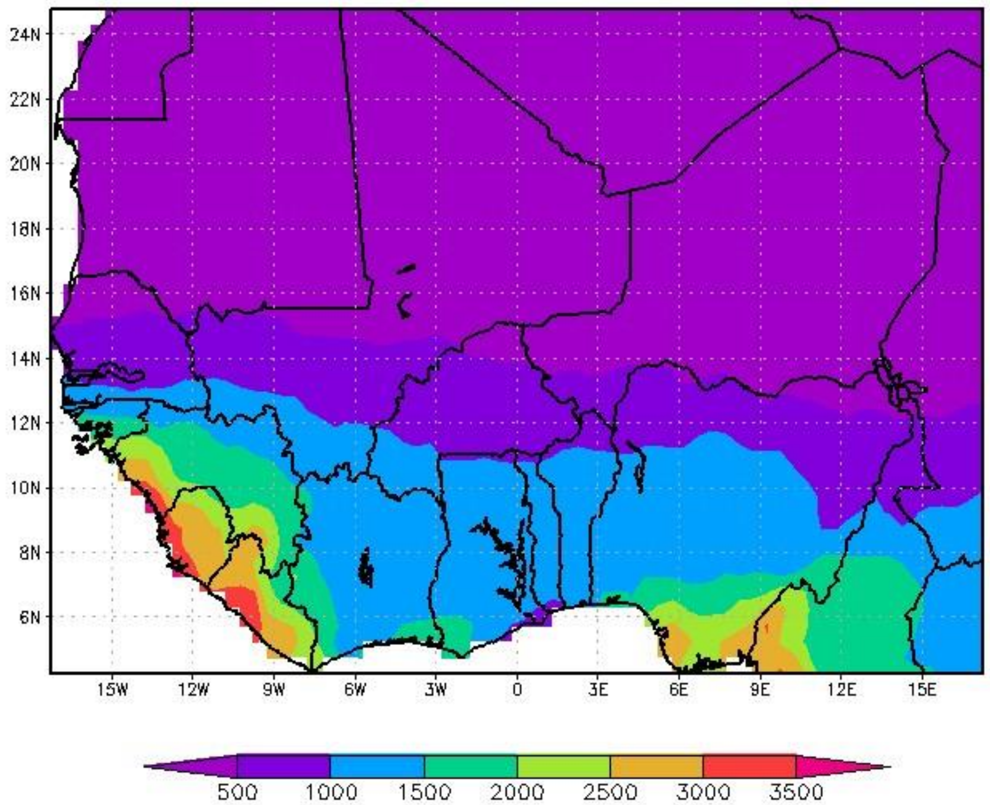
Literature review

2.1 Overview of rainfall variability in West Africa

The economy of most West African countries depends mainly on agriculture. It accounts for more than 35% of the Gross Domestic Product (GDP) and about 40% of the exports of the region (Jalloh et al., 2011). Rainfall variability therefore have direct impact on the West African economy.

The region is however among the wettest on the continent with mean annual rainfall values ranging from 200 to 4500 mm (Jalloh et al., 2011) (see Figure 2.1). It shows a high north to south climatic variability due to varying rainfall amounts from the Gulf to the Sahara (Vizy and Cook, 2002; Le Barbé et al., 2002). This results in various climatic zones in the region which includes the arid, semi-arid, sub humid and humid zones. The arid zones includes Senegal, Mali, Burkina Fasso and Niger which forms the Sahel and Saharan regions in West Africa. This region usually has less than 750 mm rainfall and an extended dry season that lasts for about 10 months (Ferguson, 1985; Kessler and Breman, 1991; Casenave and Valentin, 1992). The semi-arid zone of West Africa is a grassland area located at the northern parts of Senegal, parts of Niger, Burkina Fasso, Nigeria, Mali and Cameroon. This zone also has rainfall values that ranges from about 250 to 500 mm (Casenave and Valentin, 1992; Sivakumar, 1988). The Semi-humid zone includes the Sudan Savannah which is a shrub and grassland with mean rainfall values ranging from 500 to 900 mm. It includes the Gambia, southern parts of Mali, Niger, Burkina Fasso, Senegal, the north of Nigeria, Togo, Cameroon and Benin. The humid zone is divided into two sub zones: the Guinea/Savannah Zone and the Forest Zone (Boffa, 1999; Windmeijer et al., 1993; Valentin et al., 2004). The Savannah sub zone includes southeast Guinea, middle of Nigeria and Ghana, parts of Cote d'Ivoire, and parts of Cameroon. The sub zone has rainfall amounts varying between 1000 and 1500 mm (Windmeijer et al., 1993; Jalloh et al., 2011). The Forest Zone also includes the southern parts of Cote d'Ivoire, Ghana, Togo, Benin, Cameroon and east of Sierra Leone. It is a dense tropical Forest with rainfall values ranging from 1500 to 2000 mm (Ferguson, 1985; Eggleton et al., 2002; Jalloh et al., 2011). The east coasts of Ghana, Togo and Benin have relatively lower rainfall amount due to local atmospheric circulation and the upwelling of cold winds (Acheampong, 1982).

The climate of West Africa is made of two main seasons: the wet and dry seasons. The dry season results from the prevalence of a hot and dry tropical continental air mass driven by the Azores high pressure system known as the Harmattan (Walker, 1958; Prospero and Carlson, 1981). This wind blows over the Sahara to most countries in West Africa between November and March (Ezennia, 1989; Mensah, 2015; Amekudzi et al., 2015). The wet season on the other hand results from the prevalence of a moist tropical maritime air mass driven by the South Atlantic high pressure system. This results in a southwesterly wind which dominates the continent from March to October (Lamb, 1978; Leroux, 2001). A zone of deep convection results at the meeting point of these two prevailing winds known as the Inter-Tropical Discontinuity (ITD) (Leroux, 2001; Aryee, 2015). The climate of the region is thus modulated by the north-south movement of the ITD resulting in the high spatio-temporal variability (Lebel et al., Figure 2.1: Mean annual rainfall (mm) over West Africa.



2000; Leroux, 1997).

The region exhibits a strong inter-annual, -seasonal and -decadal variability (Fontaine and Janicot, 1996; Le Barbé et al., 2002). This includes the wet period recorded between 1930 and 1960, the dry period between 1970 and 1980 and the recovery of rain in 1990s and 2000 (Hulme, 1992; Nicholson, 1993; 1997; Jalloh et al., 2011). The mean decrease in rainfall amount between the period 1931 - 1960 and 1960 - 1990 was 15% in the Forest Zone but about 30% in the Sahel (Hulme, 1992). This significant decrease in the Sahel has resulted in serious droughts and famines (Mohamed et al., 2002). In the Semi-arid zone however, large rainfall deficits were recorded between 1972 - 1973, 1983 - 1984, 1987, 1990 - 1997 and 2004 with the 1983 - 1984 having the greatest deficit. Nicholson et al. (2000a) therefore declared the 1980s as the driest period in the century. The average precipitation in West Africa has therefore undergone serious fluctuations in the 20th century. Le Barbé and Lebel (1997) indicated that, the deficit in precipitation during the West African dry periods was as a result of a reduced number of rainy days in the rainy season. Meanwhile, recent studies have indicated a recovery in the mean rainfall amount since the 1990s (Manzanas et al., 2014; Jalloh et al., 2011).

These variabilities have been found to be as a result of some climate systems in the region such as the ITD, the monsoon winds, Sea Surface Temperature (SST) anomalies, sub-tropical high pressure systems, the African Easterly Jet (AEJ) and the Tropical Easterly Jet (TEJ) (Rowell, 2003; Vizy and Cook, 2001; Lamb and Peppler, 1992; Folland et al., 1986). For instance, the strengthening of the AEJ is found to be associated with drought conditions in the Sahel during the July-September season and the Gulf during January-March while the TEJ weakens (Nicholson, 2001). Wet periods in this region is however associated with warm SST anomalies over the tropical Atlantic.

2.2 Rainfall Variability over Ghana

Rainfall is among the most principal climatic variables in the tropics. Knowledge about rainfall and its variability is required in various research and application disciplines that have direct relation to the global energy and hydrological cycle. Some of these disciplines include climate modeling, numerical weather prediction, flood forecasting, now-casting, agro-meteorology, oceanography, aviation meteorology and water resource management (Fenta, 2010).

In Ghana, rainfall modulates all socio-economic activities especially considering the fact that, agriculture and its products provides employment for over 70% of the employed people in Ghana (Oduro-Afriyie and Adukpo, 2006) and accounts for about 28% of the

Gross Domestic Product (GDP) (CIA, 2011). The variability in rainfall onset will therefore have serious consequences on agricultural practice, water resource management and hydroelectric power generation. The studies of rainfall variability is thus required to better address the socio-economic issues in Ghana and West Africa at large (Logah et al., 2013). However, rainfall in Ghana varies seasonally and spatially since different precipitation regimes exits from the Coastal in the south to the Savannah zones in the north (Cooper et al., 2008).

The northern part of Ghana which is the Savannah Zone has a unimodal rainfall distribution starting in May and peaking in August. In the southern part of Ghana, the rainfall pattern is bimodal, the first peak occurs in March to July, with the second in September, and August remaining relatively dry (Manzanas et al., 2014; Nkrumah et al., 2014; Aryee, 2015; Mensah, 2015; Amekudzi et al., 2015). Much of the sub humid zone is transitional between unimodal and bimodal rainfall distribution (Sultan et al., 2000; Le Barbé et al., 2002). According to Manzanas et al. (2014) the rains normally reach the southern boundary of the sub humid zone in early March, and reaches the northern boundary two months after. In the northern zone, the wet season normally ends in early October and at the southern boundary 6 weeks later. However in the sub humid zone, the duration of the rainy season ranges from months in the north and 8 months in the south. Nevertheless the April to October season is invariably punctuated with some days of dry spells (Logah et al., 2013). The transitional stage of the rainfall season is marked by minimal amount of rainfall along the Guinea Coast region (between 6°N and 8°N in particular over Ghana along 5°N), characterizing a climatological feature of the rainfall area. This condition is normally associated with the little dry season (Aryee, 2015; Le Barbé et al., 2002).

Several rainfall variability studies have revealed a decreasing trend over Ghana and other West African countries since 1970 (Nicholson et al., 2000b; Yepdo Djomou et al., 2009; Owusu and Waylen, 2013). Many climate models have also predicted a decrease in rainfall amounts over all the agro-ecological zones of the country (Kankam-Yeboah et al., 2013; Obuobie et al., 2012; McSweeney et al., 2010). However, the study by McSweeney et al. (2010) revealed an increase in the mean annual rainfall over the entire country. These disparities together with the wide-range of temporal and spatial variability of rainfall makes it difficult to predict the long term rainfall trends accurately.

2.2.1 Inter-annual and Inter-decadal Variability of Rainfall in Ghana

Studies have revealed that, the rainfall in Ghana varies on inter-annual and interdecadal time scales making it difficult to identify long term trends (Nkrumah et al., 2014; Logah et al., 2013; McSweeney et al., 2010). The inter-annual and inter-decadal variability of rainfall in Ghana is controlled by both the global climate teleconnections and regional climate systems (Jalloh et al., 2011). These global teleconnections include those associated with the Madden-Julian Oscillation (MJO), El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). The global rainfall patterns and wind circulation respond significantly to the different ENSO phases. In Indonesia, Australia and other nations around the west equatorial pacific, rainfall during El Niño years is lower than average and higher than average during La Niña years (Gunawan et al., 2004). Over Ghana, the variability of the ENSO enhances the north easterlies and reduces the monsoon flow. The upper easterlies are also weakened leading to dry conditions close to the surface of the Inter-Tropical Discontinuity (ITD) during the major rainy season and the dry season (Sultan et al., 2000). Drought conditions also results from the intensification of the African Easterly Jet (AEJ) over the Sahara during the July to September and January to March seasons (Nicholson and Grist, 2001; Biederlack and Rivers, 2012).

Yorke and Omotosho (2010) observed that, a long rainy season occurred all over Ghana during the 1960's and early 70's due to early onset and late cessation dates. This however changed significantly in the 1980's where the onsets occurred late with early cessation. This change is also attributed to the strong ENSO that occurred during this period (Mawunya et al., 2011). A significant downward trend was also observed at all the stations especially Axim. The study also revealed that, wet years have early onset and late cessation and vice versa. This is proven by a study by Amekudzi et al. (2015); Manzanas et al. (2014). However in the studies by Manzanas et al. (2014), the analysis of annual precipitation totals revealed a decreasing trend for the first part of the period of study (1961-1985) and an increasing trend for the second part of the study (1986-2010). This seem contrary to the finding of Yorke and Omotosho (2010); Paeth and Hense (2004); Owusu et al. (2008) where periods of declining annual rainfall totals are rather observed from the early 1970s to about 2000. Reviewing of these two information shows that, the disparities are as a result of different reference points or demarcations of the time series; 1961-1970 and 1971-2010 in the former studies as against 1961-1985 and 1986-2010 in the latter. Moreover, the trends in the latter were more pronounced with NCEP data than GMet. Meanwhile, a studies by Nkrumah et al. (2014) confirmed a consistent downward trend for the period 1960 to 2008 which showed an average decreasing rate of 2.3 mm per month (2.4 %) per decade. A study by Owusu et al. (2008) not only confirms this decreasing trend but also founds out that, the dry season has become longer. Apart from Accra which has a slight increase in the mean annual rainfall for the past three decades, there has been a decline in the rainfall at Navorongo (Savannah), Kumasi and Axim (Forest) (Logah et al., 2013). Many cities in Ghana are faced with hash socio-economic conditions because of this continuous reduction in rainfall (Owusu et al., 2008). The complex spatial variability from the coast to the north complicates the problem and makes adaptation and mitigation strategies difficult to implement (Nkrumah et al., 2014; Cooper et al., 2008).

2.2.2 Intra-seasonal and Seasonal Rainfall Variability in Ghana

Rainfall in Ghana also exhibits a higher zonal and seasonal variability (Manzanas et al., 2014). Effective determination of the variability of the rains would help climate scientists and meteorologists to come out with a seasonal forecast which would guide farmers in deciding when to start planting (Mensah, 2015).

One factor which affects seasonal rainfall variability of West Africa is the moisture fluxes in the Tropical North Atlantic Ocean. This has been a contributor to rainfall in the West African region especially in July. The length of the rainy season ranges from 1 to 2 months in the Savannah Zone (north of Ghana) and 4 to 5 months in the Transition to Coastal Zones (south of Ghana) (Mensah, 2015; Amekudzi et al., 2015; Nicholson and Grist, 2001).

Unlike the northern zone, stations in the southern part of Ghana have a lower rainfall amount in August that separates the two peaks. This accounts for one farming season in the Savannah Zone and two in the southern zones (Mensah, 2015; Aryee, 2015; Nkrumah et al., 2014).

From most local studies of rainfall variability and distributions in Ghana, intense dry spells are expected within the agricultural season (Owusu and Waylen, 2013; Adiku et al., 2007; New et al., 2001). The probability of experiencing a dry spell in the rainy season is higher in the south than in the north (Adiku et al., 2007; Gyau-Boakye and Tumbulto, 2000). This has been attributed to the lower SST and relatively high pressure system that exists over the coast during this period (Nkrumah et al., 2014; Adegoke and Lamptey, 2000).

Adiku et al. (2007) identified similar trends in the intra-seasonal variability in the rainfall of Accra in the south and Tamale in the north. Annual mean rainfall amounts between 1400 and 1900 mm is experienced in the south-western parts of the country, covering three regions: Western, parts of the central and Brong Ahafo regions (Logah et al., 2013). According to Anang (1977) annual mean higher rainfall amounts exceeding 1900 mm occurs in part of Ashanti and western regions with high rainfalls shifting to the westing part of the country.

