UNIVERSITY OF NAIROBI

ASSESSING THE TEMPORAL AND SPATIAL CHARACTERISTICS OF RAINFALL AND TEMPERATURE OVER SOUTH SUDAN

BY

PAULINO OMOJ OMAY

I54/69929/2013

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN CLIMATE CHANGE

JULY 2015

DECLARATION

I declare that this dissertation is my original work and has not been presented for a degree in any other University.

Signature……………………………………………….…………Date…………………………

Paulino Omoj Omay

I54/69929/2013

This dissertation has been submitted for examination with our approval as University Supervisors:

Signature……………………………………………….…………Date…………………………

Prof. Laban Ogallo

Signature……………………………………………….…………Date…………………………

Dr. Christopher Oludhe

Signature……………………………………………….…………Date…………………………

Dr. Wilson Gitau

Department of Meteorology

University of Nairobi

P. O. Box 30197 – 00100

Nairobi, Kenya

www.uonbi.ac.ke

DEDICATION

This work is dedicated to my family, friends and IGAD Climate Prediction and Application Center (ICPAC).

ABSTRACT

Climate extremes including droughts, floods, and high/low temperatures are recurrent in southern Sudan and whenever they occur, they are associated with many socio-economic miseries. Recent assessment by IPCC, (2013) has shown that climate change is real with many parts of the world likely to face more frequent and severer climate extremes. This study is aimed at enhancing our understanding of past and present characteristics of climate extremes over South Sudan based on space-time patterns of the past rainfall and temperature extremes. The datasets used in this study were monthly rainfall and temperature, Sea Surface Temperatures over tropical Indian Ocean and Niño regions (Niño1+2, Niño3, Niño3.4 and Niño4) over the equatorial Pacific Ocean for the period 1961 to 2013. Temperature records included both maximum and minimum values for the period 1954 to 2013. The temporal characteristics examined included seasonal trends, and inter-annual recurrences of the extreme lowest/ largest values. The trends were examined using graphical and statistical techniques. This included fitting determination of trends and testing their significance using non-parametric statistical approaches that included the use of Mann Kendall Statistics. Standardized Precipitation Index, Simple probability of occurrence statistics and Spectral analysis were also used to investigate the characteristics of the interannual recurrences of the rainfall and temperature extremes. The Pearson correlation and composite analyses were also used to investigate linkage between seasonal rainfall and El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) events.

The seasonal patterns of both rainfall records showed that the June, July and August (JJA) season is the peak rainfall season over south Sudan, which contributes more than 50% of annual rainfall. The highest maximum temperatures were observed during the March, April and May (MAM) season, while lowest minimum temperature was observed during the December, January and February (DJF) season. Results from the trend analysis showed insufficient statistical evidence of a significance of increasing/ declining tends in amount of annual and seasonal rainfall at many locations, while both maximum and minimum temperature indicated statistical significant evidence of increasing trends for all locations considered in study at 0.05 level of significant. The inter-annual patterns of rainfall indicated recurrent patterns of floods and droughts over

some locations used in the study. The Spectral analysis of rainfall and temperature showed significant recurrent modes of one to two spectral peaks within period of 3 to 8 years, which can be attributed to some common large scale forcing mechanisms within atmosphere and ocean components such as Quasi-Biennial Oscillation (QBO) in the lower stratospheric zonal winds, El Niño and La Niña events.

The observed spatial patterns of rainfall and temperature for current period1984-2013 relative to 1954-1983 and 1961-1990 indicated that, climate change and variability signals are real in south Sudan and results showed insignificant decline in amount of rainfall and significant increasing of temperature over most locations in south Sudan. The variations in spatial patterns confirmed by probability distributions of Long Term Mean (LTM) of rainfall and temperature of two periods (1954-1983) and present (1984-2013), which showed increase in both means and variance and changes in asymmetry toward the hotter and heat waves for temperature and high probability of occurrence of drought, floods for rainfall.

The correlation coefficients and regression model between seasonal rainfall and IOD and ENSO events at zero and one Lag season indicated weak teleconnection and IOD and ENSO contributing less than 20% of variability in rainfall. The composite analysis established facts that most of locations observed normal rainfall and some of the extreme rainfall conditions that occurred over South Sudan were found not coincide with positive and negative IOD and weak, moderate and strong ENSO phases. These results can help policymakers to make more informed knowledge based decisions for mainstreaming of climate related risks into sustainable development policies, Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA) strategies.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AGCM	Atmospheric Global Circulation Model
AMS	America Meteorological Society
AR4	Fourth Assessment Report
CCA	Climate Change Adaptation
CDKN	Climate and Development Knowledge Network
CLIVAR	Climate Variability and Predictability project
CMIP5	Coupled Model Intercomparison Project Phase 5
CO2	Carbon Dioxide
CPC	Climate Prediction Center
CRU	Climate Research Unit
DJF	December, January and February
DRR	Disaster Risk Reduction
DTR	Monthly mean difference between TX and TN
EALLJ	East African Low Level Jet stream
ENSO	El Niño Southern Oscillations
EOF	Empirical Orthogonal Function
ETCCDI	Expert Team on Climate Change Detection and Indices
EWS	Early Warning System
FEWS NET	Famine Early Warning Systems Network
GDP	Gross Domestic Product
GHA	Greater Horn of Africa
GHGs	Green House Gases
GMST	Mean Surface Temperature
GOSS	Government of South Sudan
ICPAC	IGAD Climate Prediction and Application Center
IFAD	International Fund for Agricultural Development
IGAD	Intergovernmental Authority on Development
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change

IRI	International Research Institute
ITCZ	Inter-Tropical Convergence Zone
JGCRI	Joint Global Change Research Institute
JJA	June, July, August
Km^2	Kilometers Square
MAM	March, April, May
NAO	North Atlantic Oscillation
NCAR	National center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
OI	Optimum Interpolation
PRECIS	Providing Regional Climate for Impact Studies
ProUCL	Protection Upper Confidence Level
QBO	Quasi-Biennial Oscillation
RAI	Rainfall Anomaly Index
SAI	Standardized Anomaly Index
SAI	Standardized Anomaly Index
SCOR	Scientific Committee for Ocean Research
SLP	Sea Level Pressure
SON	September, October, November
SRES	Special Report on Emissions Scenarios
SSMD	South Sudan Meteorological Department
SSTAs	Sea Surface Temperature Anomalies
SSTs	Sea Surface Temperatures
UNDP	United Nation Development Programme
UNEP	United Nation Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
USGCRP	United Stated Global Change Research Program
USAID	Unites State Agency for International Development
WMO	World Meteorological Organization

CHAPTER ONE

1.0 Introduction

This chapter provides background information including problem statement, objectives and justification and description of the location, physical features, all geographical and climatic information concerning the area of study as well as factors that influence rainfall and temperature such as Inter-Tropical Convergence Zone (ITCZ), warm and cold ENSO, Indian Ocean Dipole (IOD), Tropical Monsoons winds and subtropical anticyclones.

1.1. Background Information

The issues of climate change are real and pose risks to human health, ecosystems, social and cultural systems, and sustainable development. Climate change and variability result from natural and non-natural processes, interaction of climate system component and manmade Man-made carbon dioxide emissions. The natural processes are associated with any changes in the natural processes that determine the climate of the planet earth including solar radiation intensity, earth – sun distance, earth's orbital parameters resulting in the daily movement and seasonal movement of the earth. Anthropogenic factors include those associated with human action such as the burning of fossil fuels and the conversion of land for forestry and agriculture. Intergovernmental panel on climate change (IPCC), definition of climate change are restricted to those associated with human forcing and can therefore be reduced through human interventions (IPCC, 2007a) and IPCC, 2013a). Also IPCC assessments have associated the recent climate change with changes in rainfall and temperature patterns at various spatial and temporal scales including changes in extreme climate events such as drought, floods and heat waves among others. Most of the anthropogenic climate change has been linked to continuing and increasing concentration of Green House Gases (GHGs) in the atmosphere especially carbon dioxide.

Agriculture and food security sectors in south Sudan are considered as main weather-dependent, and therefore can be affected negatively by climate extremes and fluctuations (UNDP, 2012). IPCC (2013) report indicated that climate change accelerate the frequency, intensity, spatial extent and duration of climate extreme events in many regions especially in Africa where resilience is too low. Many studies on long term climate and prediction of seasonal rainfall over

Greater Horn of Africa (GHA) revealed an increase in variability of seasonal rainfall that makes it less predictable (Oludhe, 2010; Nicholson *et al*., 2013). Shifts in the onset and cessation of rainfall have been observed in some parts of South Sudan, particularly in Malakal County (Chan, 2011).

Some of the past studies indicate that the climate of the Greater Horn of Africa, of which South Sudan is an integral part, is variable in time and space. Changes of annual, seasonal and monthly rainfall and temperature patterns have affected many people and caused negative impacts on the country's economy in recent years. Williams and Funk (2011) highlighted that over the last three decades, rainfall has decreased over Eastern Africa between March and May/June, due to rapid warming of tropical Indian Ocean. Similarly, Lyon and DeWitt (2012) showed a decline in the March–May seasonal rainfall over Eastern Africa. Summer (June–September) monsoonal precipitation has declined throughout much of the Greater Horn of Africa over the last 60 years (1948–2009) because of the changing Sea Level Pressure (SLP) gradient between Sudan and the southern coast of the Mediterranean Sea and the southern tropical Indian Ocean region (Williams *et al*., 2012).

El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are among systems influencing rainfall and temperature distribution and variability over South Sudan. The ENSO phenomena is known to be a fundamental and quasi-periodic feature of the Ocean-Atmosphere system and in most cases it occurs within periodicities ranging from 2 to about 8 years (Rasmusson and Carpenter, 1983; Halpert and Ropelewski, 1992). Some extreme rainfall anomalies in East Africa have been associated with ENSO (Ropelewski and Halpert, 1987; Janowiak, 1988; Ogallo, 1988). Indian Ocean Dipole (IOD) is a seasonally phase-locked phenomenon that develops in early May, peaks in October and decays by December in the equatorial Indian Ocean. It has been defined by Saji *et al*. (1999) as the difference in SST anomalies of the Tropical western Indian Ocean (50°E – 70°E, 10°S – 10°N) and the Tropical south-eastern Indian Ocean (90°E – 110°E, 10°S – 0°N). The positive phase of the IOD is associated with warm SST in the Tropical western Indian Ocean and cold SST in Tropical south-eastern Indian Ocean.

South Sudan, as a young nation, is more vulnerable to the past and present extreme variability of rainfall and temperature especially including the recurrences of hydro-meteorological hazards (droughts, floods, etc) due to weak resilience and low adaptive capacity of the society. High vulnerability levels and low adaptive capacity are linked to factors such as conflicts, , high poverty rates, and a lack of safety nets, limited ability to adapt financially and institutionally due to lack of established climate resilience infrastructures among others. For South Sudan to ensure food security through sustainable rain-fed agricultural activities, there is need to understand the spatial and temporal characteristics of rainfall and temperature, and teleconnection between these meteorological parameters with systems causing potential climate variability, such as Indian Ocean Dipole (IOD) and El Niño Southern Oscillation (ENSO) and this will be the focus of this study to assess and fill the gaps and recommend possible adaptation measures to variability and changes in rainfall and temperature in South Sudan.

1.2. Problem Statement

Climate variability and change impacts are already being felt in many parts of the world especially Africa, and are likely to worsen in the future, Assessment Reports produced by the working groups of the Inter-Governmental Panel on Climate Change (IPCC, 1995; 2001; 2007; 2012; 2013) indicate clear evidences of changes in climate and weather patterns in many parts of the world. No sustainable development can be achieved today and in the future without effectively addressing challenges associated with present and future climate variability and change threats. These include increased frequency and intensity of drought/floods, delayed onset, early cessation, irregular distribution, which lead to widespread impacts on infrastructure, agriculture, land degradation and soil erosion, livestock including fisheries, loss of property, human health and life.

Current literature shows that limited research has been carried in relation to climate variability and change over South Sudan. Despite the presence of oil revenues that form the backbone of the economy and foreign exchange earnings now in South Sudan, agriculture, livestock and fisheries is still a major source of livelihood in terms of food and employment for local communities (GOSS, 2011).

The changes and variability in rainfall and temperature have significant impacts on crop yields, Livestock and Fisheries. Increases in temperature and carbon dioxide (CO_2) can be beneficial for some crops if warming not exceeds a crop's optimum temperature for growth and reproduction. The frequency and intensity of extreme weather and climate such as Floods, droughts and Heat waves can harm crops and reduce yields, threaten pasture and feed supplies and direct threats to livestock .also many weeds, pests and fungi thrive under warmer temperatures, wetter climates, and increased carbon dioxide (CO_2) levels. Fisheries will be affected by changes in water temperature that shift species ranges, make waters more hospitable to invasive species, and change lifecycle timing. Therefore, assessing the spatial and temporal characteristics of rainfall and temperature is crucial to planning for the major socio-economic sectors. In addition, the extreme climate events such as drought and floods, which cause serious impacts, may force poor and developing economies to redirect the resources allocated to the development and improving standard of living of citizens to the relief operations, evacuation and maintenance of what was destroyed by drought and floods, which leads to the continuity of the cycle of poverty.

Indian Ocean Dipole (IOD) and EL Niño Southern Oscillation (ENSO) are believed among the systems causing potential variability of rainfall over Greater Horn of Africa (GHA) and South Sudan in particular. Therefore, quantification of the degree of relationship between variability in observed rainfall and Sea Surface Temperature (SSTs) over IOD and Niño regions are crucial to enhance predictability and accurate skill in prediction of seasonal rainfall for sustainable agricultural production leading to long-term development and economic growth. This will also provide a better understanding of some of the mechanisms and physical processes responsible for the observed variability in rainfall over South Sudan.

1.3. Study Objectives

The main objective of this study was to assess the temporal and spatial characteristics of rainfall and temperature over South Sudan in order to better understand variability of climate in the country. This is critical in the short, medium and long term planning phases for the socio-economic development of the country. The specific objectives of this study were to:

i. Assess the temporal characteristics of observed rainfall and temperature records over south Sudan.
ii. Assess spatial variability and Extremes in the observed rainfall and temperature records over south Sudan.
iii. Quantify the teleconnection between Indian Ocean Dipole (IOD), ENSO indices and observed rainfall over South Sudan.

1.4. Justification

Rainfall and temperature are the most variable climatic elements hence required in planning and management of most socio-economic activities over South Sudan. The past characteristics of these climate elements are vital in informing risk zoning and the general planning and management of all weather and climate dependent activities.

While several studies have been done round the world to understand the temporal and spatial variability of rainfall and temperature patterns, there exists a big gap knowledge in this regard in South Sudan. The study is looking at characteristics including changes in rainfall and temperature patterns over South Sudan that will enhance understanding of the causes of these variability and change and the teleconnections between rainfall and temperature with Indian Ocean dipole (IOD) and ENSO events. The knowledge thereof will form critical basic for Disaster Risk Reduction (DRR) and strategies of Climate Change Adaptation (CCA). The knowledge of these factors will also add value in planning and decision making in order to reduce adverse impacts of the climate variability and change on the socio-economic sectors.

Further, assessment of the temporal and spatial variability and change of rainfall and temperature patterns will provide the much needed climate information for short, medium and long-term government strategies to achieve sustainable development. It will also help provide basic climatic information within the South Sudan to support farmers who still purely depend on traditional or indigenous knowledge in making decisions.

Therefore, the study aims at addressing the above shortcoming in order to help Scio-economic sectors in adapting to variability and changes in rainfall and temperature patterns through provision of better and accurate climate information which is core for Early Warning Systems (EWS) under the prevailing and predicted variability and change of rainfall and temperature over South Sudan.

1.5. Area of the study

This section deals with the description of the location, physical features and climatic information concerning the area of study.

1.5.1. Location and Physical Features of the Study Area

South Sudan is located in northeast of Africa and covers an area of 619,745 km^2. Before 9 July 2011, it was part of Sudan. It lies between latitudes 3°N and 13°N, and longitudes 24E° and 36°E. It borders Sudan in the north, Ethiopia in the east, Kenya, Uganda and the Democratic Republic of Congo in the south and the Central African Republic in the west (Figure 1). The country is mainly of plain terrain interrupted so often by hilly areas with thick equatorial vegetation and savannah grasslands. The country also has mountainous ranges along its border with Uganda. Some of these include Imatong, Didinga and Dongotona, which rise more than 3,000 metres above sea level. The river Nile is the dominant geographic feature of south Sudan, flowing 3,000 kilometers from Uganda in the south to Egypt in the north. Most of the country lies within its catchment basin. The Bahr el Ghazal and Sobat rivers are its tributaries that join at Malakal to form the White Nile River that flows to Sudan and Egypt.

Figure 1: *Map of the study area (source:* http://ds-lands.com/photo/countries/south-sudan/04/*)*

1.5.2. Climate of the study area

The South Sudan's climate is mainly tropical, ranges from semi-arid in the north to tropical wet in the far southwest. The country is generally hot during summer months (March to June) with seasonal rainfall driven in most cases by the movement and location of Inter-Tropical Convergence Zone (ITCZ).

Temperatures vary greatly (35°C to 42 °C) with seasons at any location. Highest temperatures recorded at the end of the dry season of March to May (MAM) in northern part of country and beginning of rainy season in southern part, with the hottest maximum temperatures reaching at least 38 °C. From December to end of February, the country is under the influence of the dry northeasterly wind resulting in dryness countrywide. The southern part of the country records heavy rainfall in early March due to south-westerlies resulting from the northward movement of ITCZ.

South Sudan has two features of rainfall seasons in a year. The southern parts of country has its rainy season starting from March to November, while northern parts of country has its rainy season starting from May to October. This uni-modal nature of rainfall distribution across the regions corresponds with the northward and southward migration of the ITCZ.

The semi-arid areas in the extreme northern parts are much drier and experience two seasons. The dry cold (winter) season starts from end of November to February and the dry hot (summer) season starts from March to October. The mean annual rainfall range is approximately 300-700mm in the extreme northern and eastern part of the country while the southern part receive mean annual rainfall of approximately 700 -1000 mm.

Due to topographic lifting caused by Ethiopian plateau in the eastern part of the country and the effect of the Azores ridge of high pressure over the west, annual rainfall generally decreases from eastern to western parts of the country. The isotachs depict a meridional orientation generally running from the northeast to southwest indicating the influence of the Ethiopian highlands and the Azores ridge of high pressure.

1.5.3. Soils and vegetation

According to Van Noordwijk (1984) the soils of Sudan can be categorized into five main groups, related to landform and climate. This categorization applies to Sudan as a whole, but the five soil types described by van Noordwijk are all found in Southern Sudan. The type of siol decribed included Various desert soils, Stabilized dune soils (Goz), Dark cracking clays, Non-cracking clays and Red loam and ironstone soils.

In details the various desert soils, formed by the action of wind and a dry climate. Salt crusts and rounded stones and pebbles may occur on the surface. Important groundwater resources are found under these formations. Stabilized dune soils (Goz) formed during periods of a drier climate in recent geological history. When moister conditions returned, vegetation stabilized the dunes. These sandy soils are poor in nutrients and their humus content is low, but they are very permeable and because of the fine sand may have relatively high water availability during dry seasons. Dark cracking clays, which are also known as “black cotton soils,” are mainly found in floodplains and deposited by the Nile and its branches, but some may have been formed on the spot from basalt rock formations. These soils crack deep and wide when dried out. Non-cracking clays, occur scattered, and cover only a very small land area. Red loam and ironstone soils occur mainly in areas where annual rainfall exceeds 800 mm and where drainage of excess water is possible (USAID, 2007).

Vegetation covers a considerable portion of the earth and has an effect on weather and climate. Vegetation influences both albedo of the earth and the amount of water vapor and carbon dioxide in the air. Climate change can have a very big impact on soils and the functions that soil performs. Increasing damage to the land, or land degradation, will occur in the form of soil erosion, desertification, salinisation, or loss of peat soils, further impacting on the capability of soils to support the needs of all types of vegetation.

South Sudan has extensive and diverse forest and woodland resources that provide food, oils, medicines, timber, poles and firewood, as well as habitat for much of Southern Sudan’s wildlife. Forest ecosystems are generally robust, yet in some areas they have been degraded by decades of uncontrolled fire, uncontrolled grazing, and over-cutting of more desirable species (Lomuro, 2006, USAID, 2007).

1.6. Factors Influencing Rainfall and Temperature over South Sudan

The main factors and systems influencing climate over South Sudan include the Inter-Tropical Convergence Zone (ITCZ), Sub-tropical high pressure systems, Inter-hemispherical monsoonal wind systems, Easterly and Westerly waves, and teleconnections with El-Niño Southern Oscillation (ENSO). Other factors include Intra-seasonal Madden-Julian Oscillation (MJO) (Anyamba, 1993), Easterly Waves, Monsoon Winds, Tropical Storms, Teleconnections with SSTs and the Quasi-biennial Oscillation (QBO) in the equatorial lower stratospheric zonal wind, solar and lunar forcings (Ogallo, 1988; Indeje and Semazzi, 2000). Some of these factors are discussed in detail in the subsections below.

1.6.1. Inter-Tropical Convergence Zone (ITCZ)

The Inter-tropical convergence zone (ITCZ) is a Planetary-scale tropospheric system that is accompanied with active convection and rainfall in the tropics. It is a region of zonal low-pressure belt in the lower troposphere. These yields inter-hemispheric convergence of the trade winds and thereby produce vertical motions, which are responsible for the intensified cumulus activity near the ITCZ. It also constitutes the main synoptic scale system that affects the intensity, distribution and migration of seasonal rainfall over the South Sudan. The onset and cessation of seasonal rainfall over the region depends on the onset and fluctuation of the ITCZ. Mesoscale circulations induced by factors like inland lakes and varied topography as well as maritime effects influence the large-scale pattern of the ITCZ (Black *et al.,* 2003). The movement of the ITCZ during the season is not uniform. It retreats faster southward compared to northward. The features of the ITCZ can defined depending on its location and strength. By location, the ITCZ can be north, south or double with respect to the geographical equator. Based on intensity, the system characteristics can be full or weak.

The ITCZ crosses South Sudan border in early February and continue advancing northward till reaches northern parts of country in early May. During this period, all the country is under the influence of southwesterly wind. The south-westerlies carry the moisture to the lower parts of the troposphere from Atlantic Ocean and Congo basin, and the easterlies in the mid-troposphere, which inject this layer with moisture, carried from the Indian Ocean (Nicholson, 1996; Okoola, 1999). During the advance of the monsoon, the high pressure systems tend to weaken and due to the direct rotation of the sun, a thermal low develop over the region and this situation tends to enhance amount of rainfall associated with strong thunderstorms. In September, the ITCZ moves rapidly southwards and the rainy season cease (Hammer, 1973).

1.6.2. El-Niño Southern Oscillation (ENSO)

The El Niño-Southern Oscillation (ENSO) is a global coupled ocean-atmosphere phenomenon. It is a leading mode of tropical climate variability at interannual timescales and characterized by Sea Surface Temperature (SST) and surface pressure anomalies across the Pacific Ocean. Positive "El Niño" phase occurs when SSTs are warm in the eastern tropical Pacif0ic Ocean contrasted by its negative "La Niña" phase when they are cool. ENSO impacts on Africa are believed to occur in part via tropical Atlantic (Chiang and Sobel, 2002) and Indian Ocean teleconnections (Alexander *et al*., 2002).

The positive/negative phases of the ENSO are associated with enhanced/depressed rainfall over equatorial East Africa especially during the OND season (Ogallo and Suleiman, 1987; Indeje and Semazzi, 2002).The positive/negative ENSO phase, called El Niño/ La Niña, was defined by the Scientific Committee for Ocean Research (SCOR) working group as "is the appearance of anomalously warm/cool water along the coast of Ecuador and Peru as far south as Lima (12°S). This means a normalized sea surface temperature (SST) anomaly values exceeding one standard deviation for at least four (4) consecutive months to conform existence of El Niño or La Niña. This normalized SST anomaly should occur at least three (3) of five (5) Peruvian coastal stations," SCOR, (1983).

There are four Niño regions (indices) across the central Pacific namely Niño 1+2, Niño 3, Niño 3.4 and Niño 4. Niño Indices are computed as the area-averaged sea surface temperature of each of the four Niño regions. Niño 1+2 region covers the extreme eastern equatorial Pacific between 0˚-10˚S, 90˚W-80˚W. Niño 3 covers the eastern equatorial Pacific between 5˚N-5˚S, 150˚W-90˚W. Niño 3.4 region covers the east-central equatorial Pacific between 5˚N-5˚S, 170˚W-120˚W. Niño 4 region spans the date line and covers the area 5˚N-5˚S, 160˚E-150˚W (Reynolds and Smith, 1998) see Figure 2.

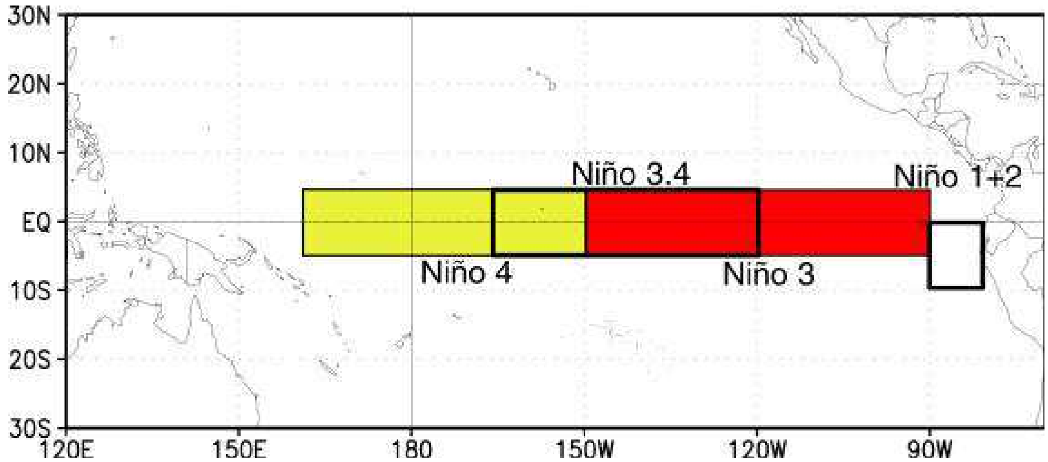


Figure 2: *The various Niño regions over the Equatorial pacific (Source:http://t0.gstatic.com/images)*

More recently in 2003, National Oceanic and Atmospheric Administration (NOAA) has revisited the concept of El Niño and defined it as a phenomenon in the equatorial Pacific Ocean characterized by a positive sea surface temperature departure from normal (for the 1971–2000 base period) in the Niño 3.4 region greater than or equal in magnitude to 0.5° C, averaged over three consecutive months.'' The opposite phase, La Niña, also defined as "a phenomenon in the equatorial Pacific Ocean characterized by a negative sea surface temperature departure from normal (for the 1971-2000 base period) in the Niño 3.4 region greater than or equal in magnitude to 0.5° C, averaged over three consecutive months (NOAA, 2006, IRI, 2006).

Through research, a unique anomalous warming of the central pacific within the equatorial region has been reported. This phenomenon is called 'El Niño Modoki,' (Ashok *et al*., 2007a). Modoki is a term derived from the Japanese language. El Niño Modoki occurs when anomalous warming occurs in the central Pacific Ocean only, with cooling in the eastern and western regions. EL Niño Modoki events are associated with colder East African coasts during the boreal summer (JJAS) while anomalous dry weather is experienced during northern hemisphere winter (Ashok *et al*., 2007b).

1.6.3. Indian Ocean Dipole

The Indian Ocean Dipole (IOD) is a coupled ocean and atmosphere phenomenon in the equatorial Indian Ocean that have influences on the climate of Australia and other countries that fall within the Indian Ocean basin (Saji *et al.* 1999) with a positive (negative) phase characterized by warm (cool) SSTs over the western Indian Ocean and cool (warm) SSTs in the eastern Indian Ocean. The IOD is defined by the averaged SST anomalies over 50–70^o E; 10^o S–10^o N (western Indian Ocean) and 90 –110^o E; 10^{o}S – 0^o(eastern Indian Ocean). The IOD evolution has three phases namely; negative, positive and neutral (see Figure 3). The threshold anomalies are +0.4 (-0.4) for positive (neutral) conditions, otherwise, the neutral phase exists.

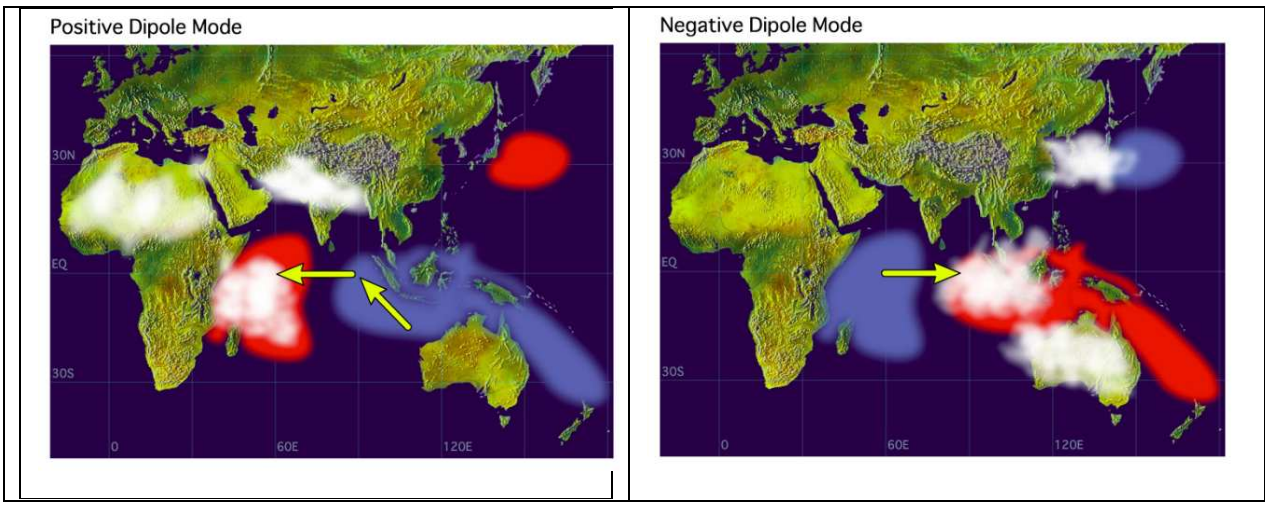


Figure 3*: Positive and negative phases of IOD*

(Source:www.jamstec.go.jp/frcgc/research/d1/iod)

There exists coupling between the IOD and the Walker circulation, hence affecting moisture transport into the Greater Horn of Africa (GHA) region. Due to this interaction, the positive (negative) phases are associated with enhanced (depressed) rainfall over East Africa but there is no specific study over South Sudan. The IOD influence on the East Africa rainfall is greatest when coupled with positive ENSO events during the short rains season (Saji and Yamagata, 2003; Owiti, 2005). The IOD has as well proved to be a viable rainfall predictor of rainfall. Modelling studies as well have revealed that the influence of ENSO to the East African short rains is highly significant when the IOD is anomalously warm (Clark *et al.*, 2003). The OND rainfall is not only influenced by the SSTs, but by the sub-surface features of the Indian Ocean as well, specifically by the sea surface height which induces equatorial Rossby waves that propagate towards the East African coast (Behera *et al*., 2005).

1.6.4. Monsoon Winds

Monsoons are seasonal winds which reverse their direction with season depending on the temperature difference between the Oceans and the Continents. They are seasonal (sometimes inter-hemispheric) wind systems, which converge at the ITCZ. They are the major transporters of moisture inland for rain formation across continent. The main rainy seasons in East Africa in general are largely associated with one monsoonal wind current receding while another one advancing. The monsoonal flows in the region are the south and the north easterlies. The active phase of the monsoons as rain bearing systems in South Sudan occurs during June to October.

During the Northern Hemisphere winter (DJF), most parts of East Africa are under the influence of the northeast monsoonal wind currents. These winds originate from the Arabian high and are generally dry since they are of continental origin and their trajectory is largely over the land (Anyamba, 1984; Okoola, 1996). The southeast/southwest monsoonal wind currents are experienced during the Southern Hemisphere winter (June-September). These winds are cool and moist, and originate from the Mascarene Anticyclone in the southern Indian Ocean. They are transported by the East African Low Level Jet stream(EALLJ) that is fully developed in July and enhance rainfall amount and contributing in advancing of ITCZ northward over South Sudan in rainy season.

1.6.5. Subtropical Anticyclones

Subtropical anticyclones are semi-permanent high-pressure systems centered over the subtropical latitudes (approximately 30^{o}S and 30^{o}N) of the north and south Atlantic, and the Indian Oceans. These anticyclones make pressure differences between the equatorial regions and the subtropical regions that are important for driving the tropical trade winds. The anticyclones that influence the synoptic flow over GHA in general are Mascarene, St Helena, Arabian, and the Azores high.

These systems are most intensive during winter seasons of each hemisphere and weaken during summer.

The moisture that comes into South Sudan depends on the location and strength of these anticyclones. For instance, the Mascarene anticyclone over the southwestern Indian Ocean determines the characteristics of the moist southeasterly monsoon flow over the Indian Ocean that influences rainfall over most GHA including South Sudan especially for June to August seasonal rainfall.

The St. Helena anticyclone over southeast Atlantic Ocean is responsible for the pronounced middle level westerly flow (the Congo air mass) over the GHA, which influences most parts of the south Sudan during all rainy seasons (March-November). The Azores high causes subsidence of warm dry air over the Sahara and neighboring regions while the Arabian anticyclone sends dry continental north easterly wind over most of the eastern parts of Africa (Griffith, 1972; Anyamba, 1984, sabiiti, 2008) and constitute the main source of cool climate over South Sudan during winter months (December to February) especially in the northern part of country.

The conditions favorable for their formation of Subtropical Anticyclones over GHA include SSTs and reduced vertical wind shear as well as moisture availability. For this reason, the formation of the Subtropical Anticyclone is usually enhanced during active MJO phase over the Indian Ocean (Hendon, 1999). Such relationships have as well been observed in the Australian region by Hall *et al*., (2001). During the long rains, the Subtropical Anticyclone over the Arabian Sea enhances rainfall along the GHA coastal regions. While the Macarena anticyclone forming along the Mozambique Channel were associated with dry conditions that caused the drought of 1984 in Kenya (Anyamba,1993), and drought in Sudan in 1983/1984, where large number of people lost their lives especially in the southern parts (now South Sudan).

.

CHAPTER TWO

2.0 Literature Review

This chapter reviews past studies on spatial and temporal characteristics of rainfall and temperature, climate change and variability including extreme climate events, teleconnection of seasonal rainfall and Indian Ocean Dipole (IOD), El Niño Southern Oscillation (ENSO) over Greater Horn of Africa (GHA) and over the South Sudan in particular.

2.1 Climate Change and Variability

Climate change and climate variability are two important characteristics of climate. According to IPCC (2007) report, climate change refers to a statistically significant variation either in the mean state of the climate or in its variability, persisting for a long period (typically decades or longer). The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (Livia *et al.*, 2009).

According to American Meteorological Society (AMS, 2010), Climate change refers to any systematic change in the long-term statistics of climate elements (such as temperature, pressure, or winds) sustained over several decades or longer time periods. On the other hand, climate variability refers to the variations in the mean state and other statistics of climate on both temporal and spatial scales beyond that of individual weather events. For climate change, human factors are more responsible for change compared with natural processes, but climate variability, natural factors have more effect than human factors (IPCC, 2007a).

The climate of the world is changing in a tragic manner; the evidences of these changes are very clear according to most recent climate researches from different regions around the world (Funk *et al*., 2012, IPCC, 2013a, Lange, 2014). Africa is the most vulnerable continent to the effect of climate change and variability due to low adaptive capacity and weak resilience in different socio-economic sectors, such as lack of adaptation strategies in case of water stress and food insecurity among others, hence increasing vulnerability of the poor communities.

During the 20th Century, Global surface temperatures showed an increasing trend in many regions around the world with interannual climate variability being observed in many regions (Salinger *et al*., 1997). The 1982/83 and 1997/98 El Nino and the 1991 Mt. Pinatubo volcanic eruption caused substantial variability in the interannual climate of tropical regions, where some regions observed above normal rainfall and other were experienced drought (Salinger *et al*., 2000).

Tayanc *et al*. (2009) in their study showed a significant warming trend in southern and southeastern parts of Turkey from 1950 to 2004. Significant decrease in precipitation was observed over the western parts of the country, although the variability of precipitation was substantially different across urban and rural areas. Suggesting that urban stations can experience more frequent and severe droughts and floods compare to rural areas.

Nicholson *et al*. (2013) analyzed temperature variability over Africa during the last 2000 years and observed that near surface temperature have increased by 0.5°C or more during the last 50-100 years over most parts of Africa with minimum temperatures warming more rapidly than maximum temperatures. Near surface air, temperature anomalies in Africa were significantly higher for the period 1995–2010 compared to the period 1979–1994 (Collins, 2011, Niang *et al*., 2014).

During the last few decades, north Africa's observed annual and seasonal trends in mean air surface temperature indicates an overall warming that is significantly beyond the range of changes due to natural (internal) variability (Barkhordarian *et al*., 2012a). During the warm seasons or summer rainy seasons (MAM-JJA) an increase in near air surface temperature is shown over north Algeria and Morocco, which is very unlikely due to natural variability or natural forcing alone (Barkhordarian *et al*., 2012b). The region has also experienced increasing trends in annual minimum and maximum temperature (Vizy and Cook, 2012).

The study carried out by Lyon and DeWitt (2012) shows a decline in the March–May seasonal rainfall over eastern Africa. Summer (June–September) monsoonal precipitation has declined throughout much of the Greater Horn of Africa over the last 60 years during the 1948–2009 periods (Williams *et al*., 2012). This happened because of the changing sea level pressure (SLP) gradient between Sudan and the southern coast of the Mediterranean Sea and the southern tropical Indian Ocean region.

Study carried out by Abaje (2010) on evaluation of rainfall trends in Kafanchan, Kaduna State, Nigeria, revealed that the rainfall regime is markedly seasonal with a long drier season. The analysis for Sub periods 1974-1983 and 1999-2008 for June and October respectively indicates that these periods were notably drier compared to average conditions. The results of the standardized anomaly index showed that rainfall amount is declining. Analysis of observed trends revealed that the decline in the annual rainfall amount is mainly because of the considerable decline in July, September, and October rainfall.

Kostopoulou and Jones (2005) studied possible changes in temperature and precipitation related climate extremes over the eastern Mediterranean region for the period 1958–2000. The most significant temperature trends were observed during summer, where minimum and maximum temperature extremes showed statistically significant warming trends. Although precipitation indices revealed regional contrasts, the eastern and southern stations indicated trends towards drier conditions.

Study by Nsubuga *et al.* (2013) examined the characteristics of mid-twentieth century rainfall trends and variability over southwestern Uganda and pointed out that % 53 of stations had positive trends where 25 % were statistically significant and %45 of stations have negative trends with %23 being statistically significant. Very strong trends at % 99 significance level revealed in 12 stations, Positive trends in January, February, and November at 40 stations observed. The highest rainfall was recorded in April, while January, June, and July received the lowest rainfall. Spatial analysis results showed that stations close to Lake Victoria recorded high amounts of rainfall.

Anyah and Semazzi (2005) assessed climate variability over the Greater Horn of Africa based on NCAR AGCM ensemble and their findings showed inter-annual variability derived from leading mode of Empirical Orthogonal Function (EOF) analysis that was dominated by ENSO-related fluctuations. The spatial pattern corresponding to the second mode (EOF2) offered a unique dipole rainfall pattern (wet/dry conditions) over the northern/southern equitable to domain during all the three months of the short rains season. Merging of different anomalous surface and mid-tropospheric flow from northwestern and eastern Atlantic Ocean and easterly flow from the Indian Ocean caused the non-ENSO related 1961 floods. However, during the ENSO-related 1997 floods, the mid-troposheric flow characterized by anomalous westerly flow from the Congo rainforest that converged with the easterly flow from Indian Ocean along the East Africa coast.

The Assessment of Sudan Post-Conflict Environmental situation identified climate change as one of the most critical threats to the development of Sudan. Expected changes in weather and climate patterns are projected to accelerate existing household vulnerabilities and to exceed current coping mechanisms hence limiting poor people's capacity to maintain sustainable livelihoods. This will also lead to increased water scarcity, accelerated desertification and soil erosion processes, decreased productivity (a 20 % drop in crop yields is predicted), damages caused by more extreme climate events such as droughts and floods, increased heath-related illnesses, and higher risk of pest and disease outbreaks (USAID, 2007; IFAD, 2009).

Recent reports from the Famine Early Warning Systems Network (FEWSNET) indicate that there has been an increase in seasonal mean temperature in many parts of Kenya, Ethiopia, South Sudan, and Uganda over the last 50 years (Funk *et al*., 2011; 2012). In addition, warming of the near surface temperature with an increase in the occurrence of extreme warm events observed for countries bordering the western Indian Ocean between 1961 and 2008 (Vincent *et al*., 2011).

Chan (2011) assessed climate variability and change impacts on livelihood and coping strategies in upper Nile state of South Sudan. He pointed out that probability of occurrence of 5 days dry spells was high and farmers are the most vulnerable to climate variability and change. Results also showed the climate change and variability have serious environmental, economic, and social impacts especially where household incomes of a number of families depend on rain fed agriculture.

2.2 Temporal and Spatial Characteristics of Rainfall and Temperature

There are significant trends in spatial and temporal characteristics of rainfall and temperature, as indicated by the many studies carried out in different parts of the globe on rainfall trends (Zhang *et al*., 2008, 2009a, b, c, 2010; Turks, 1996; De Luís *et al*., 2000; Gonzalez-Hildago *et al*., 2001; Cannarozzo *et al*., 2006). The different results from these studies showed that there is variation and distinct changes detected.

Michaelides *et al*. (2009) studied spatial and temporal characteristics of the annual rainfall frequency distribution in Cyprus and found that temporal and spatial characteristics of rainfall provide essential information to water resources planning and management. This information is also crucial in agricultural planning, flood frequency and intensities analyses, water resource assessments, and climate change impacts assessments.

Kostopoulou *et al*. (2014) examined spatial and temporal patterns of recent and future climate extremes in the Eastern Mediterranean and Middle East region using the Hadley Centre PRECIS model. Results indicated a future warming trend for the study area over the last 30yr of the 21st century. The patterns of the annual trend for both minimum and maximum temperature showed warming rates of approximately 0.4–0.6^{o}C per decade, with pronounced warming over the Middle Eastern countries.

Ngongondo *et al*. (2011) evaluated the spatial and temporal characteristics of rainfall in Malawi, and found a statistically insignificant decreasing annual, seasonal and monthly rainfall in most stations. Results on the spatial analysis showed a complex rainfall pattern countrywide. The country also was characterized by unstable monthly rainfall regimes.

Mojwok (2008) investigated the effects of rainfall fluctuations on rain-fed agricultural production in Renk area, Upper Nile State, as a representative of South Sudan cultivation areas. The results showed strong relationship between the agricultural production and rainfall performance. The results also indicate the positive and negative effects of extra-ordinary rainfall (inadequate and excessive rainfall) performance and Agricultural production.

The study carried out by Edward (2011) to understand the linkages and Indicators of Climate Change in Upper Nile State, South Sudan showed notable increase in the monthly rainfall totals and temperatures (maximum and minimum), the results also revealed the accompanying destruction of biodiversity in ecosystems of the natural environment due to illegal practices such as cutting of trees for firewood, charcoal, clearing of lands for agricultural production, mass killing of wild animals for meat among others.

2.3 Rainfall and Temperature Extremes

Climate change have a strong effect on socio-economic sectors like agriculture, water resources and energy among others through occurrence of extreme climate events, which are responsible for a major part of climate-related economic losses (Kunkel *et al*., 1999; Easterling *et al*., 2000).The major extreme climate events that are categorized under extreme precipitation and temperature are flood, drought, frost cold and heat waves. These extreme events affect property, society and the entire ecosystems in different ways. For example Extra-ordinary rainfall can cause floods due to change in rainfall patterns such as changes in frequency or in intensity while extreme temperature events can affect crop growth and reduce production differently with changes in frequency, with an increase in recurrent days of extreme maximum and minimum temperature (Li *et al.,* 2010).

Yun *et al.* (2012) examined changes in climate and extreme climate indices in present and Future Projected climate in Korea, the model results pointed out in a clear and sensible way that the spatial change in extreme climate indices is significantly modulated by geographical characteristics in relation to land-ocean thermal inertia and topographical effects. The summer-based indices showed an increasing trend, while the winter-based indices show a decreasing trend.

Ning *et al*. (2012) studied the changes of temperature and precipitation extremes in Hengduan Mountain, and detected a significant increase in the temperature of the coldest and warmest nights and in the recurrence and intensities of extreme warm days and nights. While there is clear decrease in diurnal temperature range and number of frost and ice days, averages of increasing season length also showed the trend is harmonious and significant with warming. Minimum temperature warming trends are greater than those of maximum temperature but variations of extreme precipitation events are unclear.

Michael (2011) examined the current and future characteristics of extreme events in California and found a significant increase in the frequency and intensities of both high maximum and high minimum temperature extremes in many areas of California. The frequency of extreme temperatures earlier observed once every 100 years are expected to increase by at least ten-fold in many parts of California under a moderate emissions scenario. The projected changes under a higher emissions scenario will occur almost annually in most regions. Like other projections, analysis of precipitation extremes failed to identify a significant signal of change with incoherent behavior when comparing simulations across different GCMs and different methods of downscaling.

The Fifth Assessment Report of the intergovernmental panel on climate change (IPCC, 2013a) Presented conclusive evidences that the warming over land across Africa has increased over the last 50–100 years. Surface temperatures have already increased by 0.5–2°C over the past hundred years. Data from 1950 onwards suggests that climate change has already altered the magnitude and frequency of some extreme weather events in Africa. The health, livelihoods and food security of people in Africa have been affected by climate change (IPCC, 2014, CDKN, 2013).

Tilya (2007) studied characteristics of wet and dry spells in Tanzania during the rainy seasons. The results showed the longest run of 28 days of wet spells observed in the highland stations while the longest run of dry spells of 249 days were observed in 1999 in central Tanzania. Increasing trends were observed over parts of Lake Victoria basin during MAM and OND seasons and south eastern highland of Tanzania during the October to May single season. At the same time, decreasing trends were observed over the western parts of southern Tanzania around Lake Tanganyika and north eastern highlands of the country. Spectral and wavelet analyses showed that spectral bands of 5 to 7 days, 10 to 15 days and 20 to 30 days were the most dominant spectral mode during the two wet seasons at most locations in Tanzania

Gitau (2005) studied characteristics of the wet and dry spells during wet seasons over Kenya. The main findings indicated that the frequency of wet/dry spells decreased as the length of the wet/dry spells increased. It also noted that if more days considered for wet / dry spells of a given length M, the conditional probability of the wet and dry spells were found to decrease in all locations and for all thresholds.

Ngaina and Mutai (2013) examined the observational evidence of climate change on extreme events over East Africa and found that there is general decrease in annual total rainfall with heavy and extreme precipitation being received within short spells. Maximum temperature extremes were observed to be increasing while minimum temperature extremes decreased with a statistically significant rise in the number of warm nights and hot days and decrease in number of cool days and cold nights. On the other hand, spatial and temporal patterns of observed changes were not well organized.

Hydro-meteorological disasters like floods and drought have been estimated to cause unknown percentage of loss the South Sudanese gross domestic product (GDP) every year since 1990s (USAID,2007 ,UNDP,2012). Variations in extreme weather and climate events under the background of global warming may cause major unrest in South Sudan. Unfortunately, there is big gap in the knowledge of these extremes due to long civil war in the country.