Mawunya et al. (2011) also used a thirty year rainfall time series over the Volta region of Ghana to study the variation of seasonal rainfall with the ENSO phases and realised that, rainfall onsets during the La Niña and Neutral seasons occurred in March while that of El Niño occured in April. It was also revealed that, rainfall amounts during the MAM and JJA seasons decreased during the ENSO phases. The decreasing order was however reversed during the SON season. Rainfall variability trends during the MAM and JJA seasons were therefore found to be highest during El Niño years than Neutral years.

In relation to the variability of the onsets and cessations, Amekudzi et al. (2015) indicated that, the onset of the rains for the Coastal and Forest Zones fall between the 2nd and 3rd dekads of March and ceases between the 2nd and 3rd dekads of October. The onset of the Transition Zone, is from the third dekad of March to third dekad of April and also ceases from the second and third dekads of October. However, the Savannah Zone experiences a late onset between the 2nd dekad of April to the 1st dekad of May but ceases from the 3rd dekad of September to 1st dekad of October. In the Forest Zone, rainfall usually ceases from the 3rd and 1st dekads of October and November respectfully.

2.3 Time Frequency Analysis Techniques for Rainfall Variability

The purpose of frequency analysis is to devise a a means of extracting and estimating the frequency components of a signal which is not previously known. Harmonically, the frequency components of a time series can be determined using fourier series (Oduro-Afriyie and Adukpo, 2006). A signal can be presented in a different way that reveals its frequency components when the harmonic components of the signal are known. (Boashash, 2015).

2.3.1 The Fourier and Wavelet Transforms

The Fourier and Wavelet transform are mathematical techniques which are applied to a signal to obtain the frequency component of the signal since it is not readily available in the raw signal (Polikar, 1996). When a time domain signal is plotted, a time-amplitude representation of the signal which in not always the best representation of the signal is obtained. The most outstanding information is usually hidden in the frequency content of the signal (Vishwadhar and Lavanya, 2015; Polikar, 2001).

Although the Fourier Transform reveals the frequencies in a signal, it does not indicate where in time these frequencies occur (Polikar, 2001). That is the Fourier Transform only allows either a time domain or frequency domain information.

However most signals are non-stationary in nature that is, the frequency component of the signal changes in time. As a result, when a non-stationary signal is processed to view in the frequency domain, it becomes distorted. To solve this, non-stationary signals are made to assume stationarity by using the Windowed Fourier Transform (WFT).

The WFT is used for extracting local-frequency information from a signal (Torrence and Compo, 1998). With the WFT, the non-stationary signal is windowed or cut to a place in time transforming the signal into segmented stationary signals. That is using a defined window width, sliding it along in time and computing the FFT (Fast Fourier Transform) of the signal at each time by using the data within the window. The limitation of the WFT is the consistent treatment of different frequencies: for instance at low frequencies there are very few oscillations within the window which causes the frequency localization to be lost, while at high frequencies there are many oscillations that which causes the time localization to be lost (Santos and Freire, 2012; Kaiser, 1994). There is therefore the need for a method that will take care of both the time and frequency localization problem. Wavelet analysis solves these problems by decomposing a time series into a simultaneous time / frequency space. Thus providing information on both the amplitudes of the periodic signals in the series, and how these amplitudes changes with time (Zong et al., 2013). Wavelets are therefore capable of identifying irregularly distributed data as well as multi-scaled features in space and time of climate data (Mwale et al., 2004; Smith et al., 1998).

2.3.2 Fourier Analysis of Rainfall

Fourier Transforms provide a method for transforming infinite duration signals, both non-periodic and periodic, from the time domain into the continuous frequency domain (Murray, 2011).

It assumes that a natural times series data follows a normal distribution. It also assumes that, a climate signal is periodic and has a universal wavelength with its amplitude being the reflection of the local characteristics of a particular area (Baldazo et al., 2002). The performance of fourier series in the simulation of the seasonal rainfall variability of Malaysia was accessed by Norzaida et al. (2015). Fourier series was incorporated into a spatio-temporal stochastic model in order to make model parsimonious and also capture the yearly variation of rainfall distribution. The model was fitted at two regions with distinctive rainfall characteristics, one monsoonal and the other convective. Fourier series equations were used to represent the parameters of the model in order to describe their annual periodicity. The cumulative fraction of the explained variance by the significant harmonics were used to determine the significant harmonics for each parameter. The number of significant harmonics was found to be slightly higher for monsoonal rain and lower for convective rain.

Baldazo et al. (2002) used Fast Fourier Transform (FFT) in a model to forecast long term drought and flood events. The FFT model gave high correlation coefficients (92 to 99%) between the observed and predicted values indicating that FFT model is reliable in forecasting weather or giving climate advisory.

Another studies conducted by Olofintoye and Adeyemo (2012) in Ilorin, Nigeria, revealed that, Fourier series approximation model gives a better prediction of Ilorin rainfall than other parametric methods. In a similar studies, Jou et al. (2009) compared parametric density functions with Fourier series (nonparametric) in order to estimate the annual precipitation in Iran. It was confirmed that, Fourier series gives a better prediction of annual precipitation than the prediction by other parametric methods which are based on Mean Relative Deviation (MRD) and Mean Square Relative Deviation (MSRD). Fourier series can therefore be used as a better approach for rainfall frequency analysis.

In Ghana, very few rainfall frequency analysis have been done. An example is the studies by Oduro-Afriyie and Adukpo (2006) who used power spectrum analysis to investigate the periodicities of standardised annual mean rainfall in Ghana from 19611998. The most significant periodicity was 5.6 years followed by that of 2.7 years. However, as mentioned earlier, the above methods assume that climate data is stationary and linear which is not the case with a natural phenomena like the climate. Wavelet analysis therefore promises to be a better approach.

2.3.3 Wavelet Analysis

Wavelet analysis has become a tool for analysing local variations in power within a time series. This is achieved by decomposing a time series into a time-frequency domain. By wavelet analysis, one is able to determine both the dominant modes of variability of a time series and how they vary in time (Torrence and Compo, 1998).

Since it's theoretical development by Grossmann and Morlet (1984), wavelet analysis have been used for numerous studies in meteorology and climate as well as oceanography (Gamage and Blumen, 1993; Meyers et al., 1993; Weng and Lau, 1994; Gu and Philander, 1995; Wang and Wang, 1996; Baliunas et al., 1997). It has become an alternative for Fourier Transform in the preservation of local, non-periodic, multi-scaled phenomena. Wavelet Analysis is preferred by most scientists to classical spectra analysis because different scales of temporal variability can be analysed for non-stationary time series (Santos et al., 2001).

According to Torrence and Compo (1998) most previous studies on wavelet analysis such as Wang and Wang (1996) lacked a statistical significance test which had been the main reason for the diffused time-frequency image wavelet analysis had suffered from. The paper therefore introduced a new wavelet analysis toolkit which includes a statistical significance test. This has allowed a greater confidence in the previous wavelet analysis works. The wavelet analysis of Nino 3 sea surface temperature (SST), the Southern Oscillation Index and sea level pressure were also performed in the study.

2.3.3.1 Application of Wavelet Analysis in Rainfall variability studies

Wavelet Analysis has also been used for the studies of rainfall variability in many different parts of the world such as in Okonkwo (2014); Santos and Freire (2012); Ideião and Santos (2009); Xu et al. (2005); Dai et al. (2003); Santos et al. (2001). In the studies by Santos et al. (2001) wavelet analysis was applied to the monthly rainfall totals at Matsuyama city to analyse its variability. It was revealed that the total monthly rainfall of Matsuyama city is composed of a strong annual frequency. The annual periodicity was also confirmed by the global wavelet power spectrum which presents an unbiased and consistent estimation of the true power spectrum of the time series. It was therefore recommended that the variability of rainfall in non-stationary hyetographs should be described with the Global wavelet spectra. For regions that do not reveal long-term variation in hyetograph structures, the Global wavelet spectra have proved useful in summarizing the temporal variability of a region in comparison to the rainfall in other regions. It diagnosis hydro-climatic regimes effectively because a clear qualitative difference exists in the global wavelet spectra of hyetographs from different climatic regions.

Ideião and Santos (2009) also analysed the rainfall frequencies in the semiarid region of northeastern Brazil using Wavelet Transform. In the study, monthly rainfall totals were analysed using wavelet analysis over several places in northeastern Brazil and revealed and also showed a strong annual frequency. It was also realised from the studies that, although the global wavelet spectrum of two cities showed similar frequencies, their wavelet spectrum revealed different features.

In 2012, the rainfall of the urban centers in Northeastern Brazil was also analysed by Santos and Freire (2012) using the wavelet transform. The main frequencies were studied together with the modulation in the 8 – 16 month band which was the most significant frequency band. This was to help identify periods of high and low variance. Above normal rainfall periods, were identified in the average variance of some periods such as 1947 – 1952 at Tarisina city.

In Hebei Plain in North China, rainfall variation has also been studied using wavelet analysis. However, in this case both monthly and annual rainfall data were used to investigate the multi-times scales features of annual and seasonal rainfall. Periodic oscillations of 8 – 12 years and 4 – 6 years were found for both the seasonal and annual variation of rainfall. It was also found that, the most outstanding frequencies of the variation of the annual rainfall were 1 and 12 years which was identical to that of the summer; indicating that the variation of annual rainfall of the Hebei Plain is dominated by summer rains. It was therefore concluded that the wavelet analysis can be used as an alternate approach to multi-time scale analysis of climate and short term climate variation forecast (Xu et al., 2005).

In other studies such as Dai et al. (2003), wavelet transform was mainly used to analyze the multi-scale characteristics of summer rainfall and inter-decadal decaying of summer monsoon. The Wavelet analysis revealed that, the 5 year periodic spectrum of the inter-annual component of the rainfall disappeared suddenly during the later part of the 1960s, and its biennial oscillation weakened significantly since the 1970s, followed by the decaying of the summer monsoon.

2.3.3.2 Use of Wavelet Analysis for rainfall studies in the Tropics

The spatial, temporal and frequency variability and dominant oscillations of East African rainfall and sea surface temperature (SST) of the South Atlantic and Indian oceans were studied using wavelets, Wavelet Empirical Orthogonal Function Analysis (WEOF), and Wavelet Independent Component Analysis (WICA) of individual scale power and the Scaled Average wavelet Power (SAWP). The study revealed a strong annual and seasonal relationship between the sea surface temperature (SST) Scaled Average Wavelet Power (SAWP) of the Indian and the South Atlantic oceans and the rainfall of East Africa through a Wavelet Principal Component Analysis (WPCA) that was performed. This means that the predictability of East African rainfall based on the two oceans is possible (Mwale et al., 2004).

Also, in the Sahel region, the inter-annual and decadal to multi-decadal rainfall variability was examined using the wavelet transform and coherency analysis in order to locate the main climate index that correlates better to Sahel rainfall. It was revealed that, Sahel rainfall related to NAO, ENSO, Atlantic Multi-decadal Oscillation (AMO) and Indian Ocean Dipole (IOD) at different time scales. An antiphase relationship existed between ENSO and the rainfall of Sahel at the 3-4 year band which was localised at 1982 – 1983 El niño episode indicating a cause-effect relationship between the 1983 drought and the 1982 – 1983 El niño. The wavelet coherence analysis also revealed a relatively anti-phase relationship between AMO and Sahel rainfall. However the control of the IOD on Sahel rainfall variability was limited to the east (Okonkwo, 2014).

Finally, the mode of inter-annual rainfall onset and cessation variability over Ghana was carried out using wavelet analysis by Amekudzi et al. (2015). The main frequencies of variability of the onsets and cessations at the coastal and Forest Zones of Ghana were within the 2 – 8 and 2 – 4 year band, whiles the variability in the onset and cessation of the Savannah and Transition Zones were from 2 – 4 and 4 – 8 years.

CHAPTER 3

Data and Methodology

3.1 Study Area and Data Source

The study area is Ghana which is located between latitude 5°N and 11°N and longitude 4°W and 2°E. It shares a boundary with Togo in the East, Cote d'ivoire in the West, Burkina Fasso in the north and Gulf of Guinea in the south. The total area of land in Ghana is 238 540 km^2. It extends up to about 670 km northward from the ocean and about 560 km eastward from Cote d'ivoire. For the purpose of weather and climate application, the Ghana Meteorological Agency (GMet) has divided the country into 4 main agro-ecological zones (Amekudzi et al., 2015) see Figure 3.1. These are the Coastal, the Forest, the Transition and the Savannah Zones.

Climate of the study area

Ghana is characterised by the tropical climate which is strongly influenced by the monsoon. Rainfall in the country is associated with mesoscale convective system and controlled by the movement of moisture from the ocean to the lower atmosphere (Sultan and Janicot, 2003). The movement of the moisture is driven by the temperature and pressure gradients between the dry Sahara and the humid gulf. There are two main seasons in Ghana. They are the dry (Harmattan) and the wet (Monsoon) seasons. The Harmattan season usually starts from November and ends in March while the rainy season is usually from March to October. Two main rainfall regimes exists in the country. The northern part of the country experiences a unimodal rainfall whiles the southern part of the nation experiences a bimodal rainfall. The Forest and Transition Zones are the most dominant rainfall zones in the country while the Coastal Zone has lowest annual rainfall amount. Figure 3.1 shows the map of Ghana and all the agro-ecological zones.

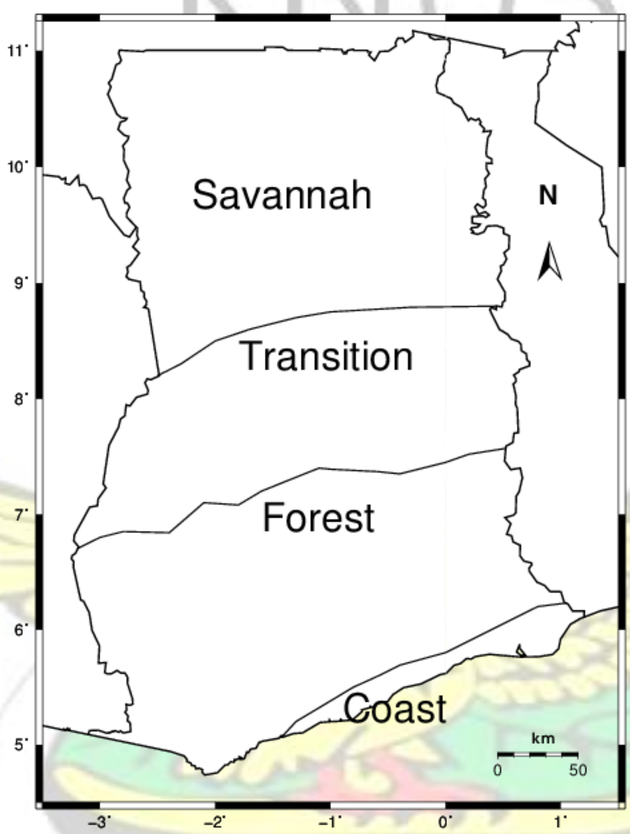


Figure 3.1: The map of Ghana showing all the agro-ecological zones.

3.1.1 Data Source

Monthly total rainfall data from the Global Precipitation Climatology Centre (GPCC) from 1901 – 2010 was extracted over all the agro-ecological zones of Ghana. The resolution of the GPCC data was 0.5° × 0.5°. GPCC Data are monthly rainfall data from the Global Precipitation Climatology Centre which is calculated from global station data. It is made up of three datasets: The first one is the monitoring product for the period 2007 to present which is based on quality controlled data from 2007 to present. The second one is the full monthly data product from 1901 – 2010, also based on quality controlled data from 67200 stations around the world that feature record duration of 10 years or longer. Precipitation anomalies at the stations are interpolated and superimposed on the GPCC climatology V2011 in the corresponding resolution. The last one is the first guess which is most up to date but has less analysed stations. The GPCC data was first validated with GMet gridded data before the analysis was carried out.