2.4 Climate Change and Variability and Extremes impacts

Climate change and variability Impacts on most of socio-economic such as agriculture sector are expected to steady manifest directly from changes in land and water regimes, the likely primary conduits of change. Changes and recurrent and intensity of extreme events such as drought, flooding, and storm damage are observed and expected to continues in next a few years (Magadza 2000, Howden,1997 and Challinor,2008). Climate change is expected to result in long-term water and other resource shortages, worsening soil condition, drought and decertification, diseases and pest outbreaks on crops and livestock, seas-level rise, among other(IPCC,2007b). Rainfall and temperature are key features of climate that threaten rain fed agricultural productivity in the tropical and sub-tropical countries. Agricultural production depends on rainfall and carbon dioxide in the atmosphere among other factors. Rainfall is affected by the change of atmospheric temperature or global warming. In the recent years scientific research based on reliable world climate data reveled that the climate is being affected by the Green House Gases(GHGs) effect and temperature and precipitation are changing globally (IPCC, 2001a, IPCC, 2007a, IPCC, 2013a,).

Climate change has already caused significant impacts on water resources, food security, hydropower, human health especially for African countries, as well as to the whole world (Magadza, 2000). Studies on climate impacts and adaptation strategies are increasingly becoming major areas of scientific concern, e.g. impacts on the production of crops such as maize, wheat and rice (Howden,1997 and Challinor,2008), water resources in the river basin catchments (Chang,2002, Wilby,2005 and Herrera,2008),forests (Lexer,2007),industry (Harle,2007) and the native landscape (Dockerty,2005 and Dockerty,2006).

Climate variability adversely impacts crop production and imposes a major constraint on farming planning, mostly under rainfed conditions across the world. Higher growing season temperatures can significantly impact agricultural productivity, farm incomes and food security (Battisti and Naylor, 2009). The moderate warming and more carbon dioxide in the atmosphere may help plants to grow faster (U.S. Census Bureau, 2011). However, more severe warming, floods, and drought may reduce yields. Livestock may be at risk, both directly from heat stress and indirectly from reduced quality of their food supply. Fisheries will be affected by changes in water temperature that shift species ranges, make waters more hospitable to invasive species, and change lifecycle timing (USGCRP, 2009).

Water availability is a critical factor in determining the impacts of climate change and variability in many places, especially in Africa. Also temperature in Africa are projected to increase at least more than global .this will have varying impacts depending upon ecological zones(IPCC,2007a). A number of studies suggest that rainfall and length of growing season are critical in determining whether climate change is positively or negatively affects agriculture (Karanga, 2007, Ariel. et al., 2008). The predicted variability of temperature, precipitation, atmosphere carbon oxide and extreme events are anticipate to have profound effect on plant grows and yield, crops, soil, weed, diseases, livestock and water availability in sub Saharan Africa (IPCC, 2007b, Ariel. et al., 2008, USGCRP, 2009, Chan, 2011).

The contribution of agriculture to GDP varies across countries but some studies suggest that an average contribution of 21% (ranging from 10% to 70%) of GDP (Mendelssohn *et at., 2000,* Biggs *et al., 2004*). South Sudan is rich in agricultural land and has one of the largest populations of pastoralists in the world (Oakland, 2011). The contribution of agriculture to south Sudan GDP has been not quantified clearly, however, The United nation Food and Agriculture Agency(FAO) report suggests that the sector contributed significant not only to national economy but also to rural livelihoods (FAO, 2008). Therefore, the impacts of climate change and variability especially frequent wet and dry spell can trigger an unprecedented tide of mass migration from one state to another (within region), from rural areas to nearby cities, and from country to the neighboring county/district and other state or province which can impacts the economy and reduce GDP in South Sudan.

2.5 Teleconnections between rainfall and Indian Ocean dipole (IOD) and ENSO events

A study carried out by Salinger *et al*. (2001) to examine climate variability found that in late 20th Century, the changes and variability in climate have been attributed to global warming, Interdecadal Pacific Oscillation (IPO), interannnual timescales El Nino/Southern Oscillation (ENSO), and the North Atlantic Oscillation (NAO). During the course of the 21st Century, it is expected that the global-average surface temperatures will increase by 2 to 4.5◦C as greenhouse gas concentrations in the atmosphere increase (IPCC, 2007a). This will also lead to changes in precipitation and extreme event such as heavy rainfall, hot days, and droughts, which are expected to increase in many areas around the world due to the direct effects of climate change and variability.

Enos (2013) investigated El-Niño Southern Oscillation (ENSO) and its influence on rainfall over Tanzania. The main findings showed weak correlation and no significant effect by El-Nino evolution phases on the MAM season rainfall. The study highlighted non-linear relationship between ENSO and rainfall, which meant a clear evidence of weak relationship between seasonal rainfall and ENSO over Tanzania.

Owiti (2005) studied Indian Ocean dipole indices as a predictor of East African rainfall anomalies. The results showed significant association between East Africa rainfall during the short rainy season with positive and negative Indian Ocean Dipole (IOD) phases. These findings indicated good prospective for improving monitoring, prediction and early warning of extreme rainfall events over East Africa, thereby reducing the vulnerability, and improve the resilience of the society of the region to negative impacts of extreme rainfall events that are common in the region.

Gitau *et al*. (2013) studied spatial coherence and potential predictability of intraseasonal statistics of wet and dry spells over Equatorial Eastern Africa, for long and short rainfall seasons. The results showed spatial coherence of the seasonal rainfall totals and the number of the wet days at sub-regional level for the long and short rainy seasons. While mean rainfall intensity and frequency of dry spells of 5 days or more showed the least coherence, but intraseasonal components of daily rainfall for short rainfall season were more coherent compared to the long rainfall season. The study also pointed out that lag-correlations with key indices depicting sea-surface temperatures in the Pacific and Indian Oceans showed that the hierarchy between the rainfall statistics in the strength of the teleconnections reflected that of spatial coherence.

Mutemi (2003) studied the climate anomalies over eastern Africa associated with various ENSO evolution phases. The study pointed out that the recurrent of some extreme rainfall events associated with certain phases of the warm or cold ENSO phenomenon. In addition, the study also observed from both composite and correlation analyses that during the long rainfall season East Africa is dominated by weak positive ENSO signals during the onset phase of warm events and a negative correlation with the maturity, and withdrawal phases of the warm events. Correlation analyses further revealed that rainfall during the short rainfall period had stronger and uniquely opposite signals for warm and cold ENSO events. Onset and maturity phases of warm ENSO teleconnected positively with rainfall during the October-December period and maximum signals occurred at the maturity phase.

A study carried out by Owiti *et al*. (2008) to understand linkages between the Indian Ocean Dipole and East African seasonal rainfall anomalies indicated that IOD events have strong influence on the regional climate system during the October to December rainfall season and some of the extreme rainfall conditions over East Africa associated with positive and negative IOD phases and teleconnection were strong during El Niño/La Niña years.

Ininda (1998) assessed the performance of rainfall in East Africa using numerical simulation. The results showed that rainfall over most regions in East Africa was influenced by the SST through modification of the east-west (Walker) circulation and the local north–south (Hadley) circulation.

Gezahegn (2001) showed significant correlation between regional Ethiopia rainfall and SST over some specific ocean regions. These formed the basic base for the predictions. In addition, study results showed that southern oscillation indices have a significant lag correlation with seasonal rainfall over some zones. The SST over the El-Nino regions featured in the model, indicating the important role played by the ENSO in the interannual variability of Ethiopian rainfall. It was further noted that predicting the March to May (MAM) using January SST has a better skill than November, December and January SSTs. The March, April and May SST predictors were found to have a good skill in forecasting the Kiremt (long) rainy season. The May SST predictors had a better skill for some climatic zones in Ethiopia.

The rainfall anomaly of Sudan has been teleconnected to Sea Surface Temperature Anomalies (SSTAs) in the Gulf of Guinea (Lamb 1978a, b). Palmer (1986) pointed out that the tropical Indian Ocean SST has a strong influence on the Sahel rainfall. Osman and Shamseldin (2002) used El Nino Southern Oscillation and sea surface temperature over Indian Ocean and tropical pacific to investigate rainfall variability in the central and southern regions of Sudan. The results showed that the driest years were associated with warm ENSO and Indian Ocean SST conditions in the tropical Indian Ocean.

From the literature reviewed considerable studies have been indicated around the world in relation to the spatial and temporal characteristics of rainfall and temperature including extreme events over Equatorial East Africa. Also the teleconnection of rainfall with some mechanism and factors affecting distribution of rainfall and temperature such as IOD and ENSO were covered in details using different statistical techniques. But for South Sudan, there are gaps of such study, the general behavior of rainfall and temperature characteristics still unclear and specific studies covering all country are rare especially during long civil war, which has been the main contributor to knowledge gaps. Therefore this study was designed to fulfill the gaps and to provide climate information need in advance early warning systems on temporal and spatial characteristics of rainfall and temperature and to evaluate the role of IOD and ENSO events on variability of rainfall over South Sudan.

CHAPTER THREE

3.0 Data and Methodology

This chapter presents the data and different methods that used in this study to achieve the objectives.

3.1 Data type and source

The data used in this study included; observed monthly rainfall, maximum and minimum temperature, sea surface temperatures (SSTs) over Indian Ocean (west and east) and different ENSO regions (Niño1+2, Niño 3, Niño3.4 and Niño 4) dataset. Details of these datasets and their sources are explained in the sub sections that follow.

3.1.1 Rainfall and temperature data

The climatic data used in this study include gauged rainfall and temperature corresponding of dataset (historical monthly rainfall totals and monthly mean temperature) covering the period 1954 to 2013 for five synoptic stations namely, El renk, Malakal, Raja, Wau and Juba. These datasets were obtained from South Sudan Meteorological Department (SSMD). The distributions of stations across South Sudan are show in Figure 4.

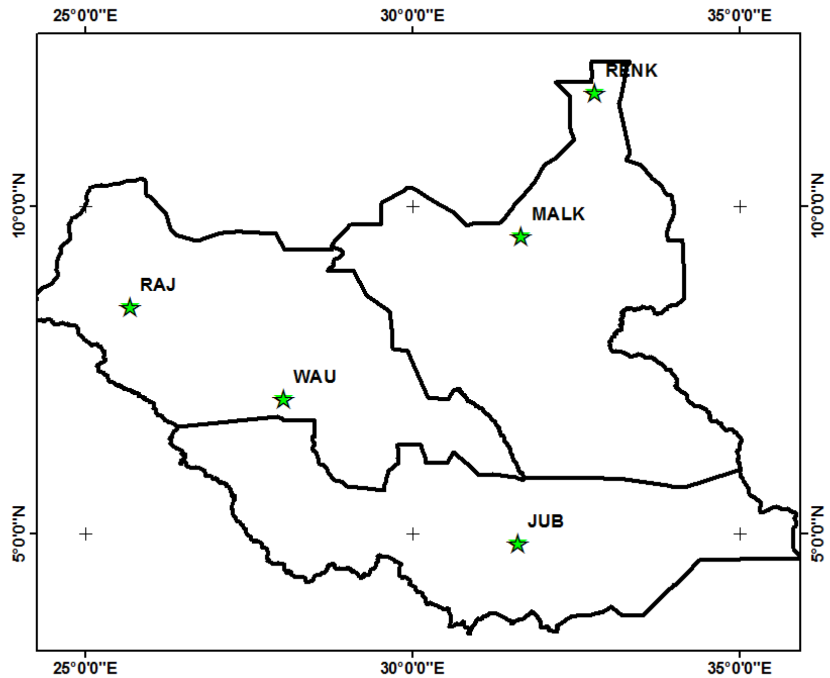


Figure 4: The study area with the location of the stations used in the study

3.1.2 Sea Surface Temperature Data

Sea surface temperature (SSTs) datasets which were used in this study included SSTs over Indian Ocean known as Indian Ocean dipole (IOD). As mentioned in earlier sections, The Indian Ocean dipole (IOD) is defined by the averaged SST anomalies over 50–70^{o} E; 10 ^{o} S–10 ^{o} N (western Indian Ocean) and 90 –110 ^{o} E; 10 ^{o} S–0 ^{o}, (eastern Indian Ocean).

In addition Sea Surface Temperature (SST) dataset over tropical Pacific Ocean known as Niño regions (Niño 1+2, Niño 3, Niño 3.4 and Niño 4) covering period (1961 to 2013) was also used. The Niño indices data was downloaded from National Center for Environmental Prediction/Climate Prediction Center (NCEP/CPC). These SST data is on 2 x 2 grid resolutions and often known as Optimal Interpolation (OI) Sea Surface Temperature (SST) in literature following Reynolds and Smith (1994).

3.2 Methodology

This section presents the methodologies that were used to achieve the specific objectives of this study. Several statistical methodologies including data quality control tests, Arithmetic mean, standard deviation, skewness and kurtosis, Mann-Kendall, linear regression, spectral analysis, standardized precipitation index (SPI), Gaussian kernel probability distributions, Pearson correlation analysis. These methods are discussed in the following sub sections.

3.2.1 Data Homogeneity Test

The main reason for undertaking data homogeneity test is to ascertain the quality of data that may compromised by the existence of outliers and inconsistencies. Inconsistent data can occur due to several reasons such as change of location of observing stations, change of instruments or due to human error such as non-trained observers and continued long civil war or any other instability activities. The need for examining data quality is to ensure that the data is complete and free from outliers and to ensure that correct and reliable statistical inferences can make from the data.

Data quality control refers to a set of techniques applied to detect and correct inconsistencies in observed rainfall data. Quality control of the data was attained using single mass curve to test for data homogeneity. This involved plotting cumulative values of climatological records against time. A single straight line indicates a homogeneous record whereas heterogeneity tendency is indicated by existence of more than one line fitted to the graphical plots of the cumulative data. The methodologies for examining spatial and temporal characteristics of rainfall and temperatures are discussed next.

3.2.2 Testing Normality Distribution of Meteorological Data

Skewness(S) characterizes the degree of asymmetry of a distribution around its mean. Positive skewness indicates a distribution with an asymmetric tail extending towards more positive values. Negative skewness indicates a distribution with an asymmetric tail extending towards more negative values (Microsoft, 1996). If the skewness S=0 then the distribution represented by *S* is perfectly symmetric. Mathematically, Pearson's moment coefficient of skewness can be calculated using eqations 1

$$SKEW = \frac{\sum_{i=1}^{N}(Y_i - \overline{Y})^3/N}{S^3} \quad \dots\dots\dots\dots\dots\dots\dots.(1)$$

Where ***Y*** sample data, $\overline{Y}$ is mean, **N** is sample of data, **S** is sample standard deviation.

Kurtosis refers to the peakedness or flatness of a distribution compared to the normal distribution. Positive kurtosis indicates a relatively flat distribution. A normal distribution has kurtosis exactly 3 (excess kurtosis exactly 0). Any distribution with kurtosis value equal to 3 is called mesokurtic. A distribution with kurtosis <3 is called platykurtic. Compared to a normal distribution, its central peak is lower and broader, and its tails are shorter and thinner. A distribution with kurtosis >3 is called leptokurtic. Compared to a normal distribution, its central peak is higher and sharper, and its tails are longer and fatter. Kurtosis computed using equation 2

$$KURT(K) = \frac{\sum_{i=1}^{N}(Y_i - \overline{Y})^4/N}{S^4} \quad \dots\dots\dots\dots\dots..\dots\dots\dots\dots\dots.(2)$$

Where ***Y*** sample data, $\overline{Y}$ is mean, **N** is sample of data, **S** is sample standard deviation.

3.2.3 Statistical Methods of Temporal Characteristics of Rainfall and Temperature

Several statistical methodologies which included standardized Anomalies Index (SAI) and trend analysis (graphic and statistical methods) were used to achieve the first specific objective. The temporal pattern that includes time series plots were achieved using of **Pro**tection Upper Confidence Level (ProUCL)-software, RStudio,XL STAT, Microsoft excel while spatial maps obtained by use of surfer software. All these methods are discussed in the next sub sections.

3.2.3.1 Rainfall Anomaly Index (RAI)

The Rainfall Anomaly Index (RAI) was developed by Van Rooy (1965). The RAI is calculated on basic of seasonal and annual time scale to examine the nature of the trends and variability in seasonal and annual rainfall and temperature time series. The RAI is simply calculated by taking the difference between the precipitation/temperature and long term mean for a particular time step, and then dividing it by the standard deviation. Equation 3 was used to compute the SAI.

$$\textbf{RAI} = \frac{X_{i} - \overline{X}}{S_x} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

Where X_i is the annual rainfall total, $\overline{X}$ is the mean of the entire series, and S_x is the standard deviation from the mean of the series. The SAI is a dimensionless index where negative values indicate dry, while positive values wet conditions. For purpose of this study, the SAI is used only to standardize rainfall and temperature datasets.

3.2.3.2 Trend Analysis

Trend presents the long-term movement of the time series. It is the underlying direction (an upward or downward tendency) and rate of change in a time series. Trend patterns can be derived from graphical and statistical techniques (Ogallo 1980, 1981; Omondi 2005; Muthama *et al.*, 2008). Trend analysis can be achieved through graphical and statistical techniques (parametric and non-parametric tests). However graphical method tends to be subjective hence statistical technique is always preferred. For this study only statistical techniques (Linear regression and Mann-Kendall) and **Pro**tection Upper Confidence Level (ProUCL 5.0)-software were used to plot general characteristics of trends in rainfall and temperature, while graphical methods were used in analysis of annual cycles. Details of these techniques (graphical and statistical) were discussed below.

3.2.3.1 Graphic Method

The Graphical techniques are a powerful data evaluation instruments that can be used to plot the annual rainfall and temperature data series. They provide a quick, easy and visual summary of essential meteorological data characteristics. Box plots, histograms, and normal probability plots are examples of graphs that commonly used to display climate data. This method involves the plotting of scatter, line graph and bar chart diagrams where various variables plotted against time. The scatter diagram shows neighboring points connected to give a time versus data point's graphs. These graphs can explain information about concentration ranges, shapes of distributions, extreme values (outliers), relationships between different data sets, and trends (increasing, decreasing, and cyclic). Graphical methods typically used with quantitative statistical evaluations and provide information that may not be otherwise apparent from qualitative statistical evaluations. Graphical method is highly subjective, they may not be appropriate as a stand-alone method to make conclusions. In this study graphical method were used in plotting of annual cycles and histograms of rainfall and temperature.

3.2.3.2 Statistical Methods

The statistical methods used for trend analysis can either be parametric and non-parametric. For parametric method, the simple regression analysis was used while for non-parametric tests, the Mann-Kendall test was used. Details of Linear regression and Mann-Kendall techniques were discussed below

3.2.3.2.1 Linear Regression Analysis

Linear regression can be simple (one dependent variable and one independent variable) or multi-regression (one dependent variable and more than one independent variable). It tests whether there is a linear trend by examining the relationship between time *(t)* and the variable of interest *(y)*. In this case *y* is either rainfall or temperature. Regression analysis can be achieved by using Equation 4.

$$\hat{y} = \alpha_i + b_1(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (4)$$

Where the symbol $\hat{y}$ represents the value of dependent variable (y), $\boldsymbol{\alpha_i}$ and $\boldsymbol{b_1}$ are the least-squares estimates of the intercept and slope coefficients also known as regression gradient, *(t) is* time.

If the slope is significantly different from zero, the trend in the rainfall and temperature variables is equal to the magnitude of the slope and the sign of the slope defines the direction of the trend (increasing if the sign is positive and decreasing if the sign is negative). If the slope is not significantly different from zero, there is no trend in the dependent variable. The P- value (probability of rejecting the null hypothesis (H_0)) is used to test for significance at 0.05 (0.95) level of confidence (Otom, 2011)

3.2.3.2.2 Mann Kendall Trend Test

This is a rank based method which is non-parametric and is based on an alternative measure of correlation called Kendall's τ. Non-parametric techniques do not rely on data belonging to any particular probability distribution. Non-parametric statistical procedures are less powerful because they employ less information in their calculation as they only consider the ordinal position of pairs of scores. Mann (1945) originally used this test and Kendall (1975) subsequently derived the test statistic distribution. Mann Kendall test only indicates the direction and not the magnitude of significant trends. In this study the procedure described by Helsel and Hirsch (2002) in carrying out the Mann-Kendall test were used which involved computation of the standardized test statistic S gave by Equation 5.

$$\boldsymbol{S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(X_j - X_i)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(5)$$

Where X_i and X_j are sequential data values, **n** is the dataset record length and sgn (X_j –X_i) is +1, 0 and −1 for X_j –$X_i$greater than, equal to or less than 0 respectively. The significance level, which indicates the strength of the trend, was determined by resampling analysis while the Kendall's correlation coefficient which is a measure of the strength of the correlation is calculated using Equation 6.

$$\tau = \frac{\boldsymbol{2S}}{\boldsymbol{(n(\,n-1))}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..\boldsymbol{(6)}$$

Where **τ** is Kendall correlation coefficient, ***S*** is standardized test statistic, and ***n*** *is* the dataset record length .A positive value of τ indicates increasing trend and negative value indicates a decreasing trend and if **τ** =**0** is no trend (Hirsch *et al.*, 1982).

3.2.4 Measures of Variability and change

In literature, there are four common techniques used to measures variability. These are the inter-range, interquartile range, variance or coefficient of variance, and standard deviation David, (2003). For purpose of this study, the standard deviation (SD) were used to measure variability and arithmetic mean were used to measure of changes in rainfall and temperature term mean (LTM).These methods are discusses in the next sub sections.

3.2.4.1 Arithmetic Mean

Arithmetic Mean is the sum of a collection of numbers divided by the number of numbers in the collection. This method tests whether the means of two different periods are statistically different. The test assumes that the data are normally distributed. This test has the ability to compare the means of two samples (or treatments), even if they have different numbers of replicates. The mean state of rainfall and temperature was computed using Equation 7.

$$\bar{X} = \frac{1}{N}\sum_{i=1}^{n} X_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (7)$$

Where $\bar{X}$ = average (or arithmetic mean), n is the sample size, X_i = the value of each individual item in the data being averaged.

3.2.4.2 Standard Deviation

The standard deviation (SD) (represented by the Greek letter sigma, σ) measures the amount of variation from the average. The t -test compares the actual difference between two means in relation to the variation in the data, which is expressed as the standard deviation of the difference between the means. The variability (standard deviation) of rainfall and temperature was computed using Equations 8.

$$\sigma_{x} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (8)$$

Where; χ_i is the i^{th} observation of any given variable and n is number of observations.

3.2.5 Determination of Extremes

3.2.5.1 Standardized Precipitation Index (SPI)

The standardized precipitation index (SPI) is a drought index first developed by Lloyd-Hughes and Saunders (Costa, 2011). The SPI is used for estimating wet or dry condition based on precipitation. Positive SPI values indicate wet condition greater than median precipitation, whereas negative indicates dry condition less than median precipitation. For purpose of this study, the SPI was computed on 12-months time scale. The classification scale for SPI values used in this study is given in table 1 ((McKee *et al.,* 1993; Lloyd-Hughes and Saunders, 2002).

Table 1: Classification scale for the SPI values

Description of state	**SPI values**	**Description of state**	**SPI values**
Extreme drought	SPI ≤ −2	Near normal	-1 < SPI <1
Severe drought	−2 < SPI ≤ −1,5	Moderately wet	1 ≤ SPI <1.5
Moderate drought	−1.5 < SPI ≤ −1	Severely wet	1.5 ≤ SPI <2
Near normal	-1 < SPI <1	Extremely wet	SPI ≥ 2

3.2.5.2 Spectral Analysis

Spectral Analysis represents a time series in terms of the wavelengths associated with oscillations, rather than individual data values. It gives decomposition of process into dominant frequencies and detection of periodicities and repeatable patterns**.**

Spectral analysis has been used extensively to examine whether a time series of any meteorological dataset exhibits any periodic fluctuations. The most common methods of computations include autocorrelation transform, fast fourier transform, and maximum entropy method (Jenkins and Watts 1968; Cooley, *et al*., 1967; Burg 1972, Ogallo 1982, Gitau, 2005). In this study the Fast Fourier transform technique was employed. These methods employed to seek spectral-peaks corresponding to periodicities in the annual and seasonal rainfall and temperature (maximum and minimum) time series. Also the significant spectral peaks at 95% confidence level were tested, and Tukey - hamming statistics window were used for White noise hypothesis.

In detecting cyclic variations in a time series, a variance function known as the spectral distribution function $\mathbf{F}(\lambda)$ and spectral density function $\mathbf{f}(\lambda)$ are used. Spectral density function $\mathbf{F}(\lambda)$is the Fourier transformation of the autocorrelation function Omondi (2005).The cycles appear as peaks in the plot of $\mathbf{F}(\lambda)$against period (k). These peaks correspond to the frequencies, which account for large percentage of the total variance (Otom, 2011). The spectral density function describes the distribution of these wavelengths and involves estimating the spectral density function and Fourier analysis involves representing a function as a sum of **sine** and **cosine** terms and is the basis for spectral analysis. For rainfall and temperature datasets were used in this study, the spectral analysis is achieved through autocovariance function given by Equation 9a;

$$\boldsymbol{\gamma(\kappa)} = \int_{0}^{\pi} \mathbf{cos}\,(\boldsymbol{\lambda\kappa})\boldsymbol{dF(\lambda)} = \int_{0}^{\pi} \mathbf{cos}\,(\boldsymbol{\lambda\kappa})\boldsymbol{df(\lambda)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(\mathbf{9}\boldsymbol{a})$$

Equation (9a) called the spectral representation of the autocovariance function and $\gamma(\mathrm{k})$ is the autocovarience coefficient, $d\mathrm{F}(\boldsymbol{\lambda})$ called the spectral distribution function and $\boldsymbol{\kappa}$ denotes time units.

The autocovariance function $\boldsymbol{\gamma(\kappa)}$, can be computed from the spectral density function, $\mathbf{f}(\lambda)$, as follows:

$$\boldsymbol{\gamma(\kappa)} = \int_{0}^{\pi} \mathbf{cos}(\boldsymbol{\lambda\kappa})\boldsymbol{f(\lambda)d(\lambda)} = \int_{0}^{\pi} \boldsymbol{e^{i\lambda\kappa}f(\lambda)d(\lambda)} \ldots\ldots\ldots\ldots\ldots..(\mathbf{9}\boldsymbol{b})$$

Also the spectral density function, $\mathbf{f}(\lambda)$, can be computed from the autocovariance function, F($\boldsymbol{\lambda}$), as follows:

$$\boldsymbol{f}(\lambda) = \frac{\mathbf{1}}{\mathbf{2}\boldsymbol{\pi}}\boldsymbol{\gamma}(\mathbf{0}) + \frac{\mathbf{1}}{\boldsymbol{\pi}}\sum_{t=1}^{\infty}\boldsymbol{\gamma}(\boldsymbol{\kappa})\boldsymbol{cos}(\boldsymbol{\lambda\kappa}) \ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{9}\boldsymbol{c})$$

3.2.5.3 Probability of Occurrence of Extremes

Probability distributions of annual and seasonal rainfall and temperature in South Sudan were analyzed using Gaussian kernel smoothing based on comparison between the distributions derived from the means for 1954-1983 and 1984-2013. The degree of smoothing was determined by smoothing parameter **b** values (Räisänen and Ruokolainen, 2008). For ***b*** = 1, the kernel returns a normal distribution with the same mean and standard deviation. For b ≠ 1, the mean increases/ the variance increases or both the mean and variance increase see (Figure 5)

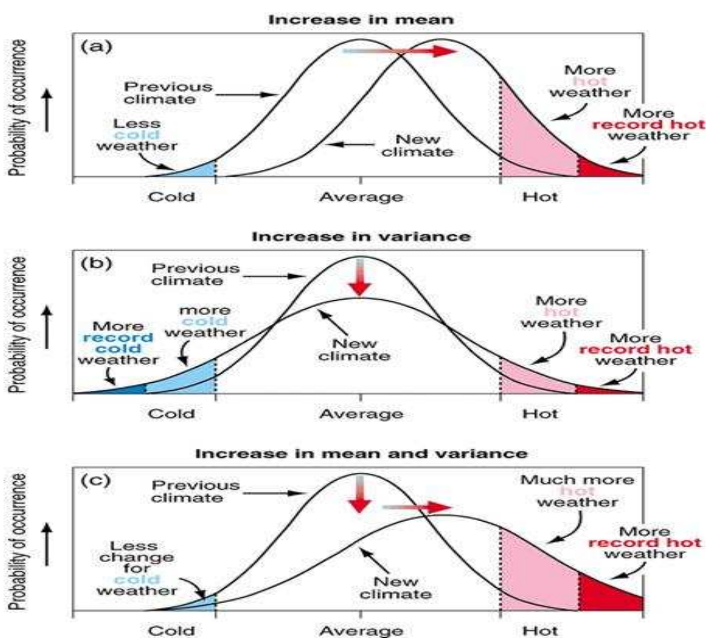


Figure 5:Illustration of effects on extreme temperature when (a) the mean increases, leading to more recorded hot weather, (b) the variance increases, and (c) when both the mean and variance increase, leading to much more record hot weather.(source:IPCC,2012)

3.2.6 Statistical Methodologies for Quantifying Teleconnections

This section described methodologies that used to examine Teleconnections between observed rainfall on one hand and ENSO, and Indian Ocean dipole (IOD) events on the other hand. These included Pearson correlation analysis, composite analyses and regression analysis..

3.2.6.1 Pearson Correlation Analysis

In this study, Pearson Correlation analysis was used to assess the teleconnection between seasonal rainfall anomalies over South Sudan on one hand and Indian Ocean Dipole (IOD) indices and Niño indices (Niño1+2, Niño3, Niño3.4 and Niño4) on the other hand. Teleconnection was analyzed at **Zero** and **one** time **lags** with the targeted main three rainy seasons (MAM, JJA and (OND). The Pearson correlation coefficient was computed using equation 10a.

$$\boldsymbol{r_{xy}} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\{(x_i - \bar{x})^2 \cdot \frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2\}}} \ldots\ldots\ldots\ldots\ldots (10a)$$

Where r_{xy} is the Pearson correlation coefficient, $\bar{x}$ and $\bar{y}$ are sample means of x_i and y_i respectively. Where r_{xy} the correlation coefficient and **n** is the total number of observations. The value of r_{xy} range from **-1** to **+1** and is independent of the units of measurement. A value of r_{xy} near zero (0) indicates little correlation between attributes; a value near **+1** or **-1** indicates a high level of correlation.

The significance of the correlation coefficients computed using the student's **t** test as shown by equation 10b.

$$\boldsymbol{t = r_{xy}\sqrt{\frac{n-2}{1-r_{xy}^2}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{10b})$$

3.2.6.2 Composite Analysis

Composite analysis was used in this study in order to further study patterns of associations between South Sudan seasonal rainfall anomalies and the Indian Ocean dipole (IOD) and ENSO (El Niño and La Niña) phases. The classification of positive and negative IOD and weak, moderate and strong El Niño and La Niña phases were classified based on the threshold mentioned in Table 2

Table 2: Classification of IOD and ENSO severity

Category	**Threshold of SST anomaly**	**Category**	**Threshold of SST anomaly**
Positive IOD	≥ 0.5	Negative IOD	≤ -0.5
Weak El Niño	0.5 to 0.9	Weak La Niña	-0.5 to -0.9
Moderate El Niño	1.0 to 1.4	Moderate La Niña	-1.0 to -1.4
Strong El Niño	≥1.5	Strong La Niña	≤ -1.5

CHAPTER FOUR

4.0 Results and Discussions

This chapter presents and discusses the results obtained from the different analyses of rainfall, maximum and minimum temperature data in order to achieve the overall and specific objectives of the study. The results from homogeneity test for both rainfall and temperature (maximum and minimum) are presented first.

4.1 Data Homogeneity Test and Quality Control

This section presents the Homogeneity Test for rainfall and temperature (maximum and minimum). Cumulative values of the rainfall, minimum and maximum air temperature against time for the period 1954 – 2013 for selected representative stations were plotted.

Figures 6a to 6c give samples of Single Mass Curves of rainfall, maximum and minimum for Malakal, Wau and Juba as selected representative stations over south Sudan respectively. All the mass curves gave straight line plots, signifying that the rainfall and temperature records were homogeneous hence suitable for use in analyzing the study objectives.

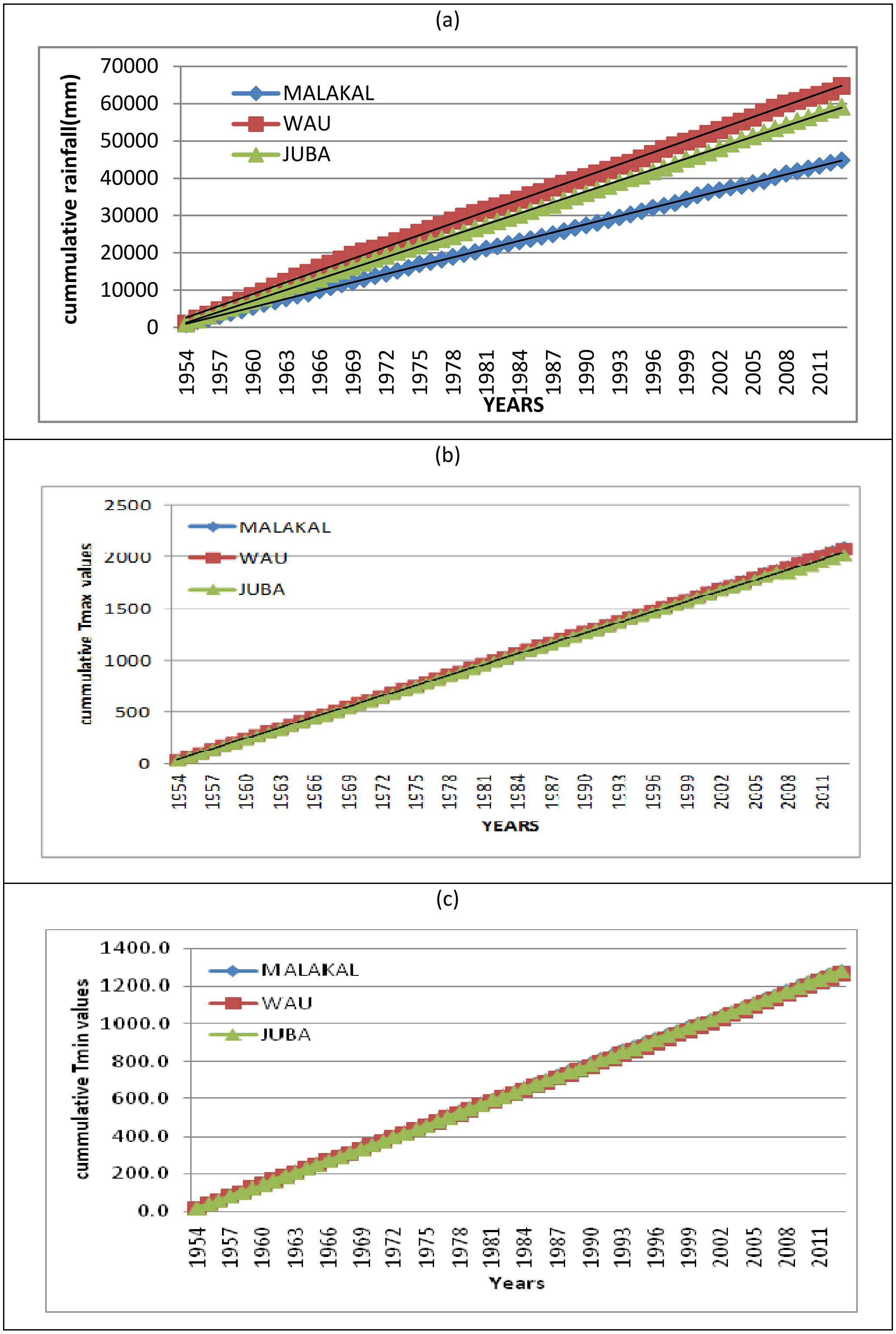


Figure 6: *Single mass curves: (a) annual rainfall, (b) maximum, (c) minimum temperature*

4.1.1 Testing Asymmetric Distribution of Rainfall and Temperature Dataset

Tables 3 to 5 presented the results obtained from skewness and kurtosis statistical test for asymmetric distribution of the rainfall and temperature dataset for two periods (1954-1983) and (1984-2013).

Table 3: Results of Skewness and Kurtosis statistic for rainfall

	Skewness and Kurtosis	Ann.Rainfal	MAM.Rainfal	JJA.Rainfal	SON.Rainfal
RENK	Skew(1954-1983)	0.4	2.7	0.2	0.1
	Kurt (1954-1983)	-0.6	10.7	-0.9	-0.5
	Skew (1984-2013)	-0.3	1.8	0.3	0.1
	Kurt (1984-2013)	-0.4	6.2	-0.6	-0.1
MALAKAL	Skew(1954-1983)	0.0	1.0	1.0	0.3
	Kurt (1954-1983)	-0.2	0.7	0.9	-0.1
	Skew (1984-2013)	0.6	0.7	0.1	-0.6
	Kurt (1984-2013)	-0.4	-0.6	-0.6	0.1
RAJA	Skew(1954-1983)	-0.3	-0.2	0.0	0.1
	Kurt (1954-1983)	-0.5	0.3	-1.2	-0.7
	Skew (1984-2013)	0.3	0.0	0.4	0.0
	Kurt (1984-2013)	-0.4	0.5	1.3	-0.5
WAU	Skew(1954-1983)	-0.1	0.5	0.8	0.2
	Kurt (1954-1983)	-0.5	-0.2	1.1	0.2
	Skew (1984-2013)	0.0	0.2	0.1	0.3
	Kurt (1984-2013)	-0.8	1.5	-0.5	-0.3
JUBA	Skew(1954-1983)	0.5	0.9	0.7	1.1
	Kurt (1954-1983)	0.7	1.1	1.0	1.4
	Skew (1984-2013)	-0.2	0.5	-0.5	0.2
	Kurt (1984-2013)	-0.5	0.2	0.5	-0.7

Table 4: Results of skewness and kurtosis statistic for maximum temperature

	Skewness and Kurtosis	Ann.Tmax	MAM.Tmax	JJA.Tmax	SON.Tmax	DJF.Tmax
RENK	Skew(1954-1983)	-0.9	-0.9	0.4	-0.1	-0.5
	Kurt (1954-1983)	2.0	0.7	-0.2	0.2	-0.4
	Skew (1984-2013)	-0.4	-0.2	-0.3	0.5	-0.3
	Kurt (1984-2013)	0.4	-0.4	1.2	0.8	-0.1
MALAKAL	Skew(1954-1983)	-0.2	-1.0	-0.2	-0.1	0.2
	Kurt (1954-1983)	0.0	1.7	-0.9	-0.3	0.1
	Skew (1984-2013)	-0.2	-0.3	0.7	-0.1	-0.4
	Kurt (1984-2013)	-0.2	-0.5	-0.2	-0.6	-0.1
RAJA	Skew(1954-1983)	-0.3	-0.5	-0.2	0.2	-0.7
	Kurt (1954-1983)	-0.4	-0.7	1.3	-0.1	0.0
	Skew (1984-2013)	0.1	0.1	1.7	-1.4	0.9
	Kurt (1984-2013)	-0.2	-0.9	3.6	3.9	2.2
WAU	Skew(1954-1983)	-0.5	-0.1	-0.2	-0.3	0.0
	Kurt (1954-1983)	-0.4	-0.3	-0.8	0.2	-0.1
	Skew (1984-2013)	-0.5	0.0	-0.1	-0.6	0.2
	Kurt (1984-2013)	-0.4	-0.7	-0.1	-0.1	-0.8
JUBA	Skew(1954-1983)	-0.5	-0.5	-0.2	-1.0	-0.7
	Kurt (1954-1983)	-0.1	-0.2	-1.0	2.0	0.4
	Skew (1984-2013)	0.4	-0.8	0.9	0.1	0.5
	Kurt (1984-2013)	0.4	-0.1	0.2	1.4	0.9

Table 5: Results of skewness and kurtosis statistical for minimum temperature

	Skewness and Kurtosis	Ann.Tmin	MAM.Tmin	JJA.Tmin	SON.Tmin	DJF.Tmin
RENK	Skew(1954-1983)	-0.2	0.2	0.5	0.0	0.1
	Kurt (1954-1983)	-0.4	0.5	1.9	-0.5	0.7
	Skew (1984-2013)	-0.9	-0.3	-1.4	-0.5	-0.6
	Kurt (1984-2013)	1.2	-0.1	3.2	-0.2	0.5
MALAKAL	Skew(1954-1983)	-0.3	-0.1	0.2	-0.1	-0.7
	Kurt (1954-1983)	-0.4	-0.5	-0.4	-0.9	1.0
	Skew (1984-2013)	0.2	-0.8	-0.4	-0.1	0.1
	Kurt (1984-2013)	-0.9	0.7	0.5	-0.5	-0.3
RAJA	Skew(1954-1983)	0.9	-0.1	0.3	0.3	-0.3
	Kurt (1954-1983)	0.8	-0.5	0.9	0.1	-0.2
	Skew (1984-2013)	-0.3	-1.3	0.0	1.4	1.9
	Kurt (1984-2013)	0.1	2.1	1.5	2.3	4.1
WAU	Skew(1954-1983)	0.3	0.1	0.1	0.0	-0.7
	Kurt (1954-1983)	-0.4	-0.5	1.2	-1.2	0.2
	Skew (1984-2013)	0.0	-0.3	-0.2	-0.6	-0.7
	Kurt (1984-2013)	-1.1	-0.8	-1.4	0.1	0.8
JUBA	Skew(1954-1983)	-0.7	-0.2	-0.7	-0.6	-0.8
	Kurt (1954-1983)	0.5	-0.9	2.9	0.5	0.7
	Skew (1984-2013)	0.0	-1.0	1.2	0.2	-0.5
	Kurt (1984-2013)	-0.8	0.8	1.4	-0.8	0.3

The results show, the dataset for annual and seasonal rainfall indicated a distribution with an asymmetric tail extending towards values that are positive (positive skewed) for most stations. MAM, JJA and SON seasonal rainfall, characterized with an asymmetric tail extending towards values that are positive for all station except MAM for Raja during period (1954-1983), JJA for Juba during period (1984-2013) and SON season for Malakal during period (1984-2013). The rainfall data for Wau and Juba stations and Raja stations during MAM season are scoring perfectly symmetric distribution (skewness = 0.0).

Results for the annual and mean seasonal maximum and minimum temperatures dataset are registered symmetric distribution (most of values close to zero) with a tail extending towards negative values and non symmetric distribution with a tail extending towards positive values. The kurtosis results for rainfall and temperatures (maximum and minimum) shows the platykurtic distribution (kurtosis values < 3) and characterized by flat distribution (Positive kurtosis) compared to rainfall data. The skewness and kurtosis statistics showed asymmetric distribution of rainfall and temperature datasets.

4.2 Temporal Characteristics of observed Rainfall and Temperature over South Sudan

This section presents the results obtained from the different analysis of rainfall, maximum and minimum air temperature. The results of observed monthly rainfall and temperature distribution are presented first.

4.2.1 Observed Monthly Rainfall and Temperature distribution over South Sudan

Figures 7a to 7d show the mean monthly rainfall patterns for selected stations (Renk Malakal, Raja and Juba).

The mean Monthly rainfall distributions for long term means to (1954-1983) and (1984-2013 revealed that rainfall is uni-modal, with a peak in July and August. The main rainy period in southern parts of country starts from March to November compared to northern parts where rainy period start from May to October. Historically the months of December to February are dry, may due to cold and dry North East winds; therefore extreme north, northeast, northwest, and central received less than 5 mm per month compared to southern parts, which received light rains not exceeding 10 mm per month in average, especially in the months of December and January (figures 7a-d).

Normally in the period of December to January, the inter-tropical convergence zone (ITCZ) lies outside the greater equatorial states of South Sudan and the entire country is under the cold and dry North East winds. Therefore DJF is winter season not a rainy one in south Sudan.

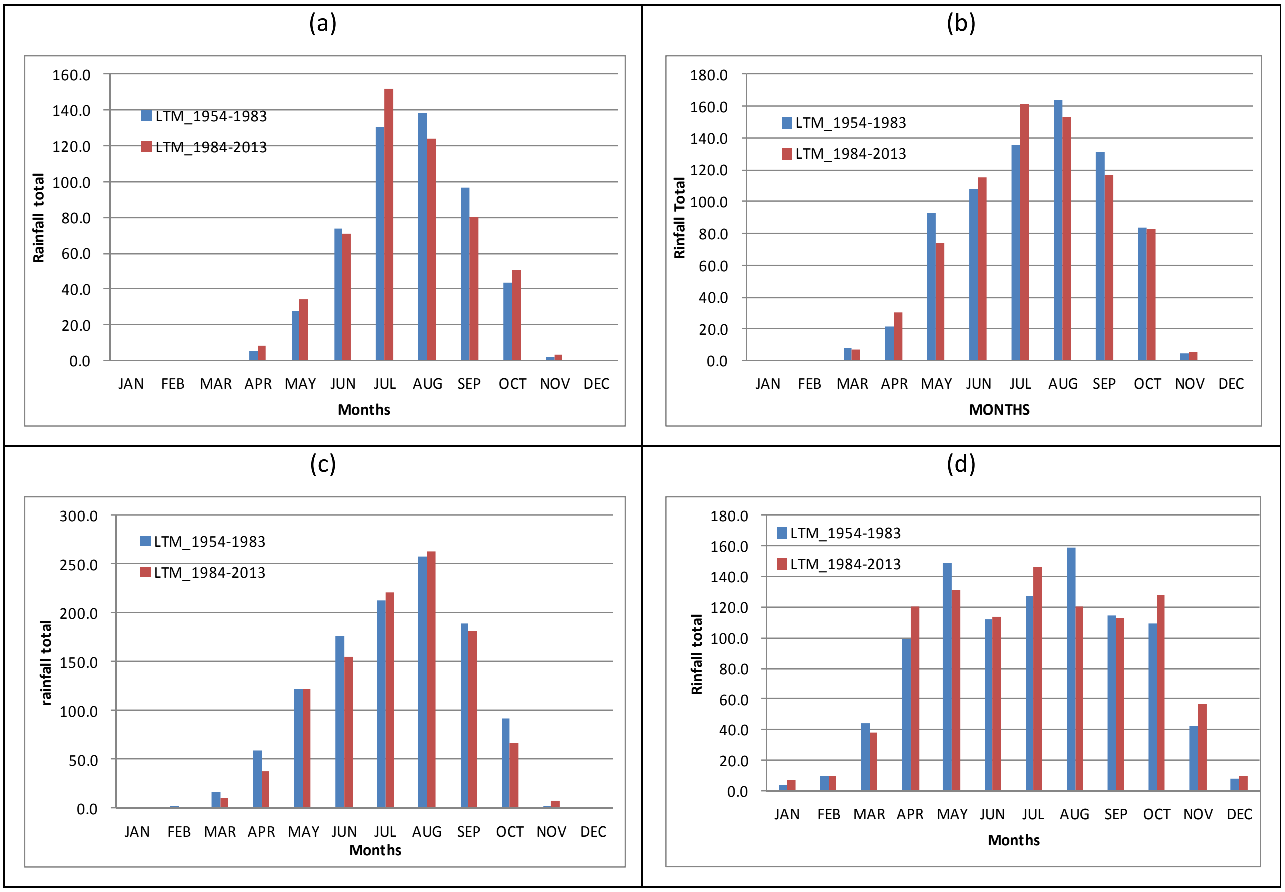


Figure 7: Mean monthly rainfall characterstics for selected stations (a)Renk,(b)Malakal,(c)Raja, (d)Juba over south Sudan

Rains normally commence in the month of February when the ITCZ crosses into the south Sudan border. ITCZ then migrates northwards in mid-February. By Early March, most areas in southern parts of country represented by Juba (figures 7d) begin to receive light to moderate rainfall not exceeding 50 mm per month. Major rainfall months occur between April–October with its peak in May and August, while central and northwest region represented by Wau and Raja (figures 7b and 7c) have major rainfall occurring between May to October with its peak in months of July and August. Extreme north and northeast which presented by El renl and Malakal, have major rainfall occurring between May to September with its peak in months of July and August (figure 7a).