The GMet data used for the validation is a gridded data by Aryee (2015), collected from a total of 113 stations which include all the synoptic, climatological and agrometeorological stations in Ghana. It was collected over a period of 33 years (1980 2012). The data was first reconstructed using the Regularized Expectation Maximization (RegEM) algorithm described in Schneider (2001) to estimate all missing data. It was then homogenized using the Quantile Matching Adjustments (QMadj). The resulting data is then gridded at a resolution of $0.5^\circ \times 0.5^\circ$ by the Minimum Surface

Curvature (MSC) with a tension parameter.

3.2 Methods

Monthly rainfall and annual rainfall totals were used for the monthly, inter-annual and inter-decadal rainfall variability. The Pearson Correlation coefficient, the Relative

Mean Difference (RMD) and the Relative Root Mean Square Error (RRMSE) was first used to validate the GPCC data with GMet gridded data. To demonstrate the trend in the variation, a linear regression analysis was also performed on each rainfall time series and Mann Kendal test used to detect significant trends. Yearly anomalies of the monthly rainfall are also calculated to eliminate seasonal variation influences in contrast with wavelet analysis. Wavelet analysis was then performed on the data to detect the rainfall frequencies in each zone.

3.2.1 Validation

The GPCC data is first compared to GMet gridded data in order to determine the reliability of the data. The following statistical data analysis tools that have been used for validation in works such as Amekudzi et al. (2008); Quansah et al. (2014); Aryee (2015) is employed:

Relative Mean Difference (RMD):

$$Mean\ Difference\ (M.D) = \frac{1}{N^2} \sum_{i=1}^{N} |x_i - y_i| \tag{3.1}$$

$$R.M.D = \frac{M.D}{arithmetic\ mean\ (\mu_x)} \tag{3.2}$$

Pearson's Correlation Co-efficient:

$$r_{xy} = \frac{\sum_{i=1}^{N}(x_i - \mu_x)\,(y_i - \mu_y)}{(N-1)\ std_x std_y} \tag{3.3}$$

Relative Root Mean Square Error (RRMSE):

$$RRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x-y)^2}}{\mu_x} \quad (3.4)$$

where x is the GPCC data, y is the GMet gridded data, μ is the arithmetic mean, std is the standard deviation and r_{xy} is the Pearson Correlation Coefficient (r ∈ -1,1).

3.2.2 Mann-Kendall Trend Analysis

The Mann-Kendall trend analysis was carried out on the data to determine the variability in the annual and seasonal trends for the various agro-ecological zones. This trend test is a robust and a very reliable method which has been used for the testing of randomness against trend in climatology and hydrology (Partal and Kahya, 2006). It is preferred in this study because of its low sensitivity to the effects of outliers. Given a time series of length $x_i, i = 1,\ldots,n$, Mann (1945) proposed the use of the Kendall rank correlation of x_i for $i = 1,\ldots,n$ for monotonic trend testing. The null hypothesis H_0 of no trend assumes that, the data $(x_1,\ldots,x_n)$ are a sample of n independent and identically distributed random variables. The alternative hypothesis H_1 of a two-sided test is that there exit trend in the dataset. Thus the distributions of x_k and x_j are not identical for all $k, j \leq n$ with $k6{=}j$. The test statistics S, which has mean zero and a variance given by Equation 3.7, is calculated using Equations 3.5 and 3.6 and is asymptotically normal (Hirsch and Slack, 1984):

$n-1 \quad n$

$$S = \sum_{k=1} \sum_{j=k+1} sgn(z_j - z_k) \tag{3.5}$$

where z_j and x_k are the sequential precipitation values

$$sgn(z_j - z_k) = \begin{cases} 1 & \text{if } z_j - z_k > 0, \\ 0 & \text{if } z_j - z_k = 0, \\ -1 & \text{if } z_j - z_k < 0. \end{cases} \tag{3.6}$$

$$Var(S) = \frac{1}{18}[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)] \tag{3.7}$$

where n is the number of data points, q is the number of tied groups, t_p is the number of data values in the p^{th} group. In situations where the sample size $n > 10$, the standard normal variate z is computed using Equation 3.8 (Douglas et al., 2000). H_0 is accepted if $|\ z\ | \leq \frac{z\alpha}{2}$ at the α significance level. A positive value of S indicates an increasing trend and similarly, a negative value of S indicates a decreasing trend. A normalized test statistic (or z score) is used to check for the statistical significant of S given as

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \tag{3.8}$$

3.2.3 The Wavelet Transform

In the wavelet transform, a time series is compared to a mother wavelet function ($\psi(\eta)$) and the variation of their amplitude with time is plotted to extract regions of strong concentration of power. The mother wavelet is a function that satisfies the admissibility condition. There are different types of mother wavelets: Paul, Gaussian and Morlet. However in this study, the morlet wavelet is used because of its localization in time and frequency and has been widely used for most studies of climate data (Grinsted et al., 2004; Santos et al., 2001; Mwale et al., 2004). The morlet wavelet is simply a convolution of a complex exponential wave and a Gaussian envelope:

$$\psi(\eta) = \pi^{-\frac{1}{4}} e^{iw_0\eta} e^{-\frac{\eta^2}{2}} \tag{3.9}$$

Where ψ is the wave value of non-dimensional time η , w_0 is the non dimensional frequency of the mother wavelet.

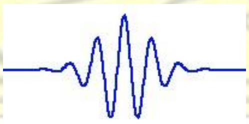


Figure 3.2: The Morlet wavelet function

First the wavenumber w_0, which gives the number of oscillations (frequency) within the wavelet itself is chosen. A dilation parameter s and a translation parameter n are then introduced to vary the wavelet scale as well as slide in time respectively. The scaled wavelet therefore becomes:

$$\psi(\eta) \approx \psi\left[\frac{(n-n\prime)\delta t}{s}\right]$$

31 (3.10)

The Wavelet Transform $W_n(s)$ is finally obtained by performing a convolution or an inner product of the above wavelet function with the original time seriesx_n:

$$W_n(s) = \sum_{n\prime=0}^{N-1} x_n \psi * \left[\frac{(n-n\prime)\delta t}{s}\right] \tag{3.11}$$

Where δt is the time interval between the time series and the $(*)$ denotes a complex conjugate.

A new time series of the projection amplitude versus time is now constructed by sliding the wavelet along the time series. The wavelet scale is also varied to construct for each scale.

Finally, a two-dimensional image is constructed by plotting the wavelet amplitude and phase.

3.2.3.1 Choice of Scales

The next thing after choosing the wavelet function is to determine a set of scales s to be used in the wavelet transform. For an orthogonal wavelet, an arbitrary discrete set of scales are used. The scales are written as fractional powers of two:

$$s_j = s_0 2_j \delta_j \tag{3.12}$$

$$j = 0,1,2,\ldots J \tag{3.13}$$

Where δ_j is the spacing between successive scales. Therefore the smaller the value, the finer the resolution.

$$J = d_j^{-1} \log_2 \left(\frac{Ndt}{s_0} \right) \quad (3.14)$$

where s_0 is the basic wavelet scale which is chosen such that all the frequencies in our time series are adequately sampled. Therefore, the s_0 is chosen such that the approximate fourier period is $2\delta t$. And J determines the largest scale. A very small value is chosen for δ_j based on the width of the wavelet function. A δ_j of 0.5 is the largest value required to provide adequate sampling in scale for the morlet wavelet.

In this study, the parameters of the wavelet scales for the monthly rainfall variability were set as follows: δt = 1 month, s_0 = 2 months since $s = 2\delta t$, $\delta j = 0.25$ in order to do 4 sub-octaves per octave. And $j_1 = 7/\delta j$ in order to do 7 powers of 2 with δj sub octaves each.

3.2.3.2 Cone of influence

Errors occur at both the beginning and the end of the wavelet power spectrum whenever a finite length time series is used since the Fourier Transform assumes that the data is cyclic (Torrence and Compo, 1998). The time series is therefore padded with sufficient zeros before applying the wavelet transform in order to limit the edge effects and speed up the Fourier Transform. However, padding with zeros reduces the amplitudes near the edges as it approaches larger scales.

The Cone of influence is therefore the portion of the wavelet power spectrum where edge effects becomes relevant and this is identified in the cross hatched region in the wavelet spectrum. It indicates the e-folding time for the autocorrelation of wavelet power in scale. The e-folding time is chosen such that the wavelet power at the edge drops by a factor e^{-2} to ensure a negligible edge effect.

3.2.3.3 The background spectrum and significant levels

Most geophysical series is modeled as either red or white noise. Torrence and Compo (1998) provided a formula for red noise on the distribution of fourier spectrum. This has since been the foundation of significance test in fourier analysis of climate signals (Zhang and Moore, 2011).

The simple model is the univariate lag-1 autoregressive (Markov) process. The lag one measures the persistence of an anomaly from one unit of a time series (month or year) to the next. The true lag-1 is computed as follows:

$$\alpha = \frac{\alpha_1 + \alpha_2^{1/2}}{2} \tag{3.15}$$

where α_1 and α_2 are the lag-1 and -2 autocorrelations respectively. Setting lag-2 to zero gives the model for white noise.

Now assuming a mean power spectrum, the null hypothesis for the wavelet power spectrum is defined as follows: if a time series is significantly above the mean power spectrum, then it is considered as a true feature at 95% confidence level.

3.2.3.4 Integration of power and averaging within a scale

To provide a simple and robust way of describing the variability of the time series, the wavelet power is integrated with time to obtain the global wavelet power. And this is given as:

$$\overline{W}^2(s) = \frac{1}{N}\sum_{n=0}^{N-1}|W_n(s)|^2 \tag{3.16}$$

The Global Wavelet Power provides a consistent and unbiased estimation of the true power spectrum of the time series. It is therefore very suitable for describing the variability of rainfall in non-stationary hyetographs.

The fluctuations in wavelet power over the range of scales where the significant frequencies are detected is then examined using the Scale Average Wavelet Power. This is the average wavelet power spectrum from scales s_1 to s_2 as shown:

$$\overline{W}_n^2 = \frac{\delta j \delta t}{C_\delta}\sum_{j=j_1}^{j_2}\frac{|W_n(s_j)|^2}{s_j} \tag{3.17}$$

In the present study, the scale averaged wavelet power is used to present the fluctuations in power over the most significant frequency band that is obtained from the Global wavelet power spectrum.

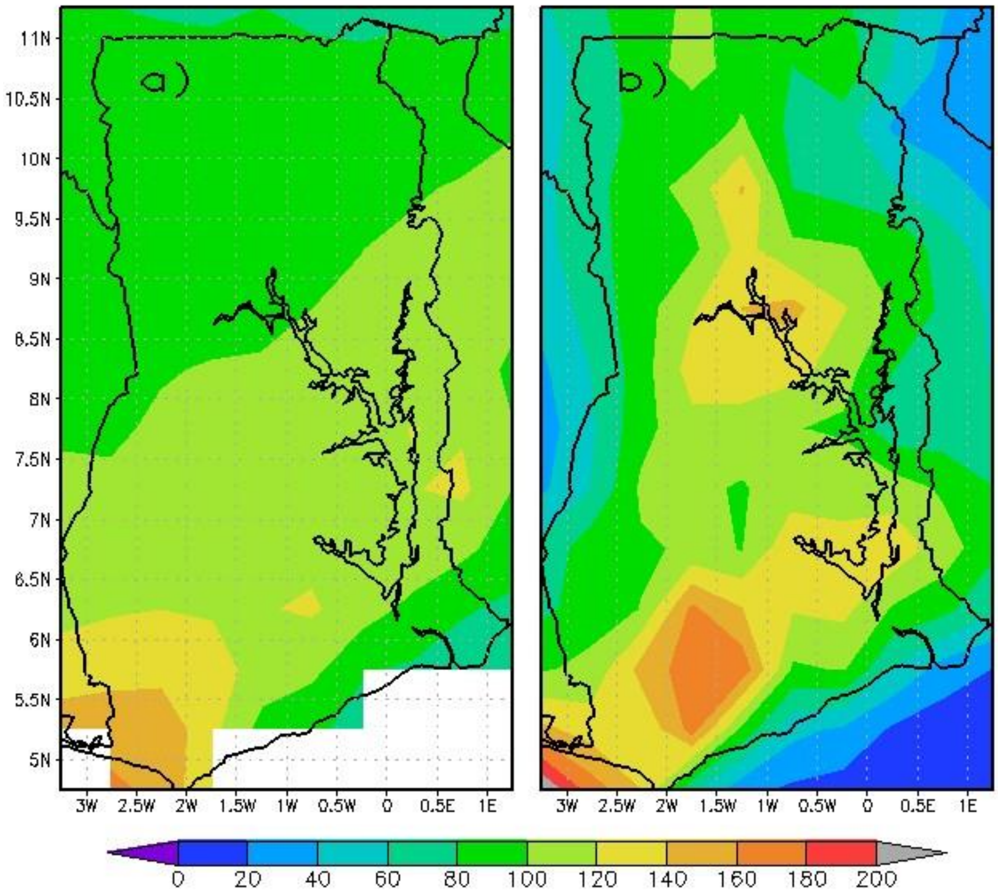
CHAPTER 4

Results: analysis and discussion

4.1 Validation of GPCC data with GMet gridded data

The GPCC data was first compared and validated with GMet gridded data for the period 1980 - 2010. It has been established that, gauge data gives a better representation of the rainfall over the region than satellite-gauge merge products, satellite derived data and reanalysis products (Manzanas et al., 2014). GMet provides quite a good amount of gauge data over the country. The data however does not cover time scales longer enough for an inter-decadal variability study as compared to GPCC data. In the study by Manzanas et al. (2014), GPCC data was found among other guage based products to give the best correlation with GMet data. That validation was however performed using only fourteen gauges from meteorological stations in Ghana instead of a gridded data. With the current availability of GMet gridded data by Aryee (2015) which was computed using 113 stations, it has become necessary to compare the two gridded data sets to ensure the reliability of the GPCC data which is to be used in this study. The comparison between GMet gridded data and GPCC data is presented and discussed below in this section.

Figure 4.1: Comparison of GPCC and GMet data from 1980-2010. In Fig. 4.1a, the Multiyear mean of monthly rainfall totals (mm) over Ghana for GPCC. Fig. 4.1b shows the Multiyear mean of monthly rainfall totals (mm) over Ghana for GMet.



From Figure 4.1 a good agreement is found between the GPCC and GMet gridded data with very few of the regions showing significant disparity. Apart from some regions along the Volta lake and some parts of the southern forest where GPCC underestimated GMet data, most of the regions had close rainfall values which fall between 80 120 mm. To confirm this agreement, the Pearson's Correlation Coefficient (r), Relative Mean Difference (RMD) and the Relative Root Mean Squared Error (RRMSE) were computed.

Pearson's Correlation Coefficient (r)

The Pearson's correlation coefficient was computed between the two datasets over the entire country in order to determine the strength of the association between them (see Figure 4.2).