Figures (8a to 8d) presents the long term means (1954-1983) and (1984-2013) monthly maximum and minimum temperature distribution for selected stations namely Renk,Malakal, Raja and Juba.

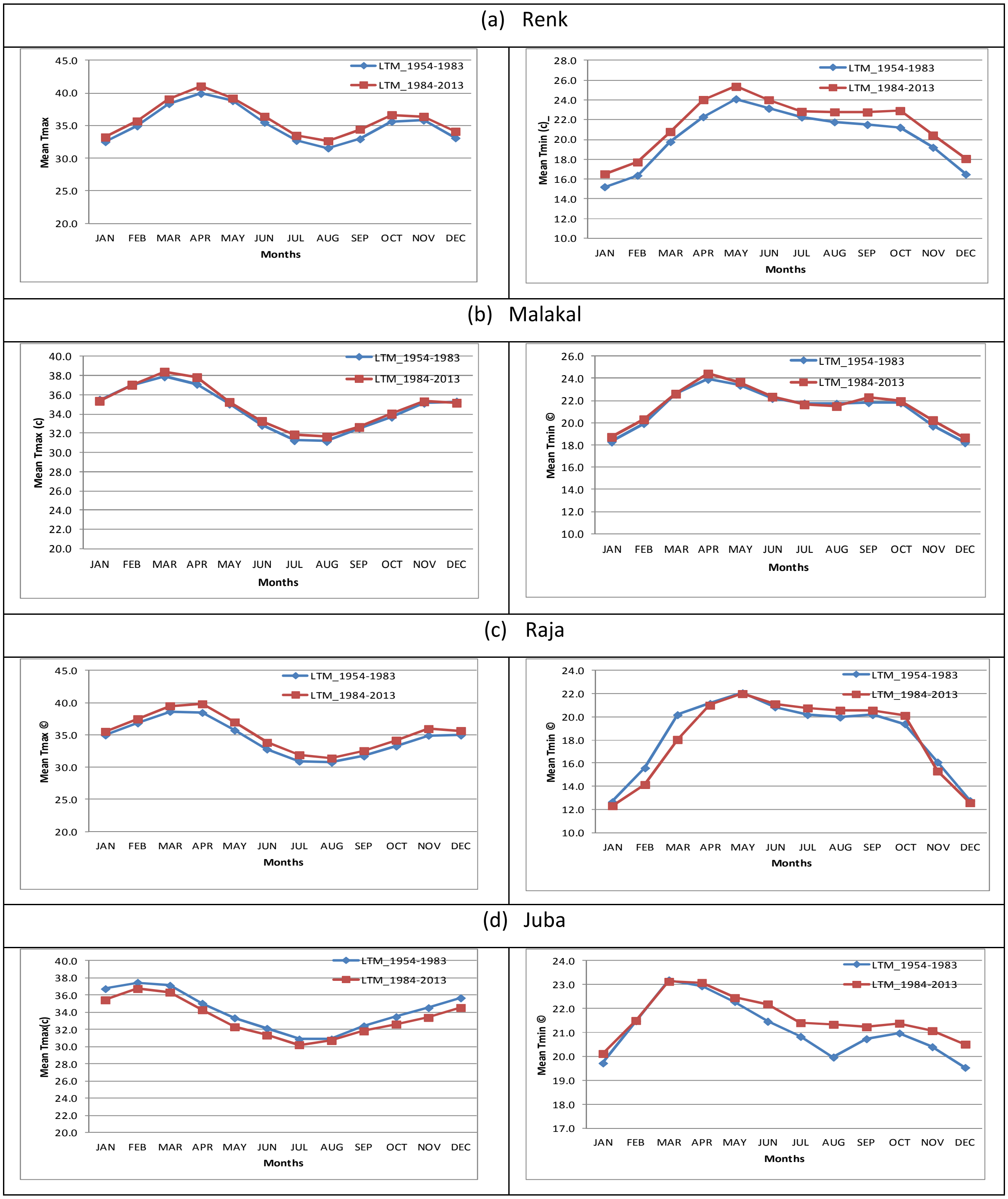


Figure 8: Annual cycle of observed maximum and minimum temperature for selected stations (a)Renk,(b)Malakal,(c)Raja,(d)Juba over south Sudan.

The results showed that maximum and minimum temperature varies from January to December and reaches highest level of maximum values in February in southern parts represented by Juba. Northwest and central parts represented by Raja and Wau stations reach highest level of maximum values in March. Extreme north and northeast, which is represented by El renk and

Malakal stations attains highest level of maximum values in April. Lowest levels of maximum temperatures are registered in July for all locations in south Sudan. While minimum temperature showed those months of December and January observed the lowest minimum temperature and with less than 20 degree Celsius across the country. Highest levels of minimum temperatures were registered over Malakal and Wau on April, El renk and Raja on May, and Juba on March and April.

The main factors contributing to the distribution and variation of monthly rainfall and temperature over south Sudan are seasonal movement of earth around the sun, oscillation of the ITCZ, strength of Azores high pressure and northeastern cold/dry winds, Congo air mass, and some local systems such as topography and evapotranspariation within river Nile among others.

The results suggests that the reasons behind the processes leading to southern parts of the country observing highest levels of maximum temperature in February, may be due to weak cold and dry northeasterly winds which appears to weaken southward. Western and northern parts of the country observed the lowest levels of minimum temperature in December and January due to strength of Azores high pressure and the prevailing northeastern cold/dry winds.

Congo moist air mass, westerly and easterly jet stream believed bring a lots of moisture from Atlantic and Indian oceans and thus have significant role in advection and convection clouds leading to increased thunderstorm activity and reduced sunshine hours leading to a decrease in amount of maximum temperature received in July. In addition, the movement and distribution of humid air masses across the country is associated with northward movement of ITCZ during March to August and southwards movement during September to November. The spatial characteristics of observed annual and seasonal rainfall over South Sudan are presented next.

4.2.2 Observed Temporal Characteristics Rainfall Trends

In this subsection the temporal patterns (time series) of annual and seasonal (MAM, JJA and SON) rainfall for selected representative stations are presented and discussed. The main objective of time series plots are to detect the trends in time series either there is statistically significant evidence of increasing/decreasing or insufficient statically evidence of a significant trends at 0.05 level. The time series of annual rainfall anomalies for Malakal and Wau stations as representative stations are presented in Figure 9.

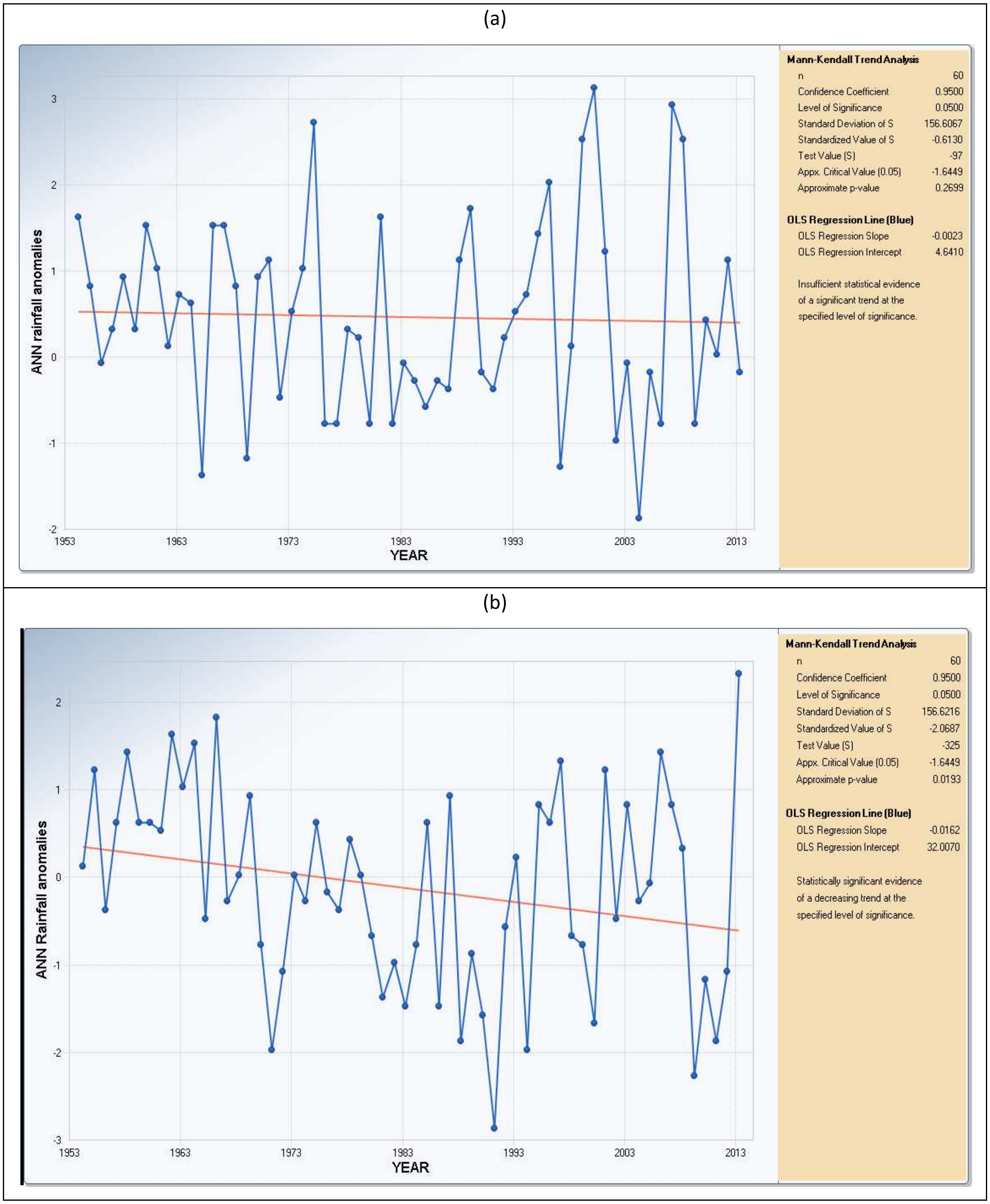


Figure 9: Time series of Observed Annual rainfall Anomalies for selected station (a) Malakal (b) Wau.

The results indicate that the annual rainfall anomalies exhibit a significant decreasing trend in central represented by Wau. Same results are observed in Raja, which represents the northwest, while extreme north represented by Renk shows a slightly an increase in annual rainfall trends. Northeast and southern parts of the country, which is represented by Malakal and Juba, had insufficient statistical evidence of a significant decreasing trend at 0.05 level of significant.

The rainfall trends appeared in annual analyzed on seasonal basis. The time series of observed March to May (MAM) rainfall Anomalies for selected representative stations (Malakal and Juba) are presented in figure 10, the results indicated that extreme northern part of the country represented by El renk experienced statistical significant evidence of an increasing in trend, while northeastern, northwest and Southern parts represented by Malakal, Raja and Juba respectively observed insufficient statistical evidence of a significant trend. Central represented by Wau had statistical significant evidence of a decreasing.

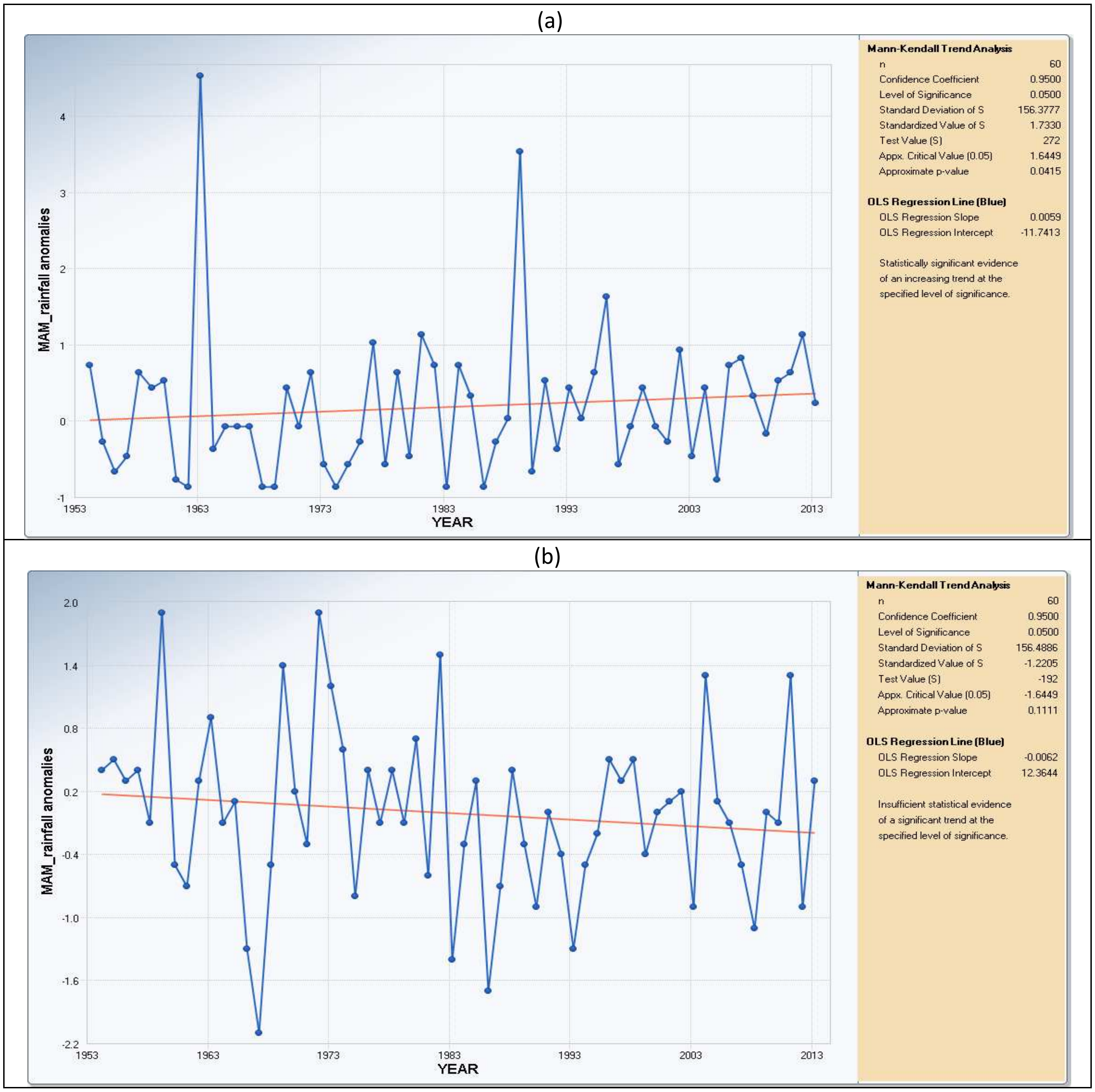


Figure 10: Time series of Observed MAM rainfall Anomalies for selected stations (a) Malakal (b) Juba.

Figure 11 shows the observed June-August (JJA) rainfall Anomalies for selected stations Renk and Raja as reprehensive of stations used in study, the results showed insufficient statistical evidence of a significant decreasing trend at 0.05 level of significant for all locations considered in study.

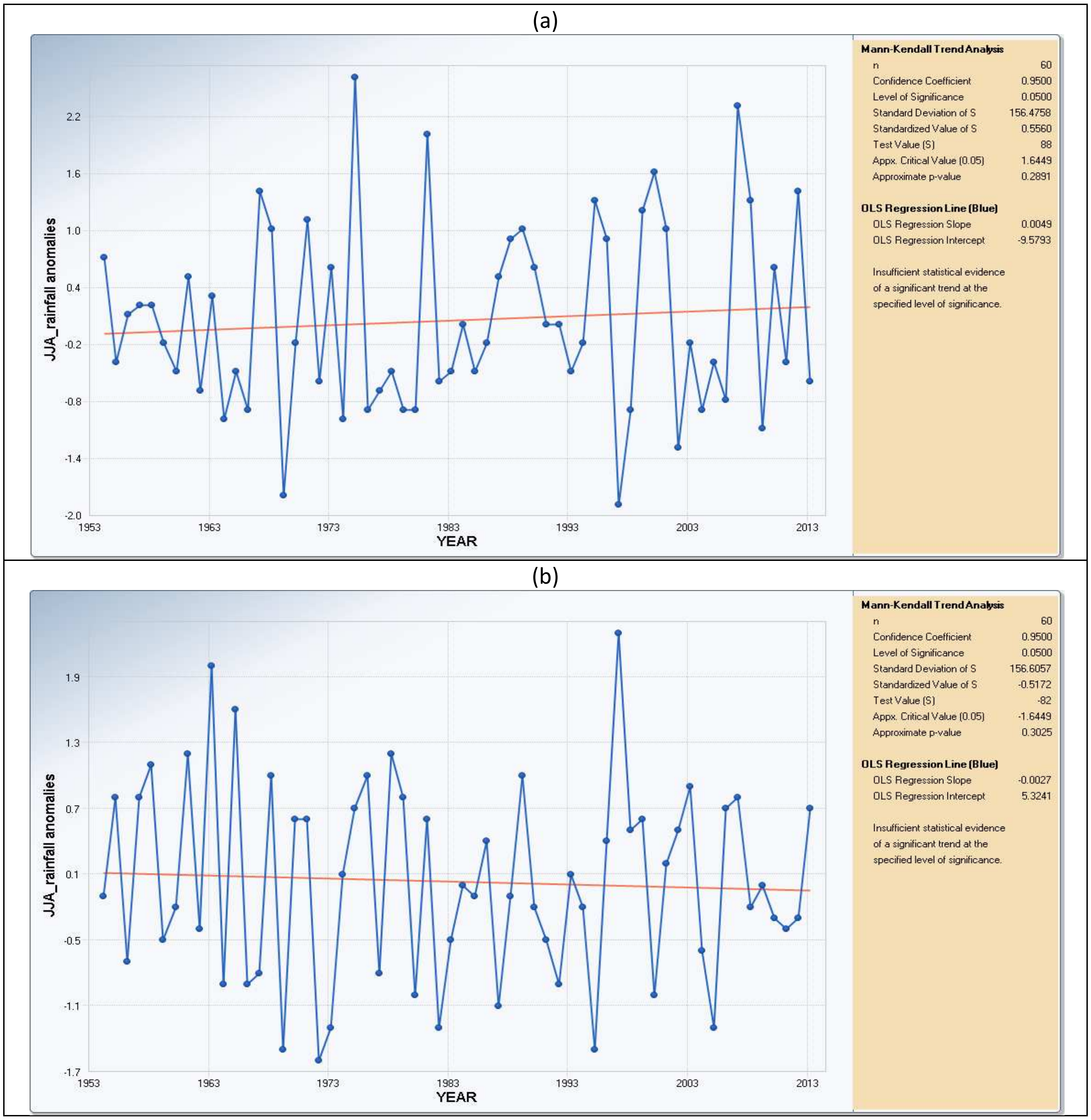


Figure 11: Time series of Observed JJA rainfall Anomalies for selected stations (a) Renk (b) Raja.

The time series of observed September-November (SON) seasonal rainfall anomalies for selected stations Malakal and Wau as sample of stations used in study are presented in Figure 12, the results indicated insufficient statistical evidence of a significant decreasing trend at 0.05 level of significant for all locations considered in study.

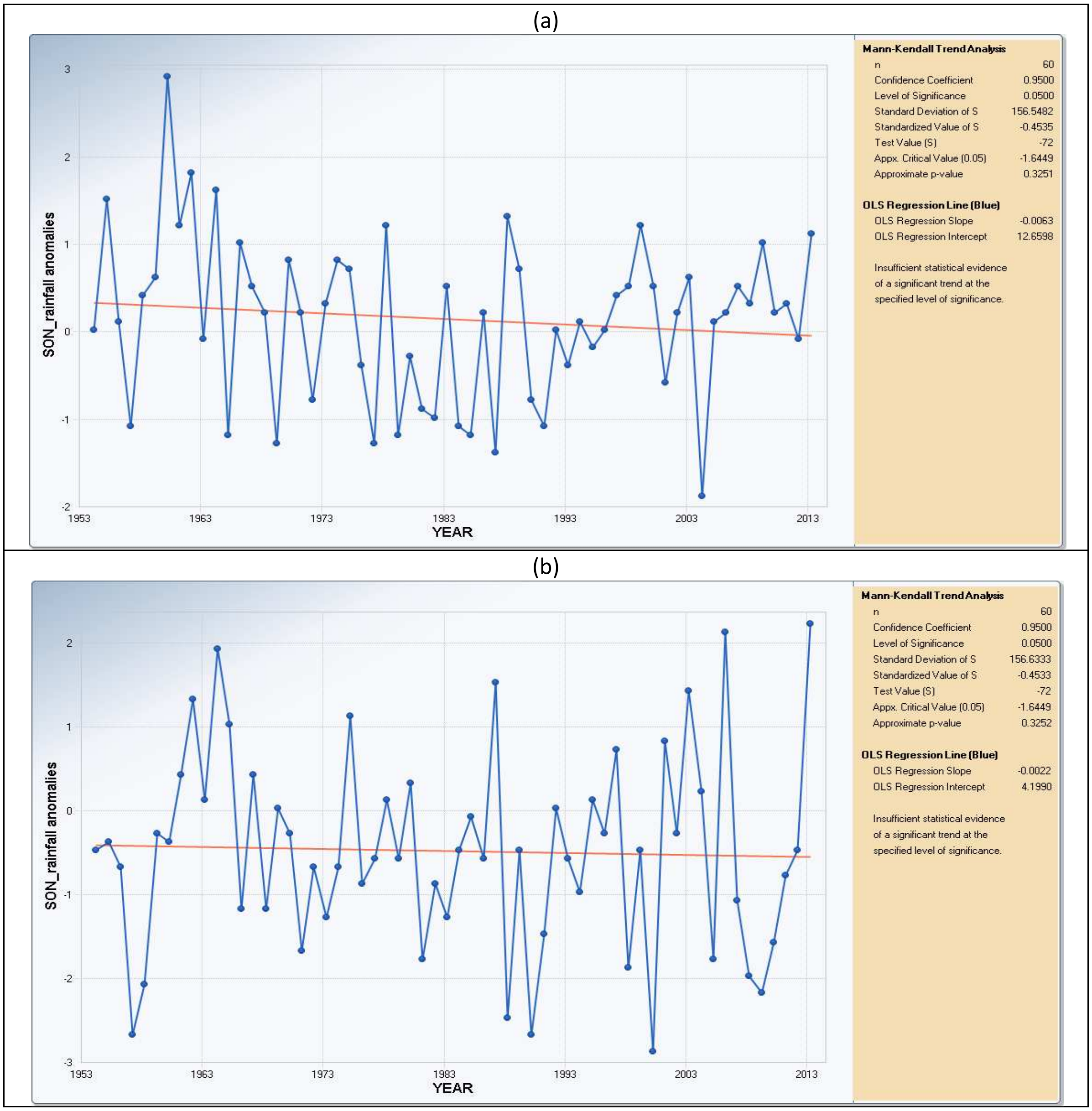


Figure 12: Time series of Observed SON rainfall for selected stations (a) Malakal (b) Wau.

The decline/increase in rainfall trends has negative/positive environmental, economic, and social impacts. Household incomes of a big number of families in south Sudan is dependent on rain fed agriculture and pastoral activities. Therefore, adaptation measures should be put in place to strengthen the resilience of communities to cope with these changes and variability in rainfall.

4.2.3 Observed Temporal Characteristics of Temperature

This sub-section presents the time series of observed annual and seasonal maximum and minimum temperature anomalies. The Time series of annual maximum temperature for selected representative stations (Malakal and Juba) are presented in Figures 13, the results indicated statistical a significance of an increasing trends at the 0.05 level of significance for all locations considered in study.

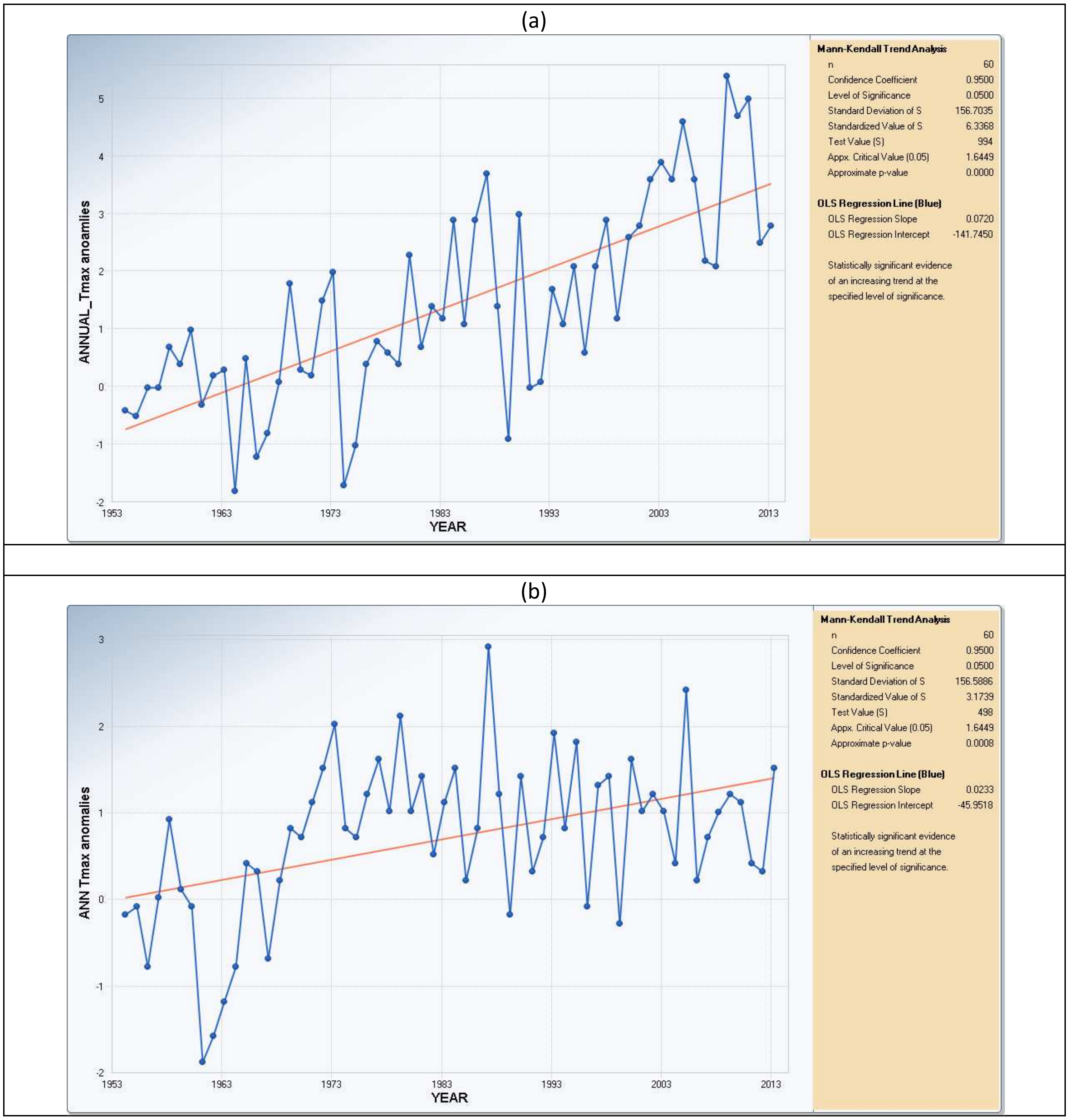


Figure 13: Time series of Observed mean annual maximum temperature Anomalies for selected stations (a) Malakal (b) Juba

On seasonal basic, Time series of March to May (MAM) maximum temperature anomalies for selected representative stations (Renk and Wau) are presented in Figure14 and the results showed a significance of an increasing trends at the 0.05 level of significance at all locations considered in study.

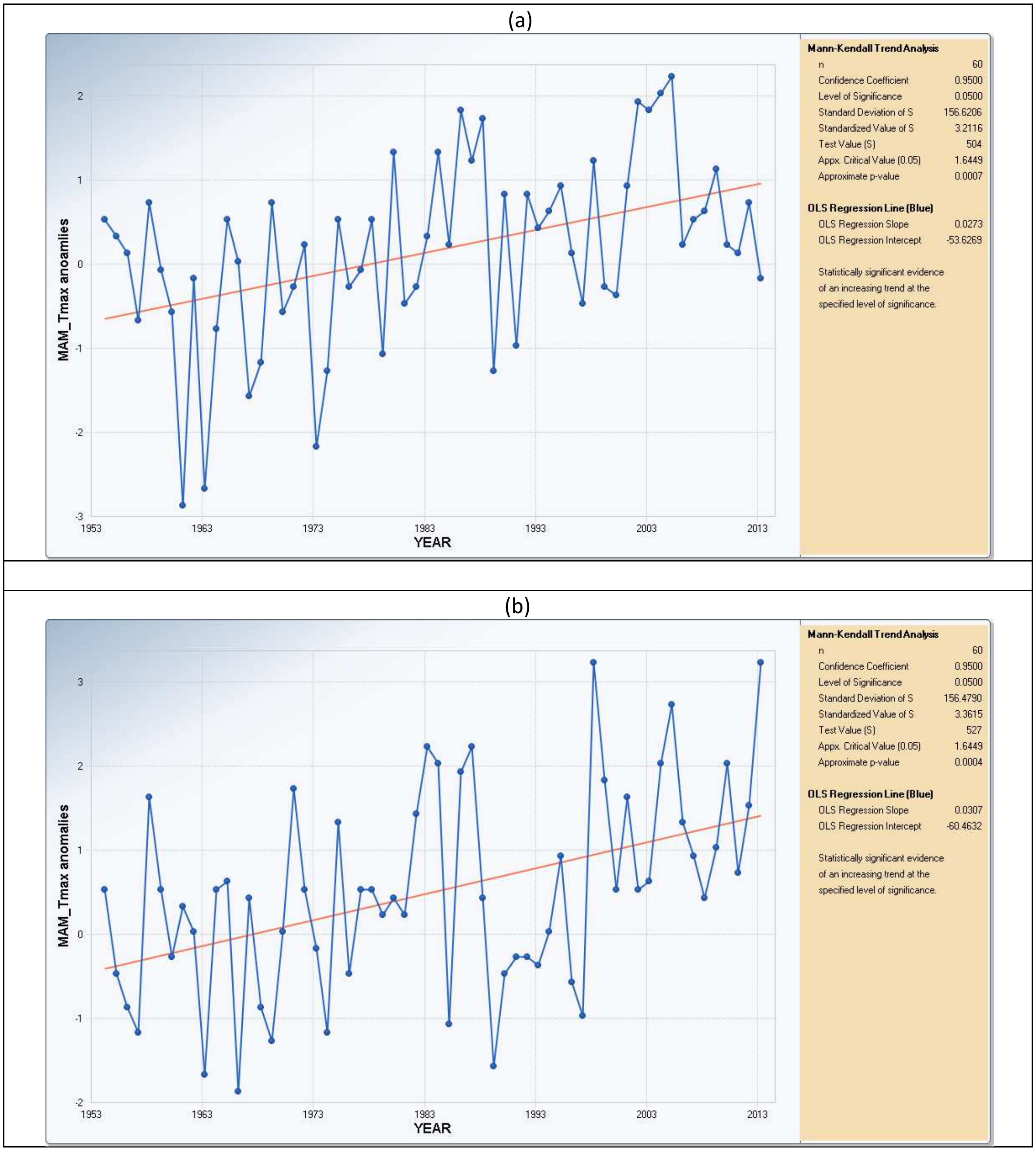


Figure 14: Time series of Observed MAM maximum temperature Anomalies for selected stations (a) Renk (b) Wau.

The figures 15 presents the time series of observed June-August (JJA) seasonal maximum temperature anomalies for selected stations (Malakal and Juba) as a sample of stations used in study, the results indicated there is a significance increasing trends in the observed maximum temperature anomalies at the 0.05 level of significance for all locations considered in study.

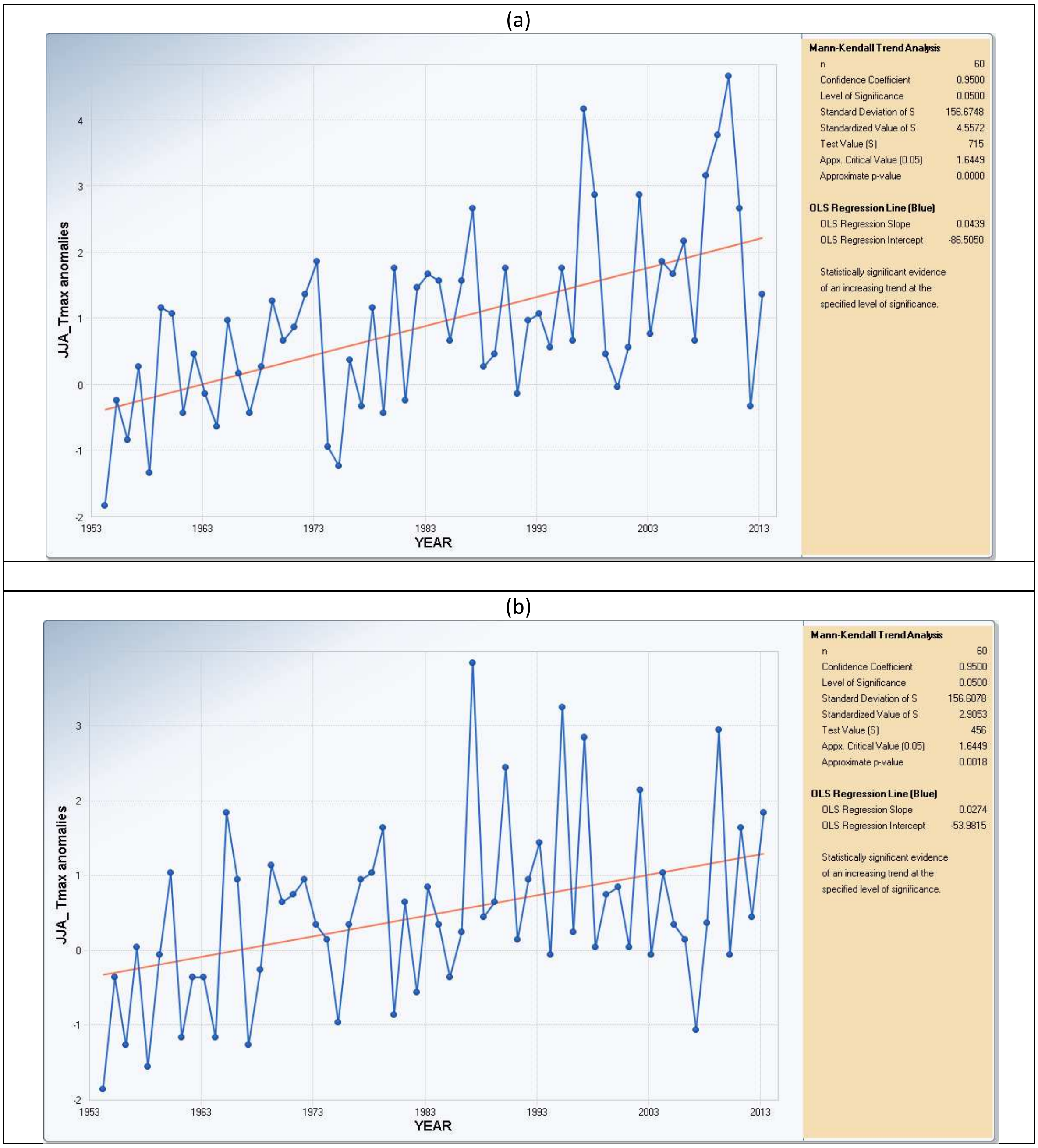
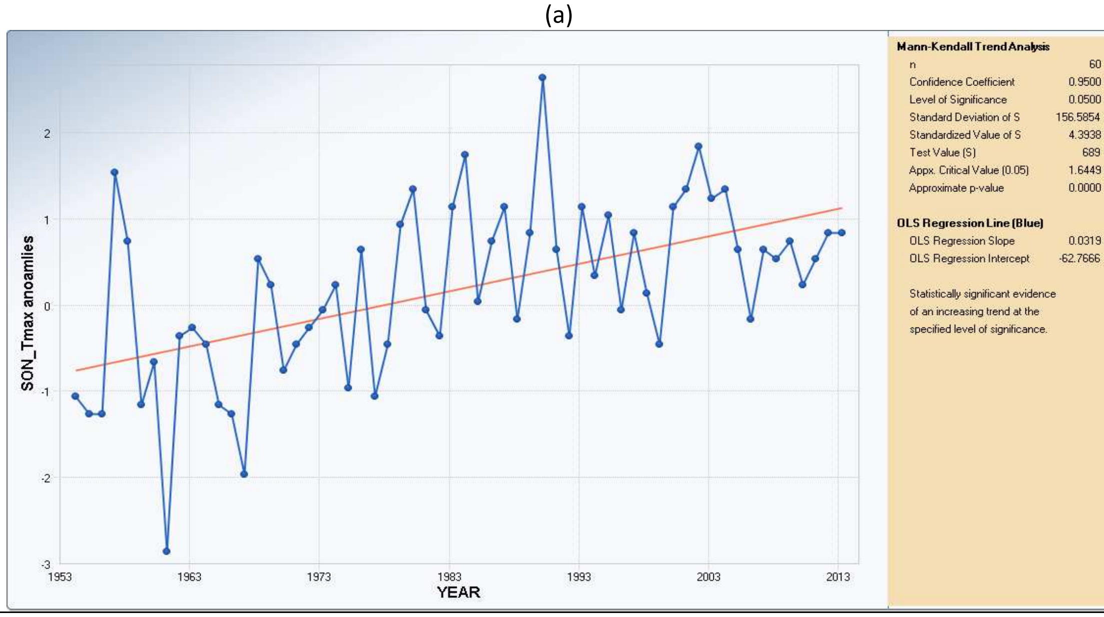


Figure 15: Time series of Observed JJA maximum temperature Anomalies for selected stations (a) Malakal (b) juba.

The time series of observed September-November (SON) seasonal maximum temperature anomalies are presented in figures 16 for selected stations (Renk and Juba) as a sample of stations used in study, the results showed there is a significance increasing trends in the observed SON maximum temperature anomalies except southern parts of country represented by Juba which observed insufficient evidence of increase in maximum temperature anomalies at the 0.05 level of significance.

(a)



(b)

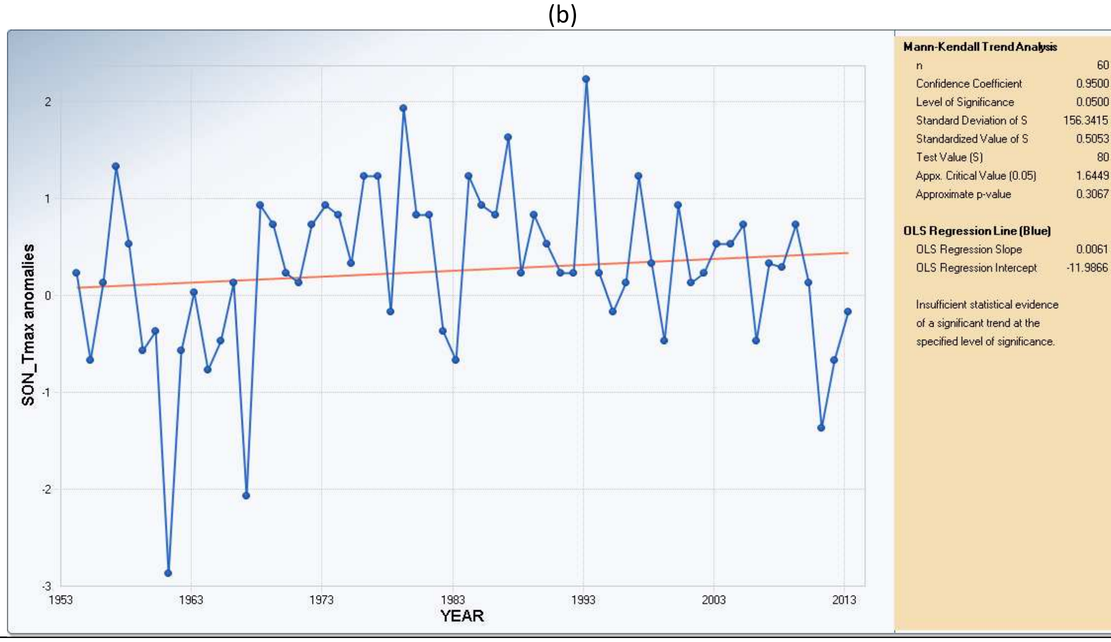


Figure 16: Time series of Observed SON maximum temperature Anomalies for selected stations (a) Renk (b) Juba.

The time series of observed December to February (DJF) seasonal maximum temperature anomalies are presented in Figure17 for selected stations (Raja and Juba) as a sample stations, the results indicates that there is significance increasing trends in the observed DJF maximum temperature anomalies except southern parts of country represented by Juba which observed insufficient evidence of increase in maximum temperature anomalies at the 0.05 level of significance.

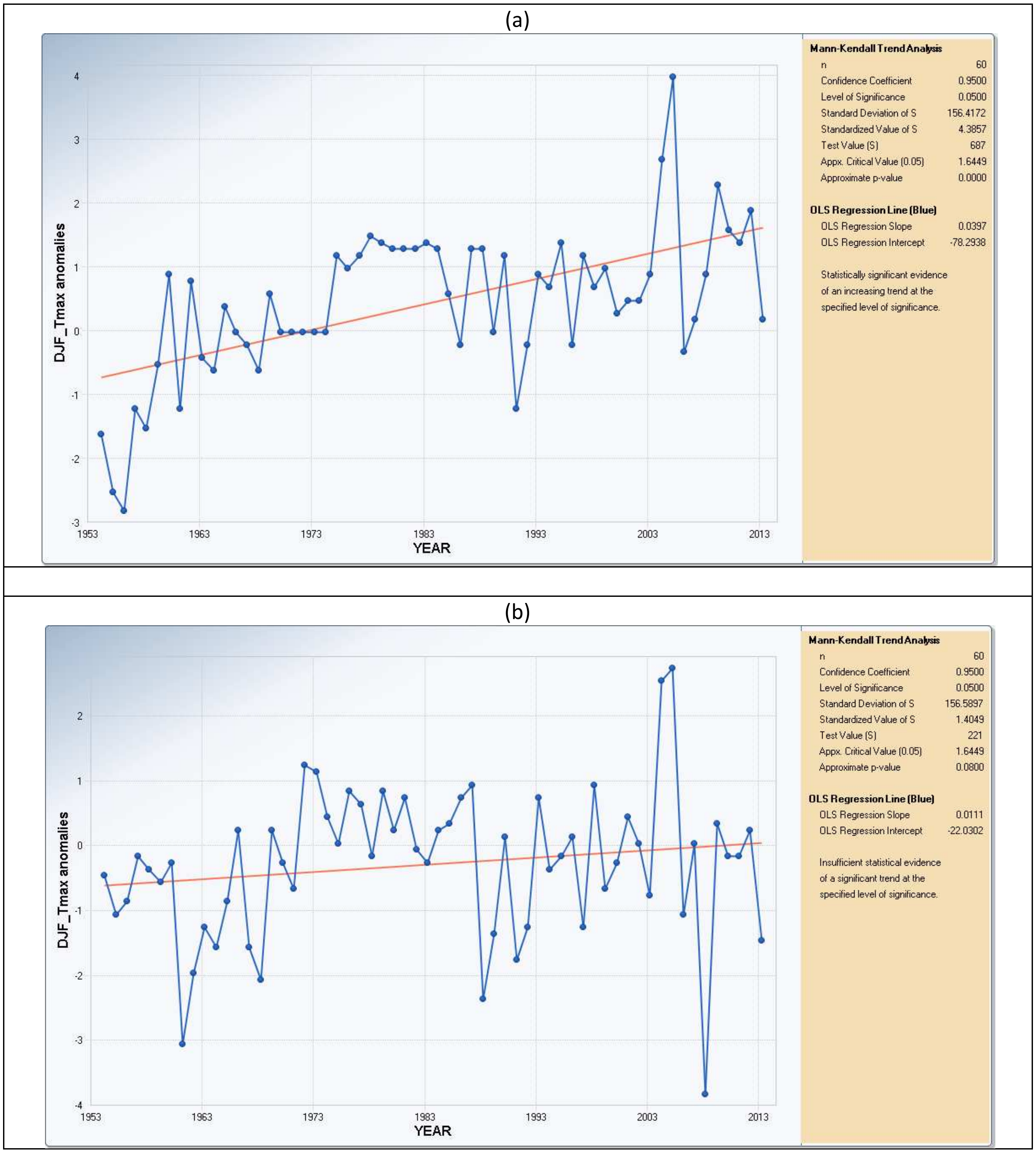


Figure 17: Time series of Observed DJF maximum temperature Anomalies for selected stations (a), Raja (b) Juba.

A part from observed mean annual and seasonal rainfall and maximum temperature, the minimum temperature were also analyzed. The results for mean annual minimum temperature indicated that all stations considered in the study experienced statistical significance evidence of a increasing trend at 0.05 level of significant except northwest represented by Raja which experienced insufficient statistical significance evidence of a decreasing trend at 0.05 level of significant (Figure 18).