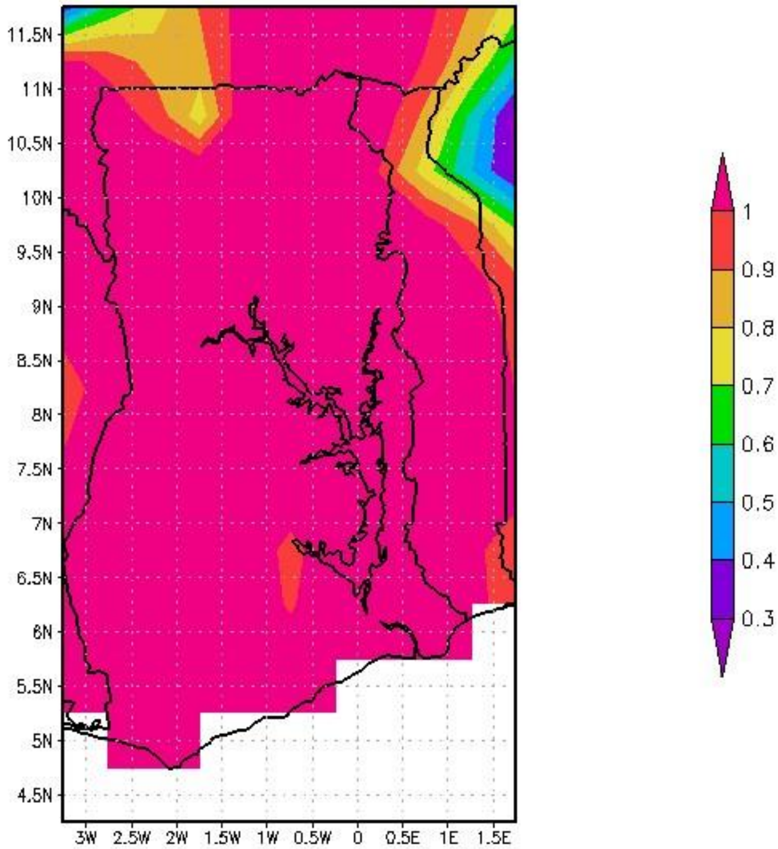


Figure 4.2: Pearson's correlation coefficient (r) between GPCC and Gmet data from 1980-2010.

A high correlation coefficient of 0.9 to 1 was obtained all over the country except for some small portion of the upper west region which gave correlation coefficients between 0.7 - 0.9 (Figure 4.2). This results indicate a strong association between the two data sets. It however does not give the difference between the two data sets. To obtain this difference, the RMD is also computed.

Relative Mean Difference (RMD)

Relative Mean Difference was also used to compute the magnitude of the variation between the GPCC data and the GMet gridded data. The RMD is the ratio of the Mean Difference (MD) to the arithmetic mean (see equation 3.2). The MD is first computed by finding the sum of the absolute difference between the data sets for each grid and then diving by the size of the mean as stated in equation 3.1. The results are shown in Figure 4.3.

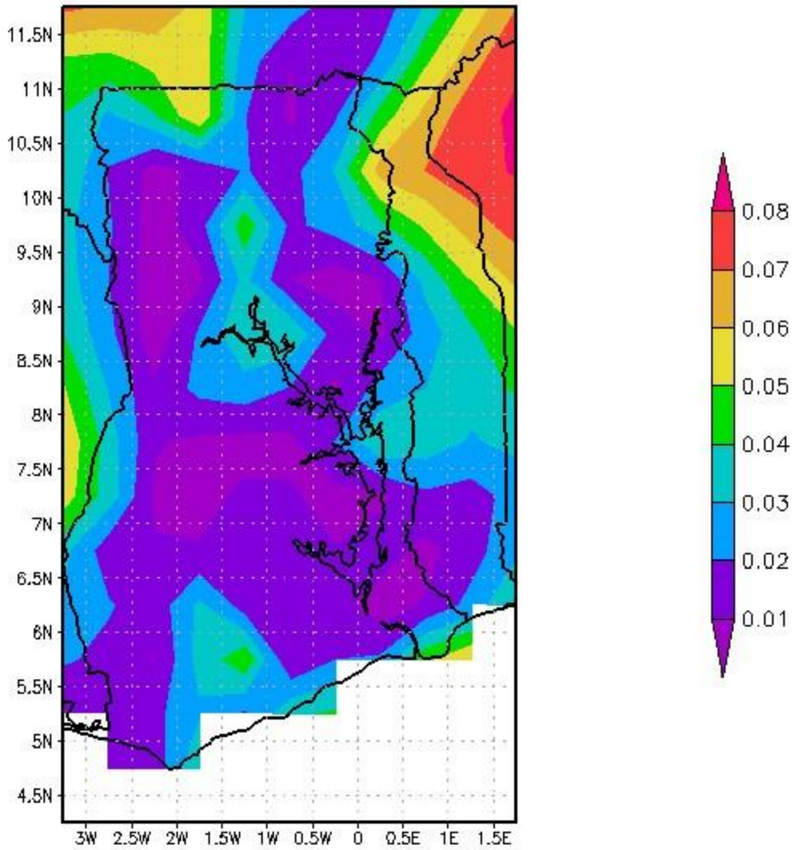


Figure 4.3: Relative Mean Difference between GPCC and GMet data from 1980-2010.

Low RMD values of 0.00 - 0.04 were recorded all over Ghana except for very small portions of the north and the forest where values between 0.04 - 0.05 were recorded (Figure 4.3). This indicates a minimal variation between GPCC and GMet gridded data.

Relative Root Mean Squared Error (RRMSE)

Finally, the RRMSE was computed to confirm the results of the Pearson Correla-

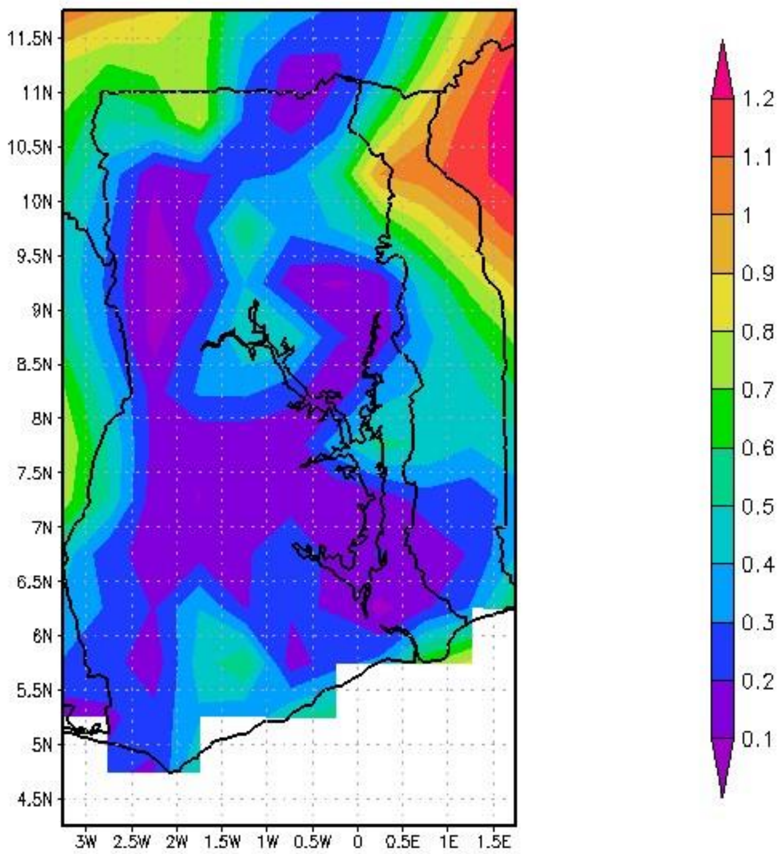


Figure 4.4: Relative root mean squared error between GPCC and GMet data from 1980-2010.

tion and the RMD. The RRMSE is the Root Mean Squared Error (RMSE) normalized by the arithmetic mean of the data (see equation 3.4). The results indicate very low RRMSE values of < 0.5 identified in most grids over the country confirming the good correlation between the GPCC data and the GMet gridded data (see Figure 4.4).

The results of the Pearson Correlation, the RMD and the RRMSE indicates a good agreement between GPCC data and the GMet gridded data. The data is therefore reliable for use in climate variability studies over the country hence the choice of

GPCC data for this studies. It is therefore recommended for long time scale (inter-decadal) studies of rainfall variability over Ghana.

4.2 Mean annual rainfall total over Ghana

The mean annual rainfall total over Ghana was computed using the GPCC data by first finding the annual totals of the data and then calculating the mean of the annual totals for each grid. The results are shown in Figure 4.5.

It can be observed from the figure that, high cumulative rainfall amounts ranging

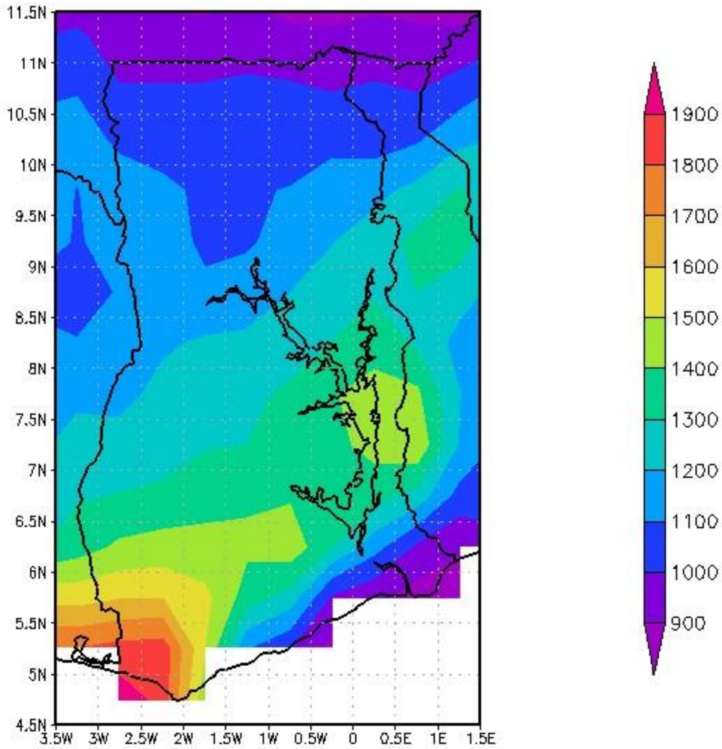


Figure 4.5: Mean annual total rainfall (mm) over Ghana for the period 1901-2010.

from 900 - 1900 mm are recorded over the the entire nation per year. Very high rainfall amounts between 1500 - 1900 mm are recorded at the south-western part of the country. Low rainfall values between 900 - 1200 mm are however recorded in the Savannah and the east coast of the country with lowest values of less than 900 mm found at the far east coast of the country. An interesting higher rainfall values between 1500 and 1600 mm is seen on the Volta indicating the significant local hydro-climatic contribution from the basin. These results confirm the findings of Logah et al. (2013); Anang (1977).

4.3 Inter-annual Variability of Rainfall over Ghana

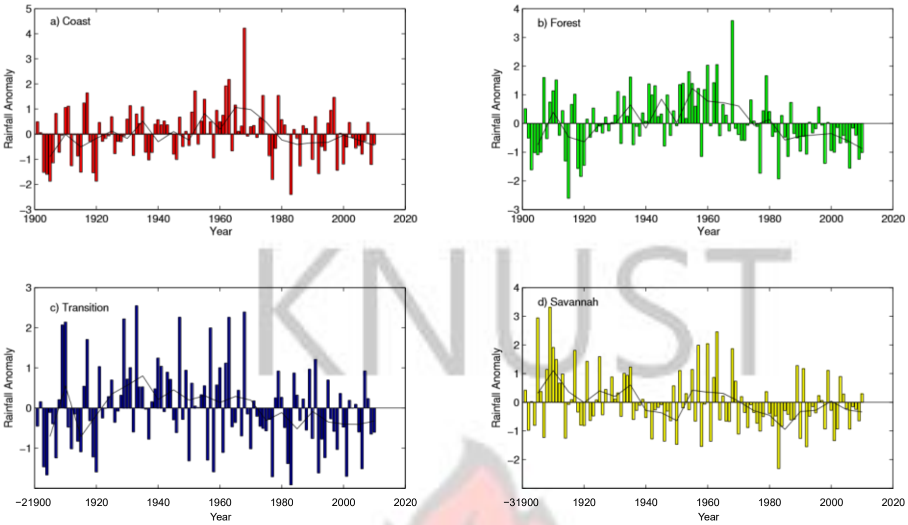


Figure 4.6: Inter-annual rainfall anomaly (bar) with a five year moving average (line) for the agro-ecological zones of Ghana from 1901-2010.

The inter-annual rainfall variability was investigated by using the standardized rainfall anomaly as described in Wilks (1995); Manzanas et al. (2014) instead of the the actual rainfall amounts due to the different zones and different precipitation amounts. Below normal rainfall was observed from Figure 4.6 in almost all the the agro-ecological zones between 1901 - 1905, 1908 - 1920, and 1980 - 2010 while above normal rainfall was found between 1950 - 1980 in almost all the agro-ecological zones. To simplify the inter-annual variation, a five year moving average was computed for all the agroecological zones.

From the 5 year moving averages, it can be seen in Figure 4.6 that below normal rainfall dominates the period 1901 - 1920 and 1980 - 2010 for all the agro-ecological zones except for the Savannah Zone where the period 1901 - 2010 is dominated by above normal rainfall values. On the other hand the period between between 1920 - 1980 is dominated by above normal rainfall values for all the zones especially the Transition Zone. The Savannah Zone however shows inconsistent above normal rainfall values for this period with below normal rains being recorded between 1940 - 1970.

The effects of the ENSO on the region as indicated by Sultan et al. (2000) can also be seen in all the agro-ecological zones around 1972 - 1973, 1982 - 1983, 1997 - 1998 where very strong El Niño episodes were recorded (Lee and McPhaden, 2010). The effects of the very strong La Niña episodes of 1973 - 1974, 1975 - 1976 and 1988 - 1989 is also seen in all the zones except for the Transition and Savannah where the effects of the 1973 - 1976 La Niña is not seen. Although the 1997 - 1998 El Niño was reported to be stronger than the 1982 - 1983 (Lee and McPhaden, 2010), the effect on the former was not as pronounced as the latter because of the strong La Niña that followed the

former.

The results of the inter-annual variability and the 5 year moving average also indicates a recent decrease in annual rainfall amount as stated by Yorke and Omotosho (2010); Paeth and Hense (2004); Owusu et al. (2008). The recent decrease in rainfall amount since the 70s might have been contributed by the very strong El Niño episodes mentioned above as well as the strong 1987 - 1988 and 2009 - 2010 El Niño (see Figure D.1). This is however opposed to the rising trend reported by Manzanas et al. (2014) when the National Centers for Environmental Prediction (NCEP v1) data was used.

4.4 Inter-seasonal rainfall variability over Ghana

The seasonal mean rainfall over Ghana was determined by first splitting the data into seasons. The seasonal averages were then computed for each grid and the values displayed by the Grid Analysis and Display System (GrADS). The results are shown in Figure 4.7.