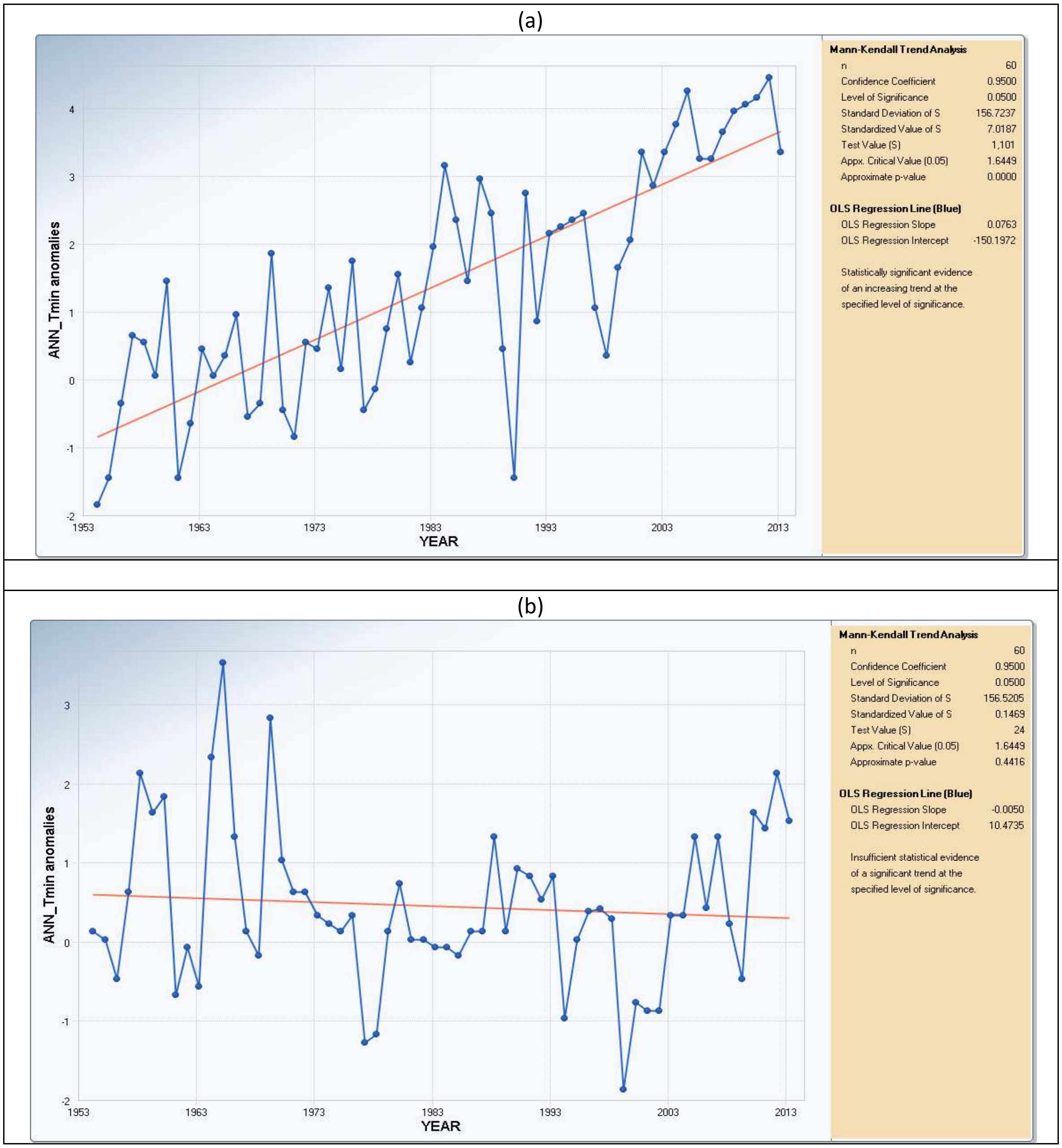
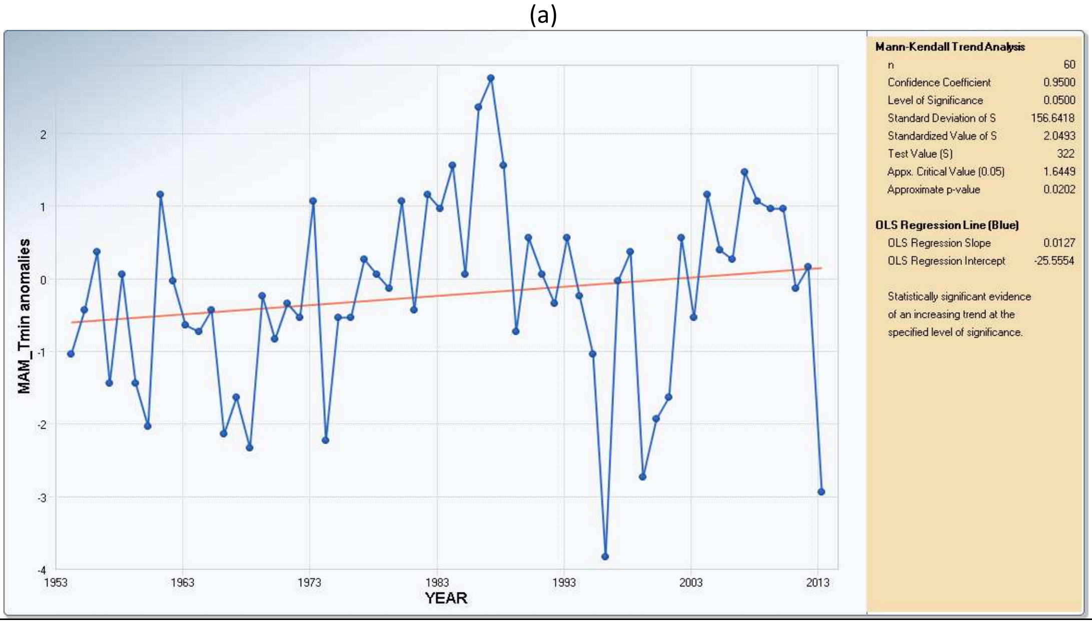


Figure 18: Time series of Observed annual minimum temperature Anomalies for selected stations (a) Renk, (b) Raja.

The trends in March-May (MAM) minimum temperature anomalies are represented in Figures 19. The results for all stations considered in the study experienced statistical significance evidence of a increasing trend except northwest represented by Raja which experienced insufficient statistical significance evidence of a decreasing trend at 0.05 level of significant (Figure 19b).

(a)



(b)

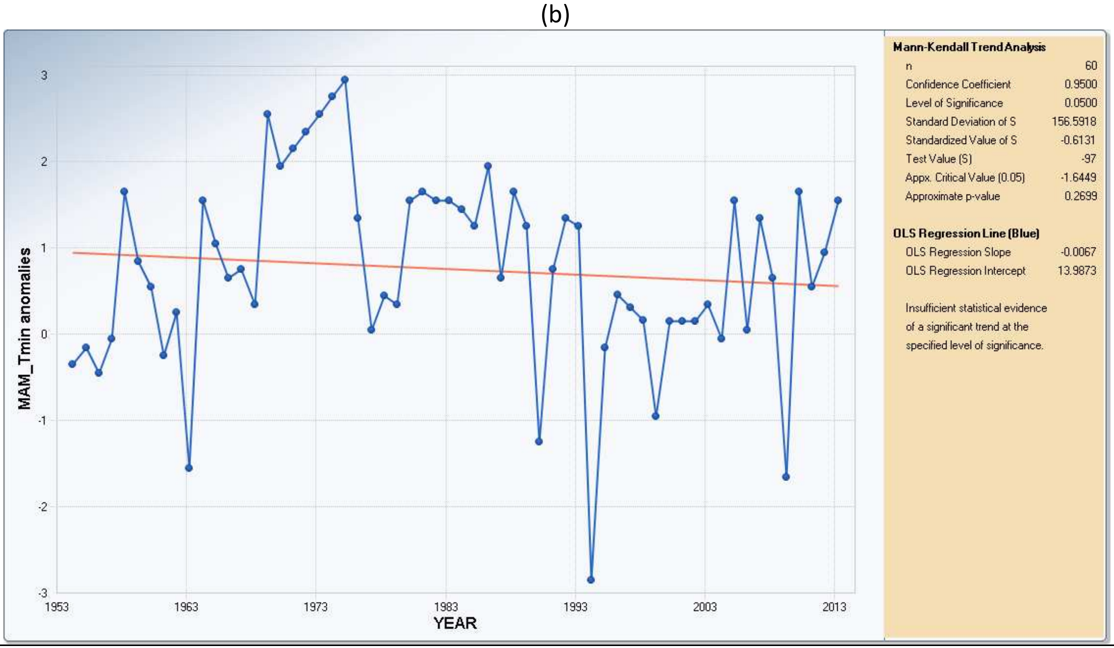
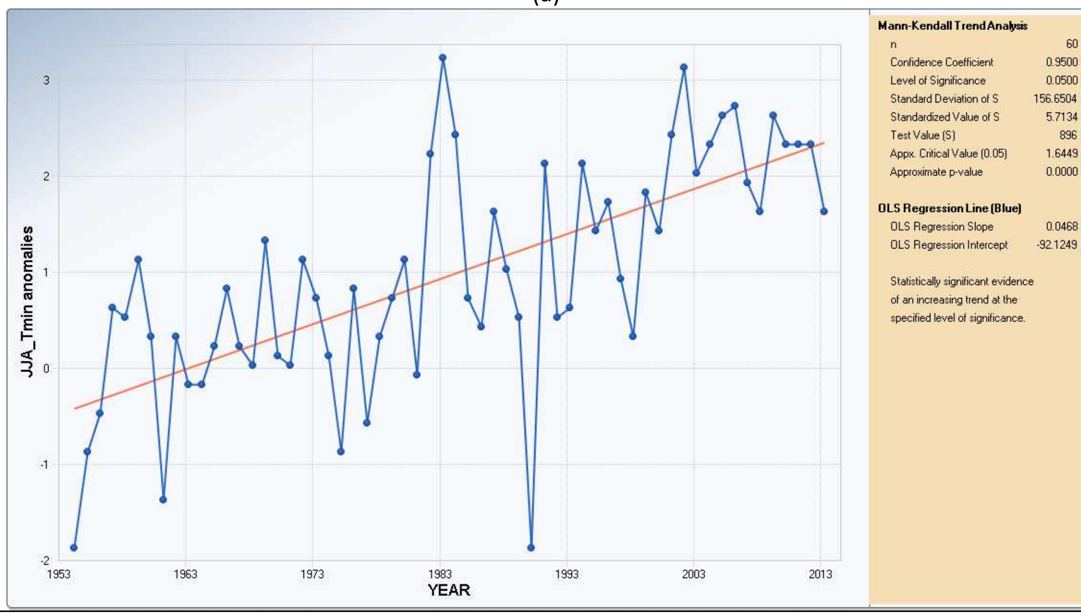


Figure 19: Time series of Observed MAM minimum temperature Anomalies for selected stations (a) Malakal, (b) Raja.

The time series for June-August (JJA) season explained the significance increasing trends at Renk, Raja, Wau and juba stations, while there is insufficient statistical evidence of increasing trend in Malakal (Figure 20).

(a)



(b)

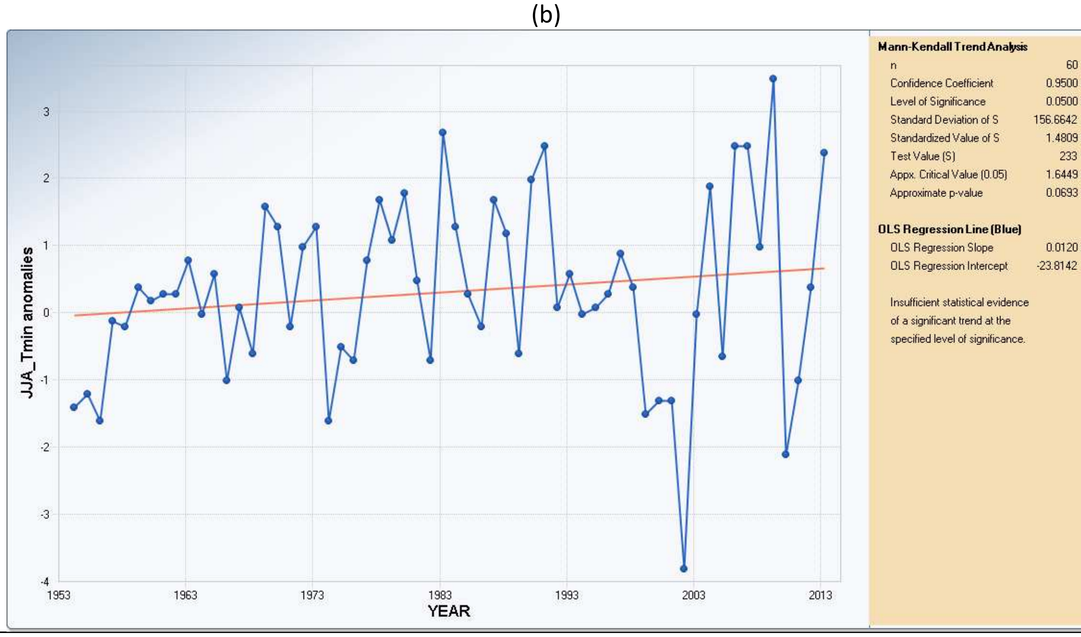


Figure 20: Time series of Observed JJA minimum temperature Anomalies for selected stations (a) Renk, (b) Juba.

The Observed September-November (SON) minimum temperature trends showed a significance increasing trend in Renk, Malakal, Raja and juba, whereas and Wau experienced insufficient statistical evidence of an increasing trend minimum temperature anomalies at 0.05 level of significance(Figure 21).

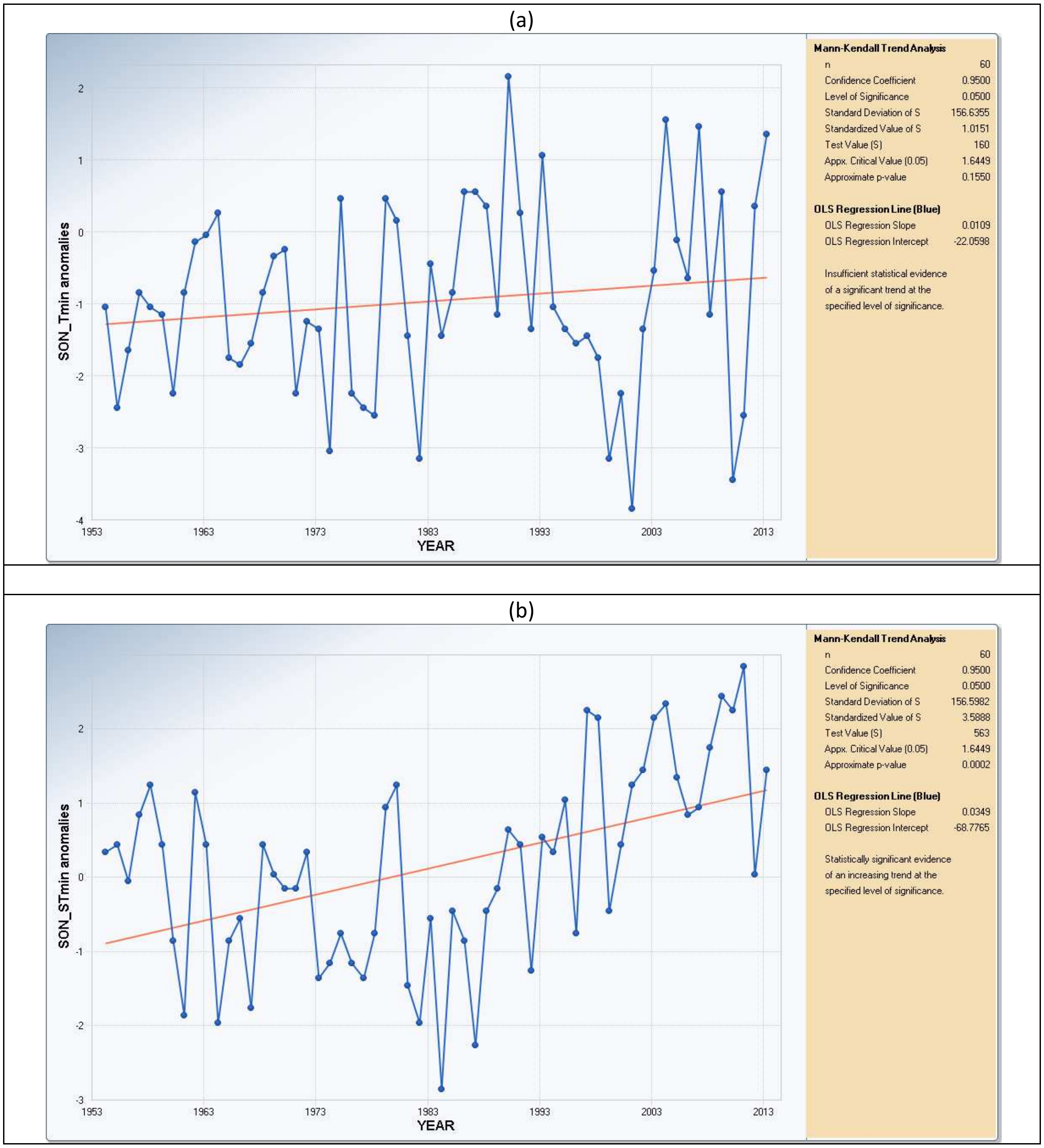


Figure 21: Time series of Observed SON minimum temperature Anomalies for selected stations (a) Malakal, (b) Wau.

December to February (DJF) season observed a significance increasing trend in Renk, Malakal, Wau and juba, whereas and Raja experienced statistical significance a decreasing trend of minimum temperature anomalies at 0.05 level of significance (Figure 22).

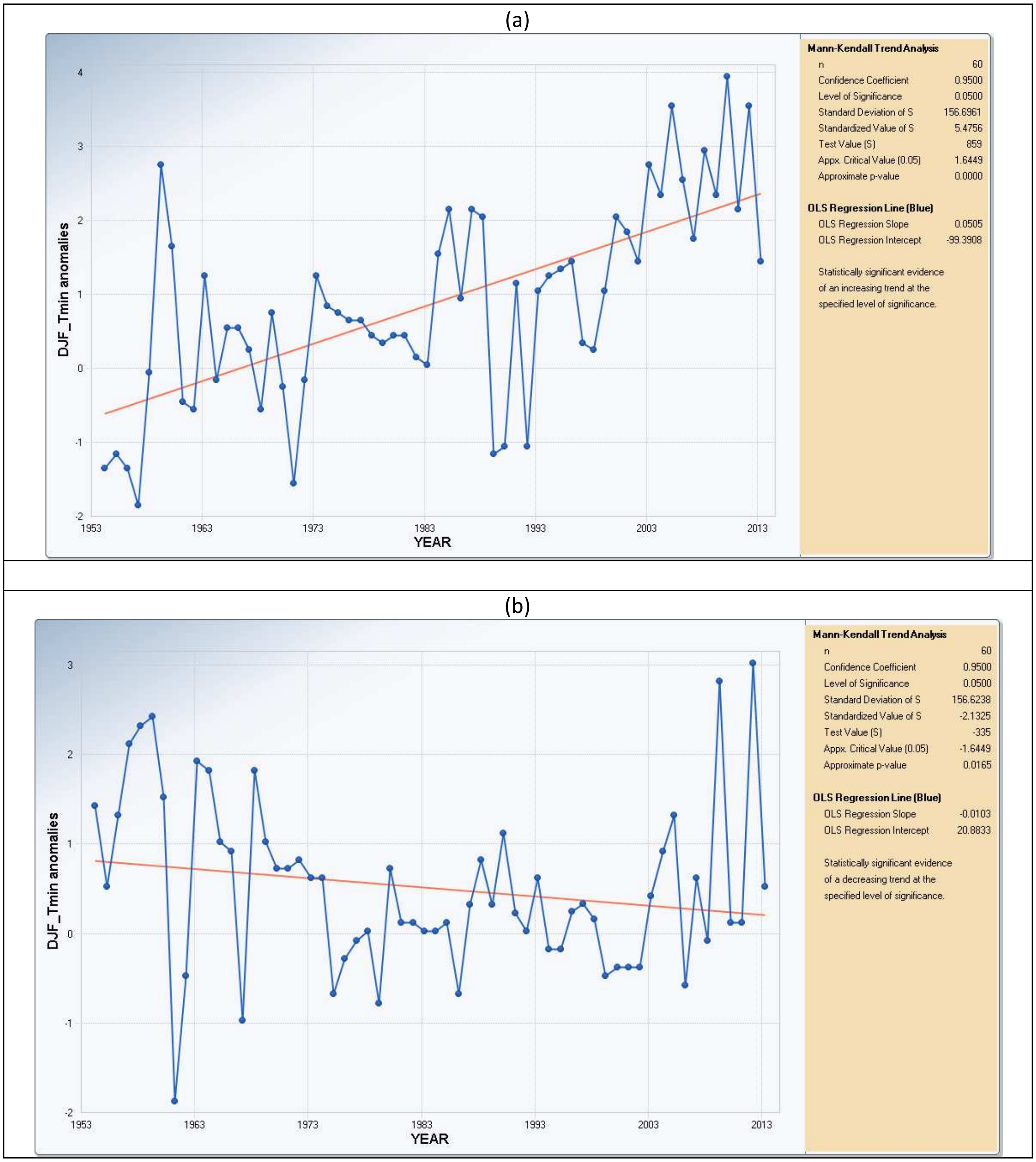


Figure 22: Time series of Observed DJF minimum temperature Anomalies for selected stations (a) Renk, (b) Raja.

The results on maximum and minimum temperature anomalies suggested clear evidence of effect of climate change and global warming and can be considered as strong evidences of climate change signals over south Sudan. This warming is expected to continue in the next decades due to the projected increase in the anthropogenic forcings. Adaptation measures should be put in place to reduce the vulnerability of the South Sudanese people. These results has confirmed the findings from Nicholson *et al*. (2013), which concluded that there is variability of temperature during the last 200 years and a significant increases during the last 50-100 years over most parts of Africa with minimum temperatures warming more rapidly than maximum temperature.

In general decreasing in rainfall and Increasing in maximum and minimum temperature showed clear evidence of climate change signals over South Sudan. These changes have negative impacts on socio-economic sectors such as Human Health, Forests, Transportation, Energy, Water Resources, Agriculture and Food Supply. Because increasing in temperature is expected to increase the risk of heat-related illnesses. The productivity of forests could be affected by changes in temperature, precipitation and the amount of carbon dioxide in the air. Also decreasing in rainfall and Increasing in temperature will increase electricity demand for cooling in the summer; also Changes in rainfall and temperature have impacts have negative impacts to transportation infrastructure through higher temperatures. For Agriculture and Food Supply moderate warming and more carbon dioxide in the atmosphere may help plants to grow faster. However, more severe warming, floods, and drought may reduce yields. Livestock may be at risk, both directly from heat stress and indirectly from reduced quality of their food supply. Fisheries can be affected by increasing temperature through changes in water temperature that shift species ranges, make waters more hospitable to invasive species, and change lifecycle timing.

4.3 Observed spatial Variability and Extremes in the observed rainfall and temperature

This sub-section presents the observed spatial variability and extremes in rainfall and temperature.

4.3.1 Observed Spatial Characteristics of Rainfall

The spatial rainfall pattern for the three main rainy seasons, which consist of March to May (MAM), June to August (JJA), and September to November (SON) seasons, where agricultural activities are predominant are presented in figurers 23. The spatial rainfall pattern based on long-term means (1961-1990) fixed to assess the spatial characteristics of annual and seasonal rainfall characteristics.

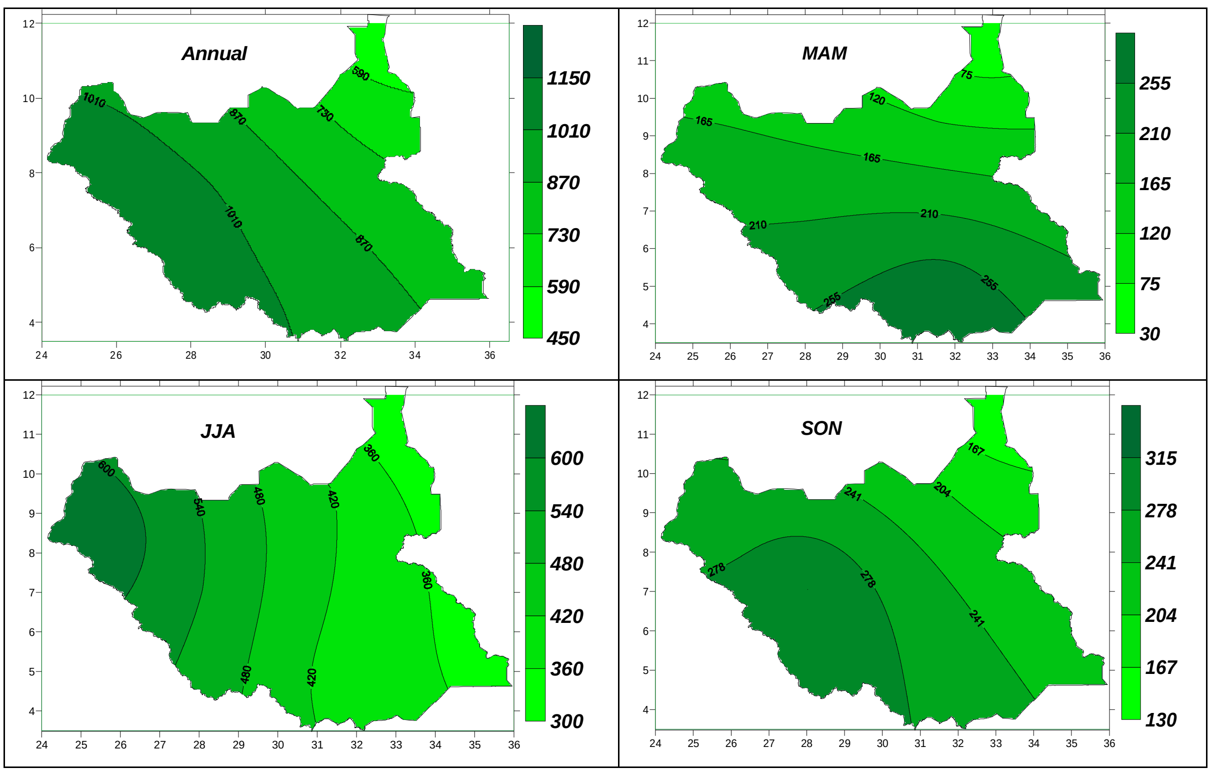


Figure 23: Annual and Seasonal characteristics of Observed rainfall over south Sudan.