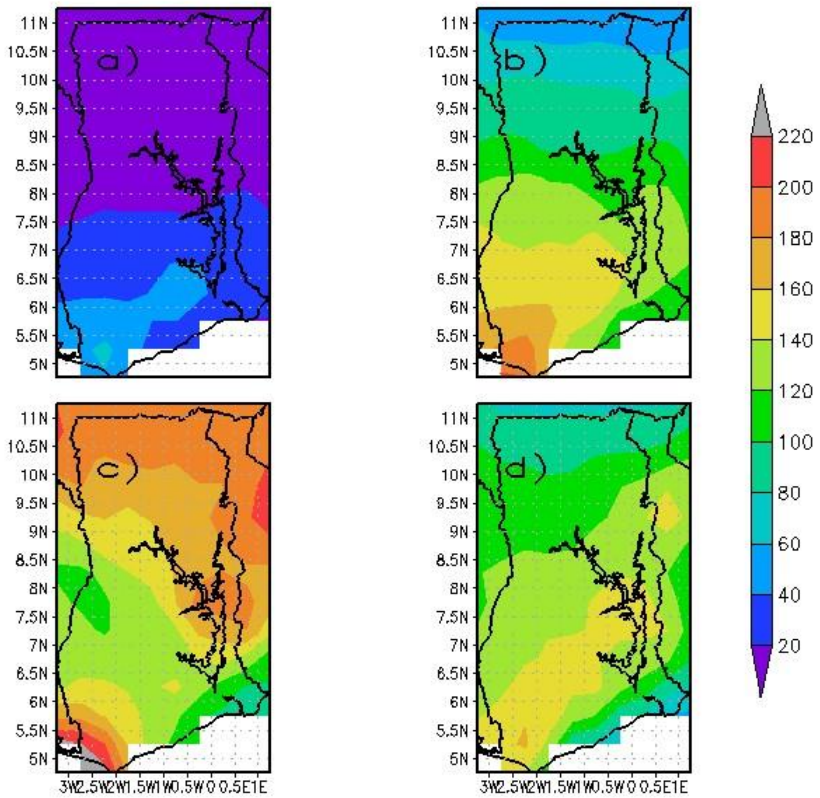


Figure 4.7: Seasonal mean rainfall (mm) over Ghana for a) DJF b) MAM c) JJA d) SON during the 1901-2010 period.

The December-January-February (DJF) season happens to be the season with the lowest rainfall amount nationwide. The maximum amount of rainfall expected within this period is about 90 mm located at the southwestern part of the country (Figure 4.7a). The remaining parts of the south has rainfall values ranging from 20 - 80 mm.

The Savannah Zone and the upper parts of the Transition Zones however record the lowest rainfall amount of < 20 mm during this season. During this season, the Azores high pressure system located at about 30 ∘ N of the Atlantic intensifies while the the St Helena (25 ∘ S South Atlantic) relaxes. This results in the dry North-East trade winds dominating over the entire country hence pushing the ITD southwards beyond the country. The whole country therefore experiences the dry and hazy conditions known as Harmattan during this period (Walker, 1958; Prospero and Carlson, 1981; Amekudzi et al., 2015).

The March-April-May (MAM) season happens to be the rainfall onset period for most parts of the country. Rainfall values begin to increase from about 60 mm in the north to as high as 200 mm in the south, especially towards the southwestern part of the country. This is shown in Figure 4.7b) and can also be found in (Aryee, 2015; Mensah, 2015).

During this period, the Azores high pressure system begins to weaken as the St Helena high pressure system starts intensifying. The south-west monsoon winds begins to prevail over the north-east trade winds. As a result, the ITD rises from its southern position and starts it's migration towards the north. It begins to carry with it, moisture which dominates over the southern part of the country (Lamb, 1978; Leroux, 2001; Amekudzi et al., 2015).

The June-July-August season happens to be the wettest season all over the nation. Very high rainfall amounts that ranges from about 90 to over 220 mm are recorded all over the nation. The west coast continues to be the wettest with rainfall amounts ranging from 160 to over 200 mm. The Savannah Zone interestingly records high values between 160 and 200 mm during this period. The local hydro-climatic effect of the Volta basin is significantly seen around Kete Krachi (7.8 ° N and 0.02 ° W) in this period with rainfall values between 180 - 200 mm (Figure 4.7c) (Aryee, 2015; Mensah, 2015).

Around this period, the strength of the St. Helena High pressure system would have intensified (Leroux, 2001). Moisture laden South West Monsoon winds dominates the country and hence pushing the ITD further north over the country. This results in a continuous and consistent rainfall experienced all over the country.

The September-October-November season is known as the minor rainy season for the southern part of Ghana. Rainfall amounts vary between 100 and 180 mm for the southern and the lower portions of the north. The lower upper parts of the north and the east coastal regions however experience a relatively lower rainfall between 40 and 100 mm (Figure 4.7d). During this season, the St. Helena High pressure system begins to weaken. The strength of the Monsoon winds therefore begins to weaken. The ITD begins to return and hence resulting in this minor rainy season (Aryee, 2015; Mensah, 2015).

4.4.1 Summary of seasonal variation

The summary of the seasonal variation in rainfall is presented in Figure 4.8. The Coastal Zone records lowest mean rainfall values for all the seasons with the highest of about 117 mm recorded in MAM. The Forest Zone on the other hand records very high rainfall values for all the seasons with the highest of about 174 mm recorded in JJA followed by about 165 mm in MAM. The Transition Zone however records almost similar rainfall values (varying between 120 and 150 mm) for all the seasons except for DJF where a lower mean value of about 21 mm is recorded. The Savannah Zone

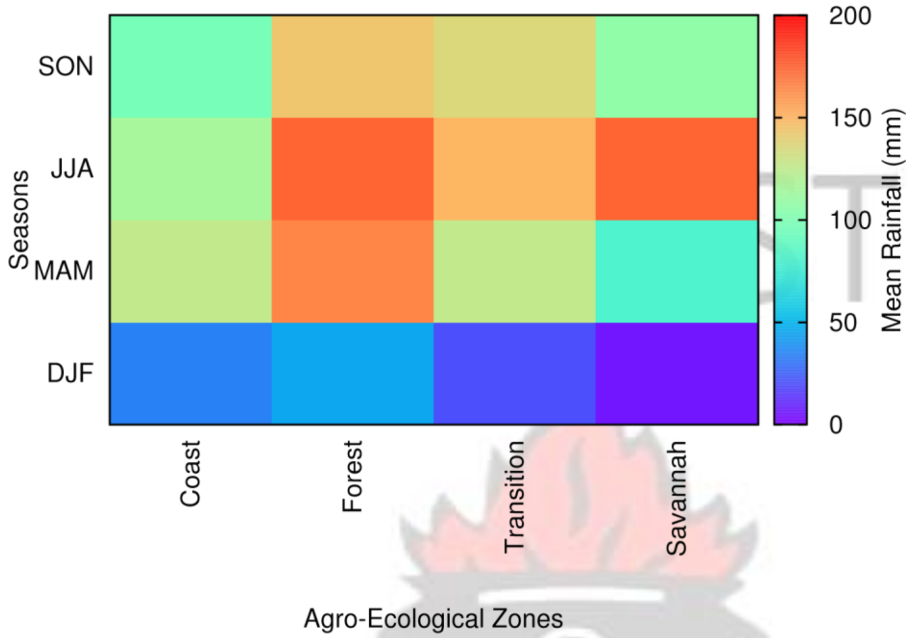


Figure 4.8: Seasonal mean rainfall amounts over the agro-ecological zones of Ghana.

records the lowest mean rainfall amount of about 6 mm in the DJF season. High mean rainfall amount of about 174 mm is however recorded in this zone during the JJA season which is interestingly the same amount recorded in the Forest Zone. However, the former has most of its rains from July and August while the latter has most of its rain contributed by the month of June. This shows the potential for extreme rainfall events in this Zone during the JJA season.

4.5 Inter-decadal variability of rainfall over Ghana

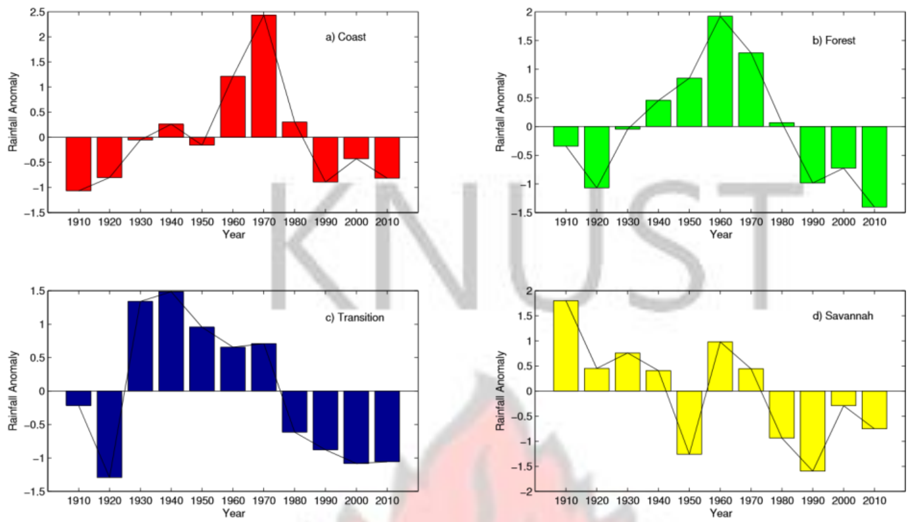


Figure 4.9: Inter-decadal anomaly of rainfall over the agro-ecological zones of Ghana.

The inter-decadal variability was also studied by using the standardized anomaly instead of the actual rainfall amounts for the same reason as mentioned earlier.

The results indicate below normal rainfall amounts observed between the 1901 - 1920 and 1980 - 2010 periods for all the agro-ecological zones except for the Savannah which shows above normal rainfall values within the 1901 - 1940 period (Figure 4.9). Likewise, above normal rainfall values are recorded between 1930 - 1980 for all the agro-ecological zones. The Savannah Zone however shows a break at around 1950 where a significant lower than normal rainfall value is recorded.

The effects of the ENSO on the region as mentioned in section 4.3 can be seen around 1970, 1980 and 2000 (Sultan et al., 2000; Lee and McPhaden, 2010).

The results of both the 5 year moving average and the inter-decadal anomaly confirm that rainfall amount is significantly decreasing even in the Transition Zone which is the food hub of the country. This decreasing trends will have serious consequences on agricultural production and food security.

4.6 Trend Analysis

4.6.1 Inter-annual Trend analysis

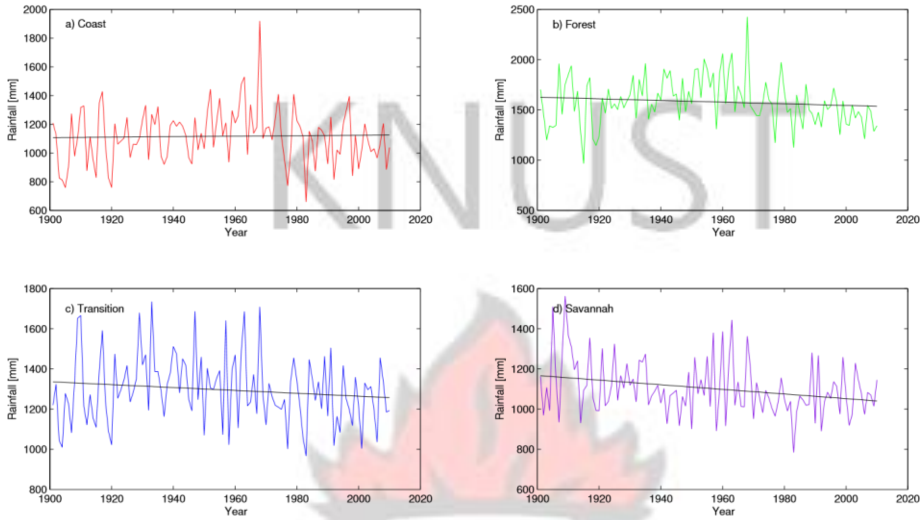


Figure 4.10: Trend analysis for the agro-ecological zones of Ghana.

In general a decreasing trend is observed in Figure 4.10 for the inter-annual rainfall over all the agro-ecological zones except for the Coastal Zone where a slight rise in trend of 0.1600 mm per year is seen. The trend in the Forest, Transition and Savannah changes at rates of -0.8300, -0.7200, -1.1500 mm per year respectively. However it is only the trends in the Savannah and the Forest Zones that were significant at the 99% and 90% confidence level respectively using the Mann Kendall Trend test. These decreasing trends might have been caused by anthropogenic factors such as deforestation and urbanization which have resulted in Urban Heat Islands (UHI) and hence increasing the warming and minimizing the atmospheric moisture in the region

(Allen and Barnes, 1985). The decreasing trends may pose a serious threat to agricultural production and food security.

4.6.2 Seasonal Trend Analysis

4.6.2.1 Trend Analysis for the DJF Season

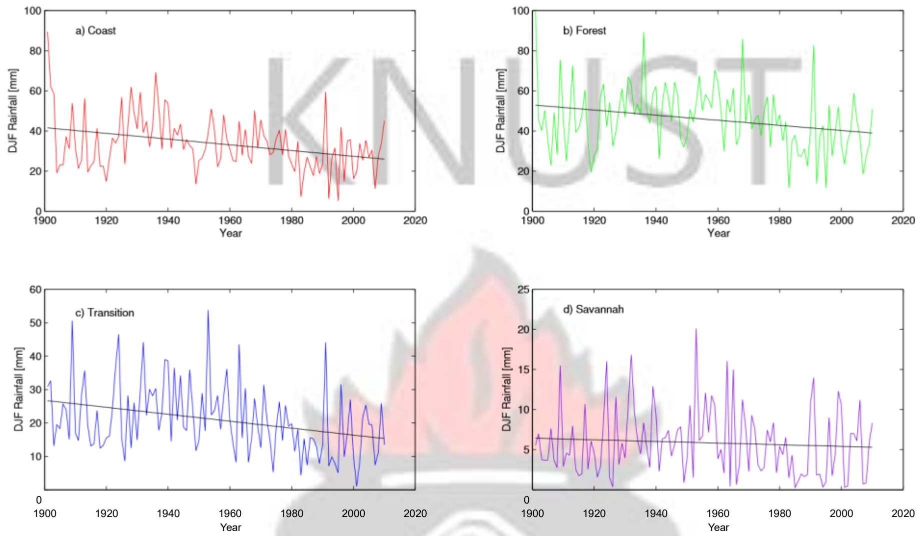


Figure 4.11: Seasonal Rainfall Trends over the agro-ecological zones of Ghana for DJF.

From Figure 4.11 a decreasing trend is observed over all the agro-ecological zones for the DJF season. The trend is more pronounced in the Coastal (-0.1429 mm per year), Forest (-0.1273 mm per year), and Transition Zones (-0.1040 mm per year) than in the Savannah Zone (-0.0102 mm per year). All the trends were shown to be significant in this season at 99% confidence level using the Mann Kendall Trend Test except for the Savannah Zone which shows no significant trends at the 90, 95 and 99% confidence levels. These findings are consistent with the observed trends from Manzanas et al. (2014).

The amount of rainfall that is recorded during the DJF season is significantly decreasing in almost all the agro-ecological zones. Although no significant decreasing trend is seen in the Savannah Zone during this season, the mean rainfall amount recorded in the zone is very small (< 7 mm). This result indicates an intensification of the Harmattan season. This might have been caused by global teleconections such as the ENSO and NAO as well as local factors such as land degradation and bush burning by farmers since most land preparation is done during this period (Mensah, 2015).

4.6.2.2 Trend Analysis for the MAM Season

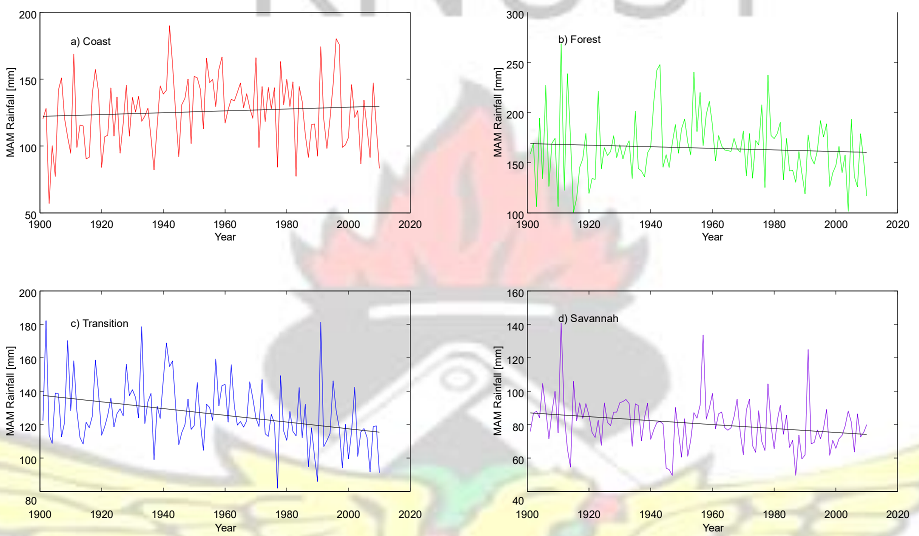


Figure 4.12: Seasonal Rainfall Trends over the agro-ecological zones of Ghana for MAM.

From Figure 4.12, the decreasing trend observed in the DJF season continues to persist for the Transition (-0.2016 mm per year), Savannah (-0.1181 mm per year) and Forest Zones (-0.0793 mm per year) for the MAM season but however weaker in the latter. The Coastal Zone interestingly shows a slight increasing tread of 0.0692 mm per year in this season. Only the trends in the Transition and Savannah Zones were indicated as significant at the 99% confidence level.

4.6.2.3 Trend Analysis for the JJA Season

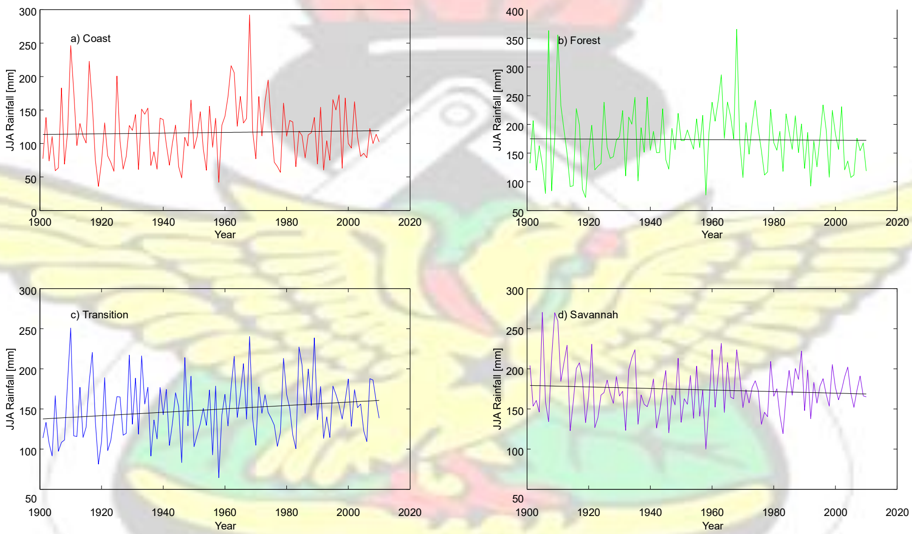


Figure 4.13: Seasonal Rainfall Trends over the agro-ecological zones of Ghana for JJA.

The JJA season shows interesting trends for different agro-ecological zones. The trend rises in the Transition Zone (0.2112 mm per year) but almost stays constant in the Coast (0.0510 mm per year), Forest (-0.0242 mm per year) and Savannah Zones. There is however a slight decreasing trend (-0.0972 mm per year) in the latter. Only the trend in the Transition Zone was indicated as significant at the 95% confidence level. This was however not significant at the 99% confidence level.

4.6.2.4 Trend Analysis for the SON Season

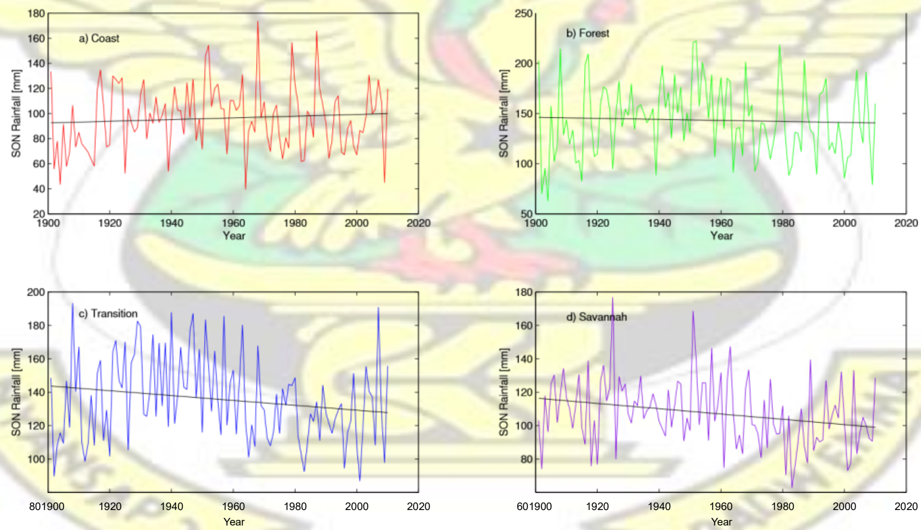


Figure 4.14: Seasonal Rainfall Trends over the agro-ecological zones of Ghana for SON.

The SON season however displays varying trends for the various agro-ecological zones (Figure 4.14). There was a decreasing trend in the Transition (-0.1460 mm per year) and Savannah (-0.1582 mm per year) Zones which were shown to be significant at the 95% confidence level. However, only the trend in the Savannah Zone remained significant at the 99% confidence level. A little rising trend at the Coast (0.0677 mm per year) and an almost stable trend at the Forest (-0.0512 mm per year) which were however insignificant at the 90% confidence level.

4.6.2.5 Summary of seasonal trend analysis

Table 4.1: Seasonal rainfall trend rate in the four agro-ecological zones (** and * indicates significant trends at 99% and 95% confidence levels respectively).

Season	Rainfall Trend Rate (mm per year)			
	Coast	Forest	Transition	Savannah
DJF	-0.1429**	-0.1273**	-0.1040**	-0.0102
MAM	0.0692	-0.0793	-0.2016**	-0.1181**
JJA	0.0510	-0.0242	0.2112*	-0.0972
SON	0.0677	-0.0512	-0.1460*	-0.1582**

The summary of the seasonal trend analysis is presented in Table 4.1 where each entry represents the seasonal trend rate in mm per year of each agro-ecological zone. Generally, there is a decreasing trend in almost all the agro-ecological zones except for the Coastal Zone which has dominant increasing trends. These increasing trends are however insignificant using the Mann Kendall Trend Test at the 99 and 95% confidence levels. The Transition Zone interestingly shows significant decreasing trends in all the seasons except for JJA. The DJF season shows a significant decreasing trends at the 99% confidence level for all but one of the agro-ecological zones indicating an intensification of the Harmattan.

4.7 Wavelet Analysis of rainfall over the agro-ecological zones of Ghana

4.7.1 The Wavelet Analysis for rainfall at the Coastal Zone of Ghana

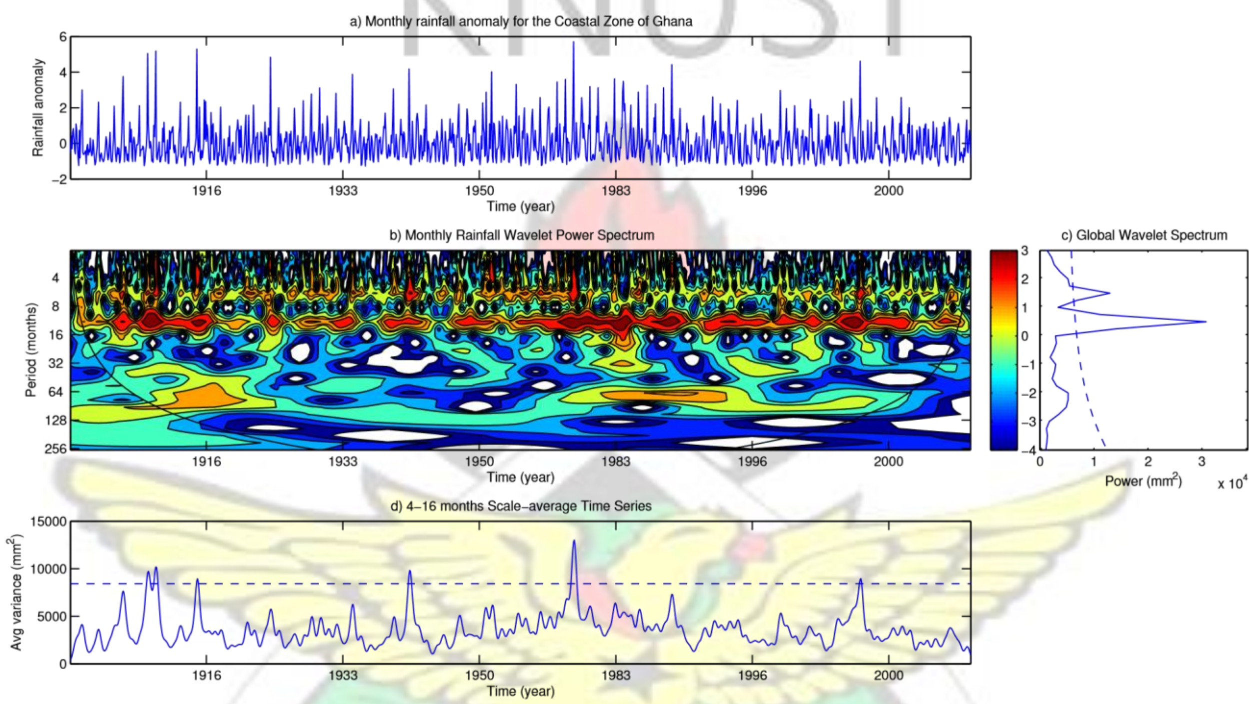


Figure 4.15: Wavelet analysis of rainfall over the Coastal Zone of Ghana.

Wavelet Power Spectrum of the Coastal Zone

The results of the wavelet analysis for the Coastal Zone of Ghana is presented in Figure 4.15. In Figure 4.15b wavelet power (actual oscillations of the individual wavelets at each scale and time) for the monthly rainfall anomaly at the Coastal Zone (Figure

4.15a) of Ghana is shown. There is a periodicity between the 4 - 8 month scale occurring specifically around the 6th month. This occurred in at many points throughout the time series. Another periodicity (a more pronounced one) also occurs between the 8 - 16 month scale. Specially around the 12th month indicating a strong annual signal. This occurred around 1910, 1914, 1930, 1960 - 1969, 1970 - 1975, 1980, 1997 - 1998. These periods are also reported as wet years since it shows a substantial increase in wavelet power (also confirmed in Figure 4.15d). Dry years can also be identified in the periods before 1904, around 1908, 1916 - 1920, 1926 - 1928, 1936 - 1938, 1944 1945, 1953 - 1954, 1974 - 1976, 1992 - 1993, 2003 - 2005. No significant information was obtained for low frequency periods (32 - 256 months scale).

Global Wavelet Power Spectrum of the Coastal Zone

The global wavelet power spectrum Figure 4.15c shows the integration of the wavelet power with time. This shows two significant peaks above the 95% confidence level between the 4 - 8 and the 8 - 16 month scale assuming a white noise background spectrum. The global wavelet spectrum is therefore a simple and robust way to summarize the variability of a time series in a region as mentioned earlier.

Scale-average wavelet power of the time series of the Coastal Zone

Figure 4.15d shows the average variance of all scales between the 4 - 16 months band giving the average year variance with time. Wetter than normal periods can clearly be seen in the years 1908, 1915, 1940, 1962 and 1997.

4.7.2 The Wavelet Analysis for rainfall at the Forest Zone of Ghana

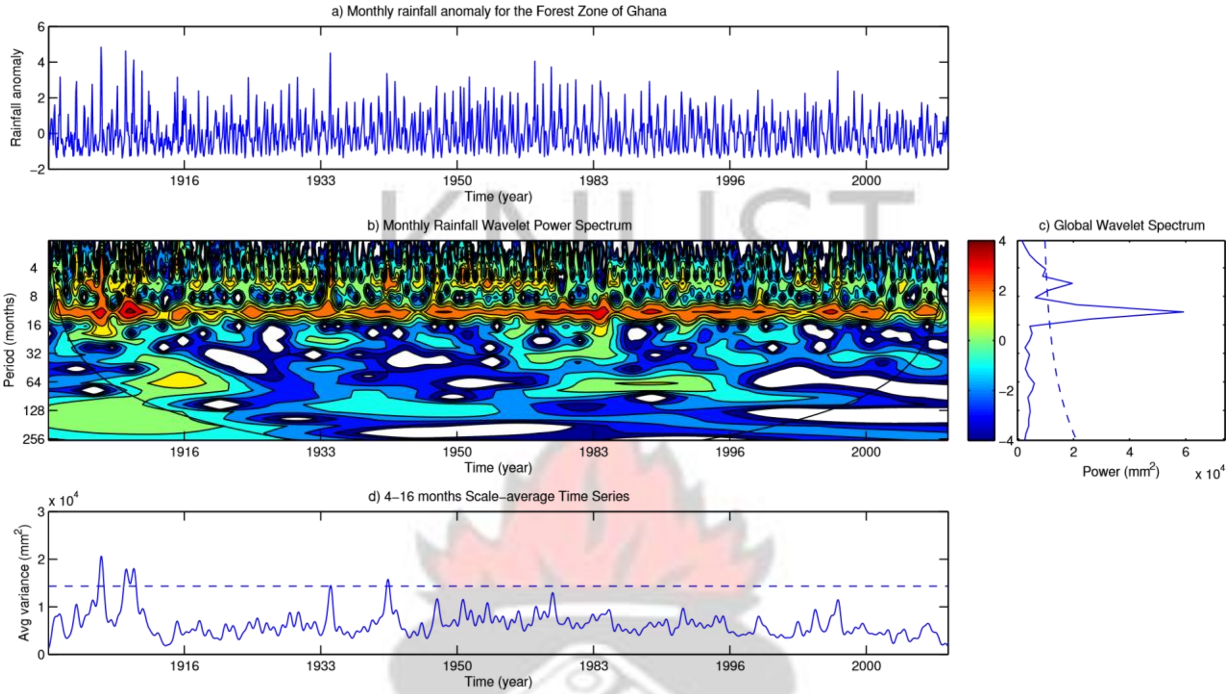


Figure 4.16: Wavelet analysis of rainfall over the Forest Zone of Ghana.

Wavelet Power Spectrum of the Forest Zone

The results of the wavelet analysis for the Forest Zone of Ghana is presented in Figure 4.16. In Figure 4.16b wavelet power (actual oscillations of the individual wavelets at each scale and time) for the monthly rainfall anomaly at the Forest Zone (Figure 4.16a) of Ghana is shown. Similar to the Coastal Zone, there is a periodicity between the 4 8 month scale occurring specifically around the 6th month in some years throughout the time series. It is however less pronounced. A more pronounced periodicity occurs between the 8 - 16 month scale, just around the 12th month also indicating a strong annual signal. These periodicities can be seen around 1906, 1908 - 1910, 1940, 1963 1966, 1972 - 1974, 1980, 1993 and 2000. These periods are also reported as wet years since it shows a substantial increase in wavelet power (also confirmed in Figure 4.16d). Dry years can also be identified around 1912, 1916 - 1920, 1926, 1934, 1942 1945, 1968, 1994-1995, 2003 - 2005. No significant information was obtained for low frequency periods (32 - 256 months scale).

Global Wavelet Power Spectrum of the Forest Zone

The global wavelet power spectrum Figure 4.16c shows the integration of the wavelet power with time. This also shows two significant peaks above the 95% confidence level between the 4 - 8 and the 8 - 16 month scale assuming a white noise background spectrum.

Scale-average wavelet power of the time series of the Forest Zone

Figure 4.16d shows the average variance of all scales between the 4 - 16 months band giving the average year variance with time. Wetter than normal periods can clearly be seen in the years 1906, 1910 - 1912, 1934 - 1935, 1941 - 1942.

4.7.3 The Wavelet Analysis for rainfall at the Transition Zone of Ghana

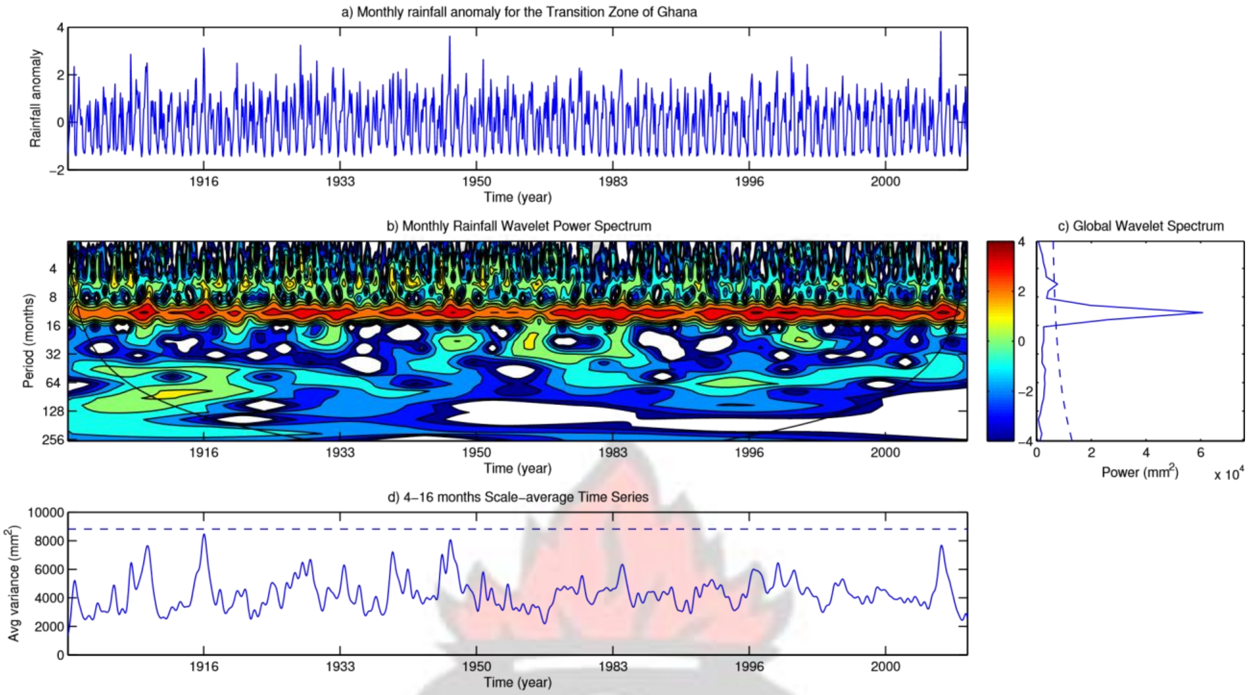


Figure 4.17: Wavelet analysis of rainfall over the Transition Zone of Ghana.

Wavelet Power Spectrum of the Transition Zone

The result of the wavelet analysis for the Transition Zone of Ghana is presented in Figure 4.17. In Figure 4.17b wavelet power for the monthly rainfall anomaly at the Transition Zone (Figure 4.17a) of Ghana is shown. Unlike the Coastal and the Forest Zones, a very weak periodicity occurs at the 4 - 8 months scale occurring at some few years in the time series. The main periodicity for this zone is the annual frequency, occurring between the 8 - 16 month scale. These strong periodicities (wet years) appears to be more consistent within this annual scale and can be seen around 1907 - 1910, 1912 - 1917, 1920, 1922-1933, 1938 - 1950, 1958 - 1973, 1975 - 2009. Very few dry years are seen in this zone occurring around 1902 and 1956. No significant information was obtained for low frequency periods (32 - 256 months scale).

Global Wavelet Power Spectrum of the Transition Zone

The global wavelet power spectrum Figure 4.15c shows the integration of the wavelet power with time. Two significant peaks are seen above the 95% confidence level between the 4 - 8 and the 8 - 16 month scale assuming a white noise background spectrum. However as can be confirmed from the the Wavelet power spectrum, the periodicity between the 4 - 8 months scale just touches the significant line.

Scale-average wavelet power of the time series of the Transition Zone Figure 4.15d shows the average variance of all scales between the 4 - 16 months band giving the average year variance with time. The scale-average wavelet time series for the Transition Zone shows no wetter than normal year at the 95% confidence level except for 1916 which indicates an almost significant wet year.

4.7.4 The Wavelet Analysis for rainfall at the Savannah Zone of Ghana

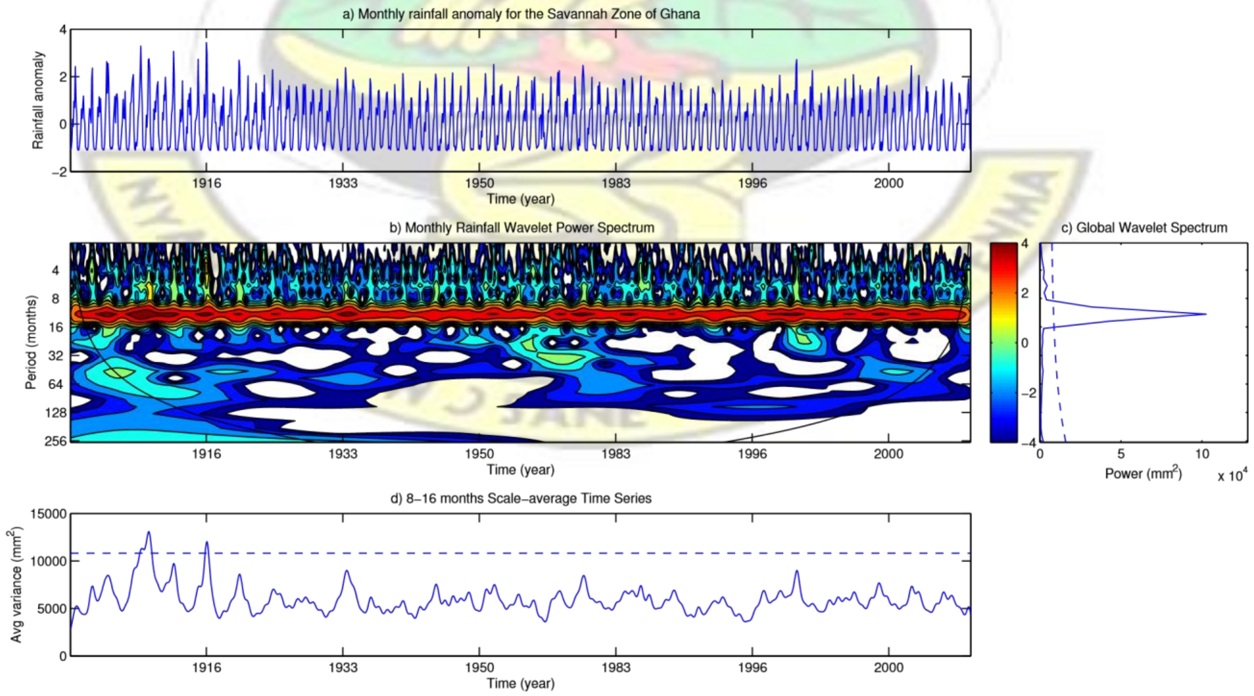


Figure 4.18: Wavelet analysis of rainfall over the Savannah Zone of Ghana

Wavelet Power Spectrum of the Savannah Zone

The result of the wavelet analysis for the Coastal Zone of Ghana is presented in Figure 4.18. In Figure 4.18b wavelet power for the monthly rainfall anomaly at the Savannah Zone (Figure 4.18a) of Ghana is shown. A very strong annual signal is seen between the 8 - 16 month band. This occurs consistently throughout the entire time series with periods of very wet years occurring around 1904 - 1905, 1907 - 1910, 1916, 1933, 1960, 1984 - 1986. No dry periods are identified within the Savannah Zone. Like all the previous agro-ecological zones no significant information was obtained for low frequency periods (32 - 256 months scale).

Global Wavelet Power Spectrum of the Savannah Zone

The global wavelet power spectrum Figure 4.18c shows the integration of the wavelet power with time. Unlike the other agro-ecological zones, only one main significant peak is identified in this zone above the 95% confidence level assuming a white noise background spectrum. And it occurs around the 8 - 16 month band. Indicating that the variability of rainfall frequency at the Savannah Zone is mainly on the annual scale.

Scale-average wavelet power of the time series of the Savannah Zone

Figure 4.18d shows the average variance of all scales between the 4 - 16 months band giving the average year variance with time. Wetter than normal periods identified at the 95% confidence level can clearly be seen at 1908 - 1909 and 1916.

4.7.5 Summary of the results of the Wavelet Analysis

Rainfall variability over the all agro-ecological zones of Ghana indicates a strong annual (periodicity of 12 months) signal. However in the Coastal and Forest Zones, this strong annual frequency is accompanied by a 4 - 8 months signal. This can be supported by the bimodal nature of the rainfall pattern in these zones as mentioned by Aryee (2015); Mensah (2015); Amekudzi et al. (2015); Nicholson and Grist (2001) as well as the results of the analysis of the seasonal variability in Figure 4.8. These show that, rainfall frequencies recorded around MAM will be followed by another one within 4 - 8 months (SON).

The annual rainfall frequency identified in all the agro-ecological zones is almost constant throughout the entire time period for the Savannah Zone, followed by the Transition Zone. The Forest and Coastal Zones however show distinct wet and dry periods within the time series especially the Coastal Zone.

A continuous wet period is seen throughout the entire time series for the Savannah Zone within the annual scale with virtually no dry period, this is followed by the Transition Zone. The Forest and Coastal Zones however show significant dry periods within the annual scale with the Forest Zone showing more consistent dry periods. It should however be noted that, the dry periods in each zone as identified in the wavelet plots are relative and corresponds to rainfall values less than the mean values of 93.0167, 131.8282, 108.0629 and 92.0133 mm for Coastal, Forest, Transition and Savannah

Zones respectively.

CHAPTER 5

Conclusion and recommendations

5.1 Conclusion

The inter-annual, inter-seasonal and inter-decadal rainfall variability over Ghana has been studied and their periodicities analysed using wavelet analysis. A rainfall time series from 1901-2010 from GPCC has been used in this analysis.

A good agreement has been found between GMet gridded data and GPCC data with Pearson correlation coefficients of 0.9 - 1, very low RMD values of 0.00 - 0.04, and low RRMSE values of < 0.5 obtained in most grids over the country. GPCC data was found to be reliable for a longer time scale (inter-decadal) studies of rainfall variability over West Africa.

It was also observed that, high cumulative rainfall amounts ranging from 900 to 900 mm are recorded over the entire nation per year with very high rainfall amounts between 1500 to 1900 mm recorded at the south-western part of the country and low rainfall amounts (900-1200 mm) recorded in the Savannah Zone and east coast of the

country.

In general a decreasing trend was observed for the inter-annual rainfall over all the agro-ecological zones except for the Coastal Zone where a slight increasing trend of 0.1600 mm per year was seen. This decreasing trends will have serious consequences on agricultural production and food security. The results of the seasonal trend analysis also reveals a significant decreasing trend at 99% confidence level in all the agroecological zones except for the Savannah Zone during the DJF season indicating an intensification of the Harmattan. The Coastal Zone records lowest mean rainfall values for all the seasons with the highest of about 150 mm recorded in MAM. The Forest Zone on the other hand records very high rainfall values for all the seasons with the highest of about 200 mm recorded in JJA followed by about 170 mm in MAM. The Transition Zone however records almost similar rainfall values (varying between 120 and 170 mm) for all the seasons except for DJF where a lower mean rainfall value of about 50 mm is recorded. The Savannah Zone records the lowest mean rainfall amount of about 6 mm in the DJF season whiles its highest rainfall amount of 173.99 mm is recorded in the JJA season. This value is interestingly slightly higher than that recorded in the Forest (173.52 mm) during this same season. However, the former has most of its rains from July and August while the latter has most of its rain contributed by the month of June.

On the inter-decadal time scale, below normal rainfall values are observed between the

1901 - 1920 and 1980 - 2010 periods for all the agro-ecological zones except for the Savannah which shows above normal rainfall values within the 1901 - 1940 period. Likewise, above normal rainfall values is recorded between 1930 - 1980 for all the agro-ecological zones. These variabilities confirm the effects of strong El Niño and La Niña episodes on the region.

The wavelet analysis has also revealed a strong annual periodicity over all the agroecological zones except for the Coastal and Forest Zones where the annual periodicity is accompanied by a 4 - 8 months signal. The results of both the 5 year moving average and the inter-decadal anomaly indicates that rainfall amount is significantly decreasing even in the Transition Zone which is the food hub of the country. This will have negative consequences on agricultural practice, water resource management and food

security.

5.2 Recommendations

5.2.1 Recommendation for Policy

- GPCC data can be used as a substitute for GMet data for future longer timescale climate variability studies in Ghana since GMet data does not give enough information about the past climate.
- Frequent fire forecasts should be issued during the DJF season due to the intensification of the Harmattan that has been observed.
- Alternate irrigation schemes should be considered over the nation especially in the Transition Zone due the significant decreasing trend observed in this region.
- Major agricultural projects should be done within the Transition Zone where the variation in rainfall amount was almost constant in order to increase production.
- The high rainfall amounts recorded in the Savannah Zone during the the JJA season indicate the potential of the occurrence of extreme rainfall events in the season. Any future development of the zone should take into consideration this

threat.

- Finally, drainage systems in the Forest Zones should be well constructed and settlements should be well planned in order to avoid floods since extremely high rainfall values are recorded in this zone.

5.2.2 Recommendation for Future Research

- Other mathematical techniques for rainfall variability studies such as the HilbertHuang Transform (HHT) should also be used to study the variability of the rainfall in the agro-ecological zones and compared to the Wavelet Analysis.
- A modified form of the Wavelet analyses technique which uses a common mean and a common standard deviation for all the agro-ecological zones should be considered in future works to enhance easy inter zonal comparison.
- To better address the issue of climate variability with change, the variability of a longer temperature data should be studied together with the rainfall data.
- Finally, other extensions of the wavelet analysis such as the Wavelet Empirical Orthogonal Function analysis (WEOF) and Wavelet Independent Component Analysis (WICA) could also be applied on the rainfall data over the various agro-ecological zones in order to identify the spatially uncorrelated modes of variability that may occur in the data set.

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Appendix A

Appendix

Matlab script for Inter-annual Variability and Trends

```
 %Trend plots
a=csvread('coast.csv');
coast=a(:,2);
date=a(:,1);
b=csvread('forest.csv');
forest=b(:,2);
```

```
c=csvread('transition.csv');

transition=c(:,2);

d=csvread('savannah.csv');

savannah=d(:,2);

e=csvread('coast_regression.csv');

rcx=e(:,1); % regression coast x(date)

rcy=e(:,2); % regression coast y(rainfall)

f=csvread('forest_regression.csv');

rfx=f(:,1);

rfy=f(:,2);

g=csvread('transition_regression.csv'); rtx=g(:,1);

rty=g(:,2);

h=csvread('savannah_regression.csv');

rsx=h(:,1);

rsy=h(:,2); %

subplots

subplot(2,2,1)

plot(date,coast,'r')

hold on

plot(rcx,rcy,'k')

hold off

text(1905,1900,'a) Coast')

xlabel('Year')

ylabel('Rainfall [mm]')
```

```
Rate_coast=rcy(2)-rcy(1)

Rate_forest=rfy(2)-rfy(1)

Rate_transition=rty(2)-rty(1) Rate_savannah=rsy(2)-rsy(1)


subplot(2,2,2)

plot(date,forest,'g')

hold on

plot(rfx,rfy,'k')

hold off

text(1905,2350,'b) Forest')

xlabel('Year')

ylabel('Rainfall [mm]')


subplot(2,2,3)

plot(date,transition)

hold on

plot(rtx,rty,'k')

hold off

text(1905,1700,'c) Transition')

xlabel('Year')

ylabel('Rainfall [mm]')


subplot(2,2,4)
```

```
plot(date,savannah,'Color',[0.5 0 0.9]) %color using the RGB

format

hold on

plot(rsx,rsy,'k')

hold off

text(1905,1500,'d) Savannah')

xlabel('Year')

ylabel('Rainfall [mm]')


%plot(date,savannah,'Color', [0.5 0 0.5]) violet Matlab script for Inter-seasonal Variability
and Trends


  %Trend plots

a=csvread('coast.csv'); %coast=a(:,2);

date=a(:,1);

coast=csvread('DJF_Coast.csv');

transition=csvread('DJF_Transition.csv');

forest=csvread('DJF_Forest.csv');

savannah=csvread('DJF_Savannah.csv');


%regression

[date ones(length(date),1)]\coast Slope_coast=ans(1:1)

yintercept=ans(2,1); R_coast=corrcoef(date,coast)

p = polyfit(date,coast,1);
```

```
r = p(1) .* date + p(2);

[date ones(length(date),1)]\forest Slope_forest=ans(1:1)

yintercept=ans(2,1); R_forest=corrcoef(date,forest)

p = polyfit(date,forest,1);

s = p(1) .* date + p(2);

[date ones(length(date),1)]\transition Slope_transition=ans(1:1)

yintercept=ans(2,1); R_transition=corrcoef(date,transition)

p = polyfit(date,transition,1);

t = p(1) .* date + p(2);

[date ones(length(date),1)]\savannah Slope_savannah=ans(1:1)

yintercept=ans(2,1); R_savannah=corrcoef(date,savannah)

p = polyfit(date,savannah,1);

u = p(1) .* date + p(2);


Rate_coast=r(2)-r(1)

Rate_forest=s(2)-s(1)

Rate_transition=t(2)-t(1)

Rate_savannah=u(2)-u(1)

%e=csvread('coast_regression.csv');

%rcx=e(:,1); % regression coast x(date)

%rcy=e(:,2); % regression coast y(rainfall)

%f=csvread('forest_regression.csv');

%rfx=f(:,1);

%rfy=f(:,2); %g=csvread('transition_regression.csv');
```

```
%rtx=g(:,1);
%rty=g(:,2); %h=csvread('savannah_regression.csv');
%rsx=h(:,1);
%rsy=h(:,2);

% subplots
subplot(2,2,1)
plot(date,coast,'r')
hold on
plot(date,r,'-k')
hold off
text(1910,90,'a) Coast')
xlabel('Year')
ylabel('DJF Rainfall [mm]')

subplot(2,2,2)
plot(date,forest,'g')
hold on
plot(date,s,'-k')
hold off
text(1910,90,'b) Forest')
xlabel('Year')
ylabel('DJF Rainfall [mm]') subplot(2,2,3)
plot(date,transition)
hold on
```

```
plot(date,t,'-k')
hold off
text(1910,53,'c) Transition')
xlabel('Year')
ylabel('DJF Rainfall [mm]')

subplot(2,2,4)
plot(date,savannah,'Color',[0.5 0 0.9]) %color using the RGB
format
hold on
plot(date,u,'k')
hold off
text(1910,22.5,'d) Savannah')
xlabel('Year')
ylabel('DJF Rainfall [mm]')

%plot(date,savannah,'Color', [0.5 0 0.5]) violet
```

Matlab script for Inter-decadal Variability

```
%Moving averages: 5 years
clear
a=csvread('coast.csv');
coast=a(:,2);
```

```
date=a(:,1);

b=csvread('forest.csv');

forest=b(:,2);

c=csvread('transition.csv');

transition=c(:,2);

d=csvread('savannah.csv');

savannah=d(:,2); New_date=date(10:110,1);


kk=0;

    for i = 0:10:110-10

        kk=kk+1;

                    cma(kk,:) = nanmean(coast(1+i:i+10))

    end


ll=0;

    for i = 0:10:110-10

        ll=ll+1;

                    fma(ll,:) = nanmean(forest(1+i:i+10))

    end


jj=0;

    for i = 0:10:110-10

        jj=jj+1;

                    tma(jj,:) = nanmean(transition(1+i:i+10))
```

```
end

hh=0;
    for i = 0:10:110-10
        hh=hh+1;
       sma(hh,:) = nanmean(savannah(1+i:i+10))
    end

    x=1
    for i=1:10:110 Mvy(x)=New_date(i)
        x=x+1
    end

    A=Mvy(1,:);
    A=A(1,:); %coast=standardise(coast);
ell = size(cma,1);
M = sum(cma) / ell;
M2 = sum(cma.^2)/ell; SD =
sqrt(M2 - M.^2);
cma = (cma - ones(ell,1)*M)./(ones(ell,1)*SD) %forest=standardise(forest);
ell = size(fma,1);
M = sum(fma) / ell;
M2 = sum(fma.^2)/ell; SD =
sqrt(M2 - M.^2);
```

```
fma = (fma - ones(ell,1)*M)./(ones(ell,1)*SD)

%transition=standardise(transition);

ell = size(tma,1);

M = sum(tma) / ell;

M2 = sum(tma.^2)/ell; SD =

sqrt(M2 - M.^2);

tma = (tma - ones(ell,1)*M)./(ones(ell,1)*SD)

%savannah=standardise(savannah);

ell = size(sma,1);

M = sum(sma) / ell;

M2 = sum(sma.^2)/ell; SD =

sqrt(M2 - M.^2);

sma = (sma - ones(ell,1)*M)./(ones(ell,1)*SD)


% subplots

subplot(2,2,1)

bar(A,cma,'r')

hold on

plot(A,cma,'k')

hold off

text(1910,2,'a) Coast')

xlabel('Year')

ylabel('Rainfall [mm]')
```

```
subplot(2,2,2)

bar(A,fma,’g’)

hold on

plot(A,fma,’k’)

hold off

text(1910,1.5,’b) Forest’)

xlabel(’Year’)

ylabel(’Rainfall [mm]’)


subplot(2,2,3)

bar(A,tma)

hold on

plot(A,tma,’k’)

hold off

text(1910,1.25,’c) Transition’)

xlabel(’Year’)

ylabel(’Rainfall [mm]’)


subplot(2,2,4)

bar(A,sma,’y’)

%color using the RGB format hold on

plot(A,sma,’k’)

hold off

text(1910,1.5,’d) Savannah’)

xlabel(’Year’)
```

```
ylabel('Rainfall [mm]')

%plot(date,savannah,'Color', [0.5 0 0.5]) violet
```

Appendix B

Appendix

GrADS script for comparing GPCC data with GMet

```
'set grads off'

'set vpage 0 9.0 0 8.5'

'sdfopen Ghana_timmean_multiymean.nc'

'sdfopen Jeff_data3.nc'

'q files'

'set dfile 1'

'set grads off'

'set gxout shaded'

#'set gxout grid'

'set clevs 0 20 40 60 80 100 120 140 160 180 200'

'set ccols 14 4 11 5 13 3 10 7 12 8 2'

'set mpdset hires'

'set map 1 1 6'

'set_parea 1 2 1 1'

'd precip'

'set dfile 2'

'set grads off'

'set gxout shaded'

#'set gxout grid'
```

```
'set clevs 0 20 40 60 80 100 120 140 160 180 200'

'set ccols 14 4 11 5 13 3 10 7 12 8 2'

'set mpdset hires'

'set map 1 1 6'

'set ylab off'

'set_parea 1 2 1 2'

'd precip'

'run cbarn'

'printim Ghana_Jeff_compare7.png white'

'quit'
```

GrADS script for seasonal variability

```
  'set grads off'

'set vpage 0 9.0 0 8.5'

'sdfopen Multiyear_seasmean.nc'

'set lon -3.25 1.25'

'set lat 4.75 11.25'

'set grads off'

'set gxout shaded'

'set clevs 20 40 60 80 100 120 140 160 180 200 220'

'set ccols 14 4 11 5 13 3 10 7 12 8 2'

'set mpdset hires'

'set map 1 1 6'
```

```
'set xlab off'
'set_parea 2 2 1 1'
#'set_parea 2 2 1 1 -m 0.3'
'd precip'
'set font 0'
'set string 1 c 7 0'
'set strsiz 0.3 0.2'
'draw string 2 7.5 a)'
#'draw title DJF'
'set t 2'
'set grads off'
'set gxout shaded'
'set clevs 20 40 60 80 100 120 140 160 180 200 220'
'set ccols 14 4 11 5 13 3 10 7 12 8 2'
'set mpdset hires'
'set map 1 1 6'
'set xlab off'
'set_parea 2 2 1 2'
'd precip'
'set font 0'
'set string 1 c 7 0'
'set strsiz 0.3 0.2'
'draw string 6 7.5 b)'
#'draw title MAM'
```

```
'set t 3'

'set grads off'

'set gxout shaded'

'set clevs 20 40 60 80 100 120 140 160 180 200 220'

'set ccols 14 4 11 5 13 3 10 7 12 8 2'

'set mpdset hires'

'set map 1 1 6'

'set xlab on'

'set_parea 2 2 2 1'

'd precip'

'set font 0'

'set string 1 c 7 0'

'set strsiz 0.3 0.2'

'draw string 2 3.5 c)'

#'draw title JJA'

'set t 4'

'set grads off'

'set gxout shaded'

'set clevs 20 40 60 80 100 120 140 160 180 200 220'

'set ccols 14 4 11 5 13 3 10 7 12 8 2'

'set mpdset hires'

'set map 1 1 6'

'set_parea 2 2 2 2'

'd precip'
```

```
'set font 0'

'set string 1 c 7 0'

'set strsiz 0.3 0.2'

'draw string 6 3.5 d)'

#'draw title SON'

'run cbarn'

'printim Multiyear_seasmean_clevs.png white'

'quit'
```

Appendix C

Appendix

GNU plot script for seasonal variability box plot

```
#!/bin/bash

filename="Thesis_data"

file=${filename}.txt

gnuplot -persist << PLOT

set term post eps enhanced color 20#"Helvetica" 20

set output ’Thesis_data.eps’

reset

set border linewidth 0

set cbtics 0.0, 0.1

set xrange [1:4]

set yrange [1:4]

set zrange[0:1]

set isosample 250, 250

set table ’test.dat’

splot "$file" u 1:2:3
```

```
unset table

set contour base set format y

"+-12.3f"

unset surface
set table ’cont.dat’
splot "$file" u 1:2:3
unset table reset

set cbrange[0.00:200]
set cbtics 0.00, 50.00,200
set xrange [0.5:4.5]
set yrange [0.5:4.5]
set ytics ("DJF" 1, "MAM" 2, "JJA" 3,"SON" 4)
set xtics ("Coast" 1, "Forest" 2, "Transition" 3,"Savannah"4)
set key
set xtics rotate
set ylabel ’ Seasons ’ font ",20"
set xlabel ’ Agro-Ecological Zones ’ font ", 20"
set cblabel ’Mean Rainfall (mm)’
```

```
set palette rgbformulae 33,13,10

#set object circle at 1,1,33.7272 size 2 #set label 1 "" at 1,1,33.7272

point pointtype 3

set object circle at first 1,1,33.7272 radius char 0.5 \
        fillstyle empty border lc rgb '#aa1100' lw 2


plot 'test.dat' with image, 'cont.dat' w l lw 3 notitle


plot "< echo '1 1 33.7272'"


set output

quit PLOT
```

Appendix D

Appendix

Nino 3 and 4 SST indices

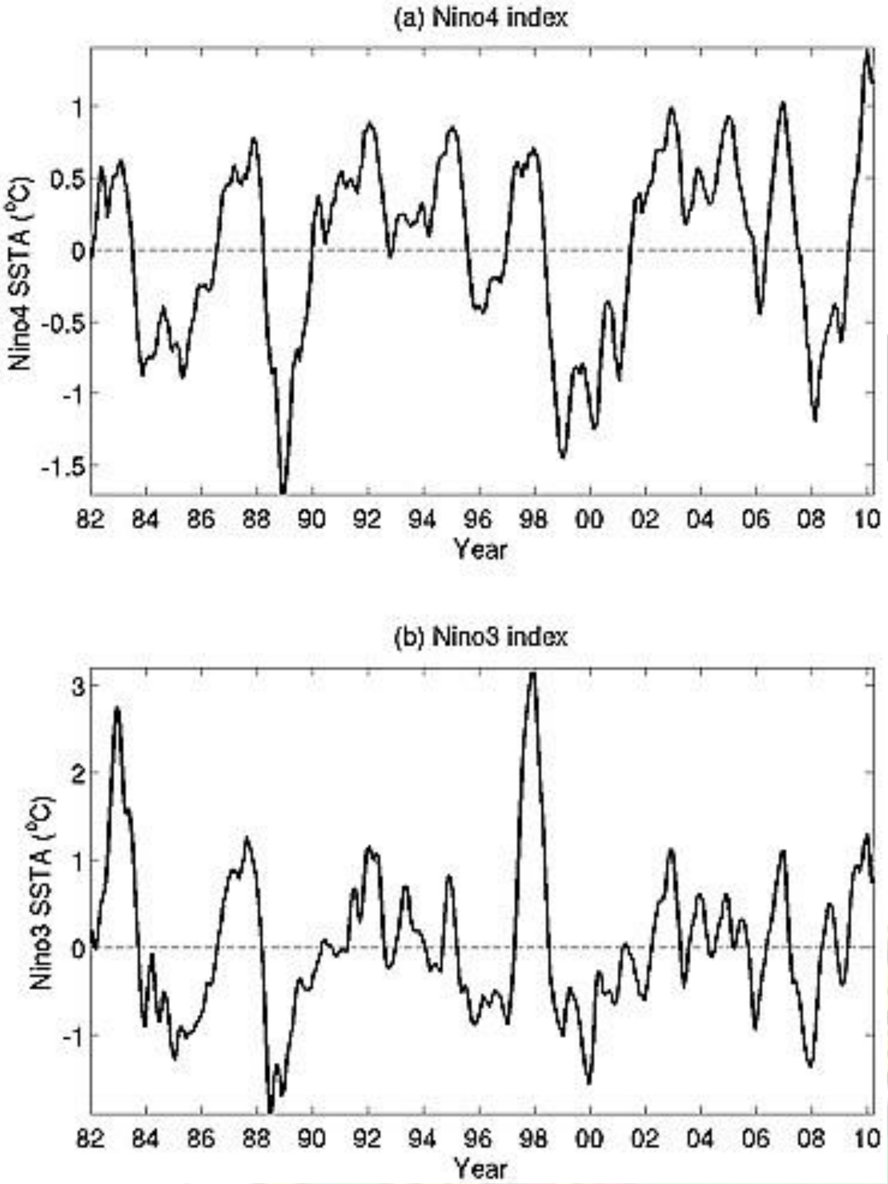

Figure D.1: Nino 3(b) and 4(a) SST indices from Lee and McPhaden (2010)