The observed spatial annual and seasonal rainfall patterns over south Sudan indicated the amount of annual and seasonal rainfall increased from northeast to southwest. Semi arid areas in northern parts of the country, received an average annual rainfall of 480 mm, while humid and semi humid areas received annual rainfall greater than 1000 mm per year on average. JJA is considered the main rainy season over most parts of the country with a seasonal average rainfall of between 300-500 mm. During MAM seasons, rainfall increases gradually from south to north (more than 250 mm in south to less than 40 mm in extreme north). In DJF, which is a cold and dry season, less than 8 mm per season in average was recorded. The decrease of amount of rainfall from northeast to southwest may be relate to topographic lifting caused by Ethiopian plateau in the eastern part of the country and the effect of the Azores ridge of high pressure over the Atlantic Ocean.

The contribution of each season on annual rainfall is also assessed in figurers 24.

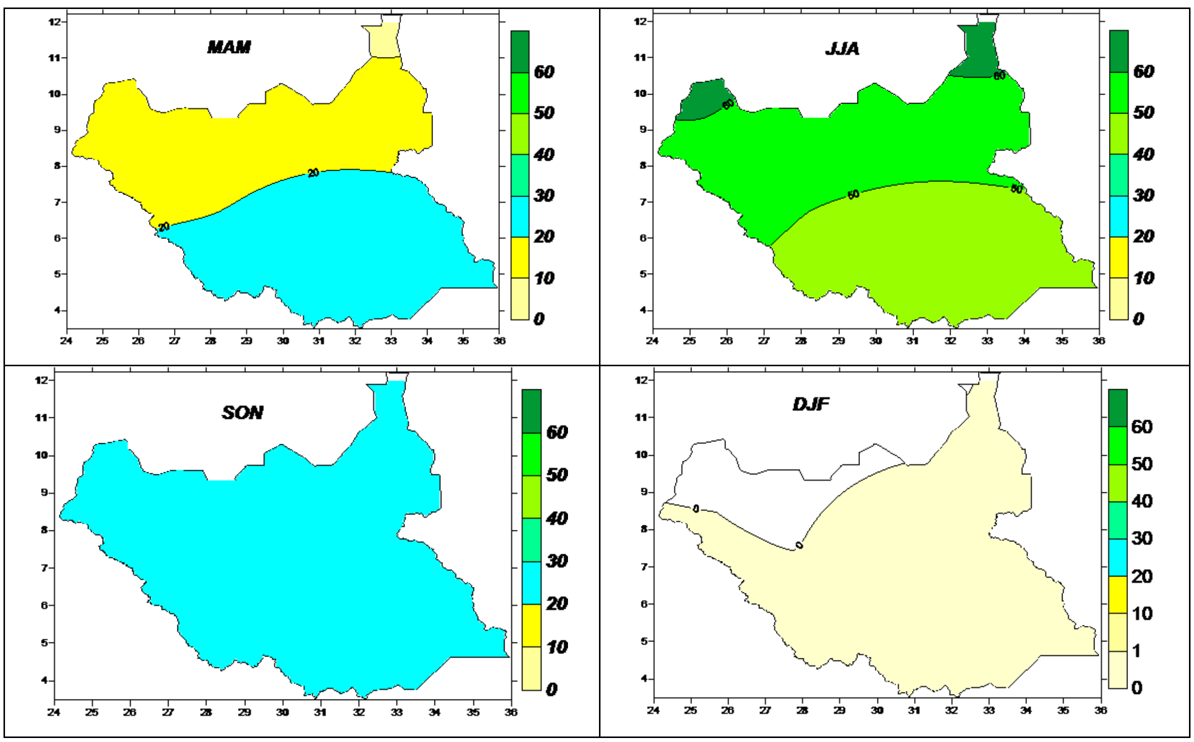


Figure 24: Contribution of observed seasonal rainfall (%) on annual rainfall

The results revealed that, the JJA season contribute more than 60 %, 50-60% and 40-50% of annual rainfall in extreme north, central and southern parts of country respectively, whereas MAM contributes less than 10%,10-20% and 20-30% of annual rainfall in extreme north, central and southern parts of country respectively. SON season on the other hand contribute 20-

30% and while DJF contribute less than 1% of the annual rainfall over the entire country (figurers 12). During DJF season, the severity of cold and dry north east wind that blows across the country push the inter-tropical convergence zone (ITCZ) southward till it crosses the border at the end of December. This leads to dry and cold conditions with no activity of advection and convection especially the northwest of country. The spatial characteristics of temperature are presented in next subsection.

4.3.2 Observed spatial characteristics of temperature over south Sudan

Figure 25 shows the annual and seasonal maximum and minimum temperature patterns. The results indicate that temperature in South Sudan is not uniform. It varies from location to location, season to season, and month to month. Highest level of mean maximum temperature is registered during MAM which had more than 38°C in northern parts of country, while JJA season recorded lowest level of mean maximum temperature not exceeding 35°C across the country. DJF season is winter in south Sudan. During this period, the northern parts of the country received low temperatures compared to southern parts due to the dry and cold northeast winds.

On other hand the lowest level of minimum temperature were registered in winter (DJF) season especially northwestern parts of the country which recorded the lowest minimum temperatures throughout the year where in some instances reached values less than 12°C. During MAM season the central parts of the country received higher minimum temperatures compared to other parts. During the JJA season, the minimum temperature differences were notably small across the country and not exceeding 25°C may be the reasons behind that are activities of convective cloud and vegetation cover. This situation extended to SON season where minimum temperature decreased from west to east.

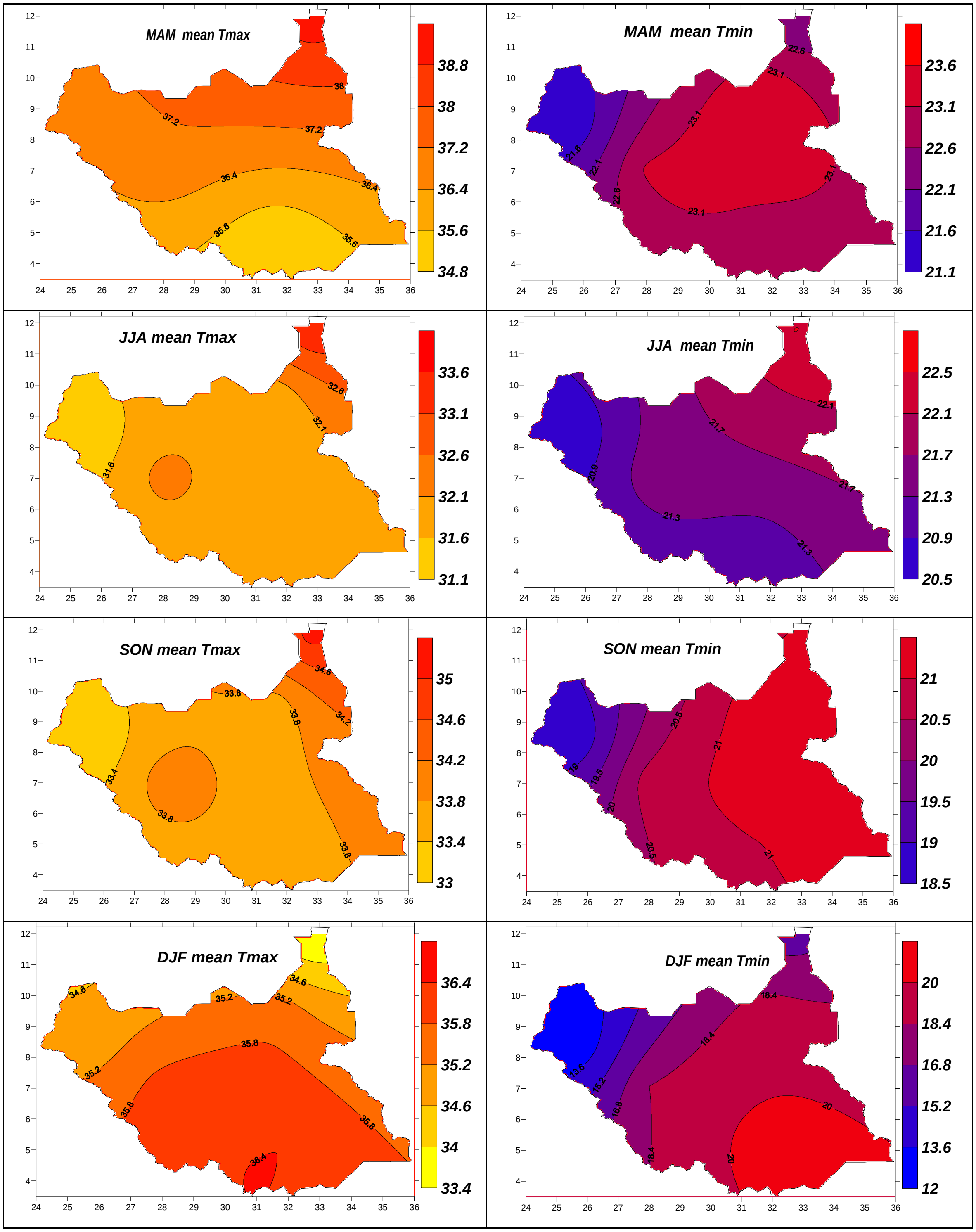


Figure 25: Spatial patterns of Mean seasonal Minimum and minimum temperature distribution.

4.3.3 Observed Spatial Changes in Rainfall and Temperature

The results obtained from the differences in means of annual and seasonal rainfall and temperature (maximum and minimum) for the current period 1984-2013 relative to 1954-1983 (left panel) and 1961-1990 (right panel) are given in Figures 26, 27 and 28 respectively.

The results for annual and seasonal rainfall indicated that there is exists a considerable increase in rainfall in some locations and decrease in others with respect to the two periods and rate of change differs from location to location and also from season to season. For annual rainfall, Northeastern observed an increase in current annual rainfall compared to southwestern which observed a decrease relative to the period 1954-1983, while northwest observed an increase in current annual rainfall relative to the period 1961-1990. Southwest and southeast regions observed a decrease in the current period for March – May (MAM) season compared to June – July (JJA), which observed small changes in northwest relative to two periods. However, during the September–November (SON) season, the results showed an increase in the current rainfall in southeast relative to period 1954-1983, while a general decrease was observed in the current mean rainfall with respect to 1961 -1990 in southwest of the country (Figures 26).

Mean while, changes in maximum temperature indicated that during all seasons considered in the study i.e. (MAM, JJA SON, and DJF, the changes in patterns of mean seasonal maximum temperatures with respect to the two periods vary from location to location and from season to season. There is clear evidence showing slight warming in current period relative to 1954-1983 which is too big compared to 1961-1990. The northern parts of the country shows more warming compared to southern parts for all seasons (Figure 27).

Apart from rainfall and maximum temperature, the minimum temperature for current period (1984-2013) relative to 1954-1983 had increasing anomalies compared to 1961-1990, which observed decreasing anomalies for most parts especially northwest of country (Figure 28).
The decline in amount of rainfall and increasing maximum and minimum temperatures in the current period compared to previous periods can be direct effect of global warming and another evidence of climate change signal over South Sudan.

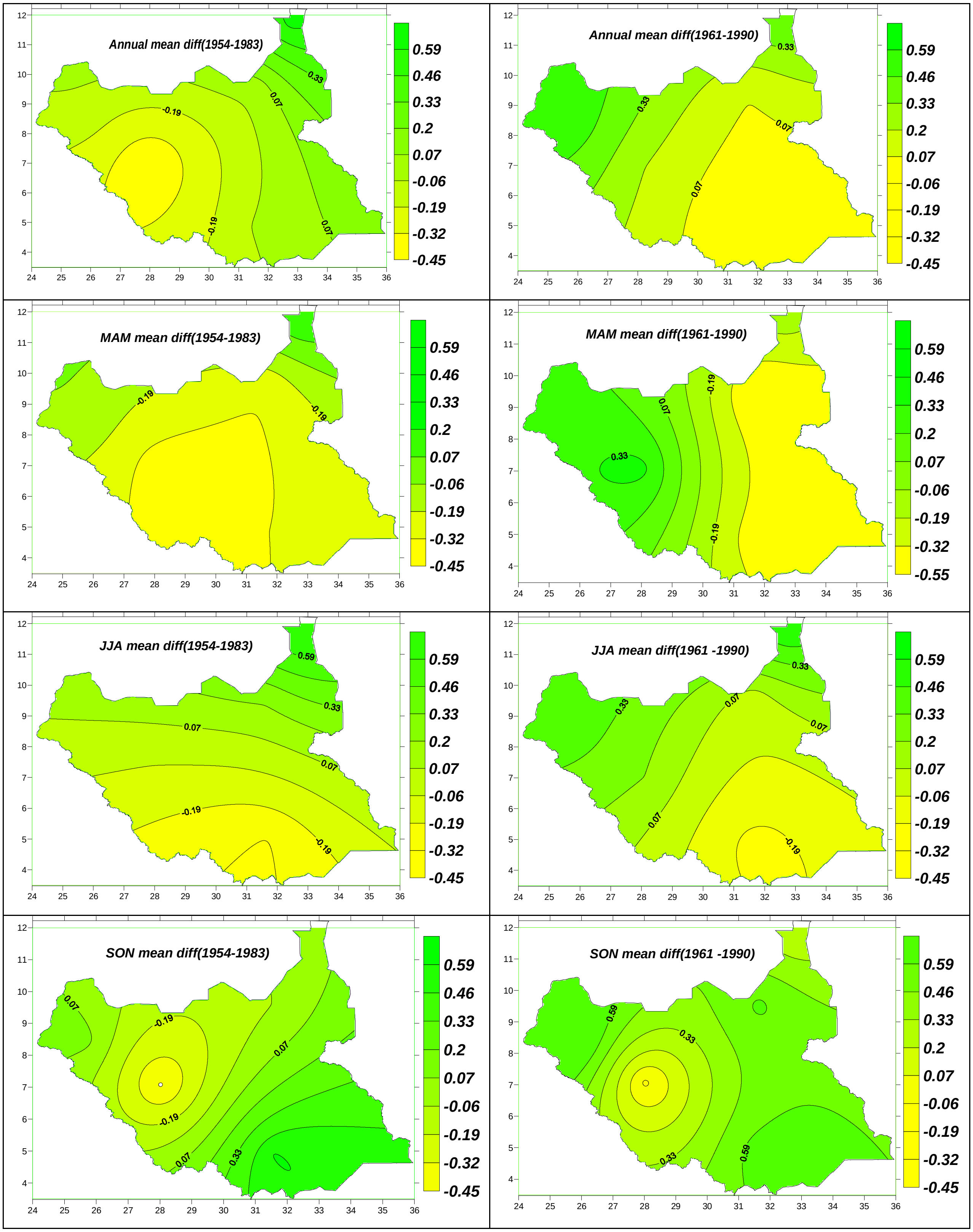


Figure 26: Observed changes in the current seasonal rainfall means.

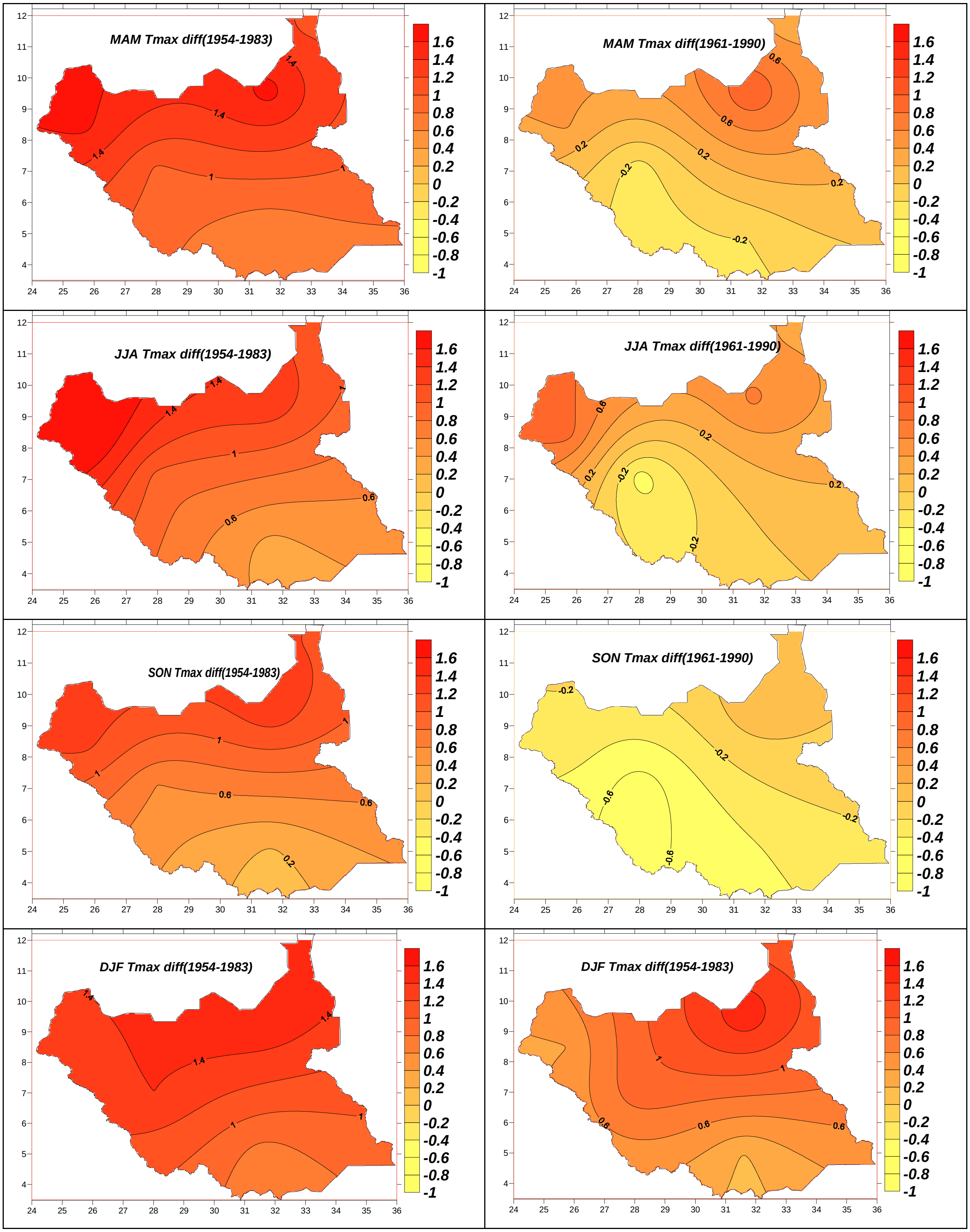


Figure 27: Observed changes current mean seasonal maximum.

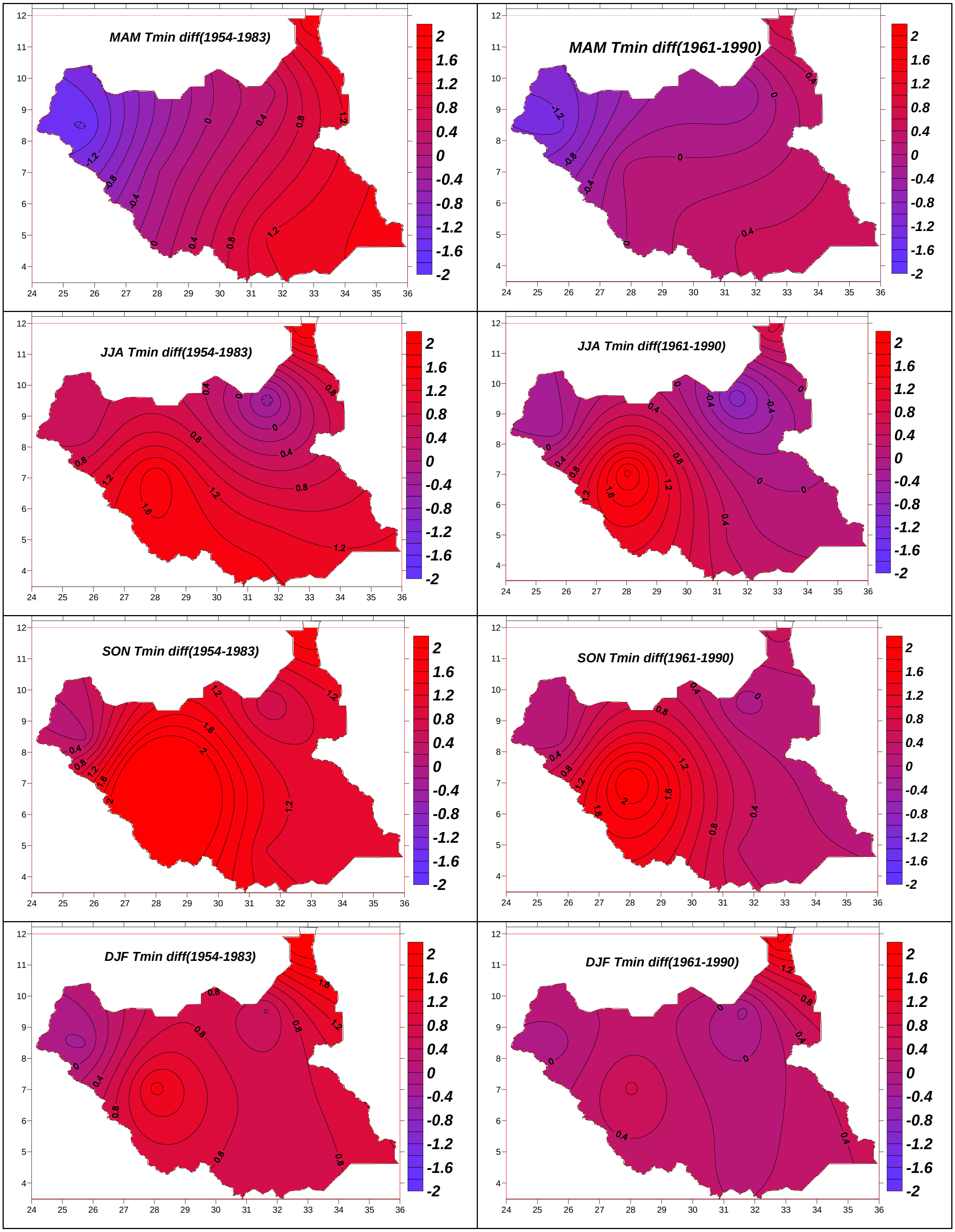


Figure 28: Observed changes current mean seasonal minimum temperature.

4.3.4 Observed Spatial Variability in Rainfall and Temperature

The results obtained from the differences in standard deviation (SD) of rainfall, maximum and minimum temperatures for the current period 1984-2013 relative to 1954-1983 (left panel) and 1961-1990 (right panel) are given in Figures 29, 30 and 31 respectively. The results indicated a notably small-observed variability in the current rainfall relative to 1954-1983 and 1961-1990. Extreme northeast and northwest of the country observed a decrease in annual current rainfall variability (standard deviation) compared to central parts that observed an increase with respect to the two periods. In addition, results indicate that there exist decreases in the current rainfall variability over most parts of the country during MAM with respect to the two periods. During JJA season, the southwest and some areas in central experienced an increase in variability, while other parts experienced a decrease with respect to the two periods. September – November (SON) experienced a decrease in the current rainfall variability over most parts of the country with respect to 1954-1983, while increases in variability were observed with respect to 1961-1990 (Figure 29).

The results for maximum temperature shows small variability compared to rainfall. During MAM season, the variability in maximum temperature anomalies in the southern parts were observed to decrease compared to the northern part of the country. JJA variability in the northwest showed a marked increase in anomalies compared to other areas. The southern and central parts during SON and DJF seasons had a decrease in variability, while western and northern parts of country recorded increased variability in maximum temperature anomalies compared to other locations (Figure 30).

On the other hand, the variability in minimum temperature anomalies slightly higher compared to the maximum temperature especially in the northwest and southwest parts of the country. During JJA and SON seasons there was increased variability from northwest to southeast. In MAM and SON seasons, the variability decreased from west to east, while southwest and central parts during DJF season had less variability compared to other locations (Figure 31).

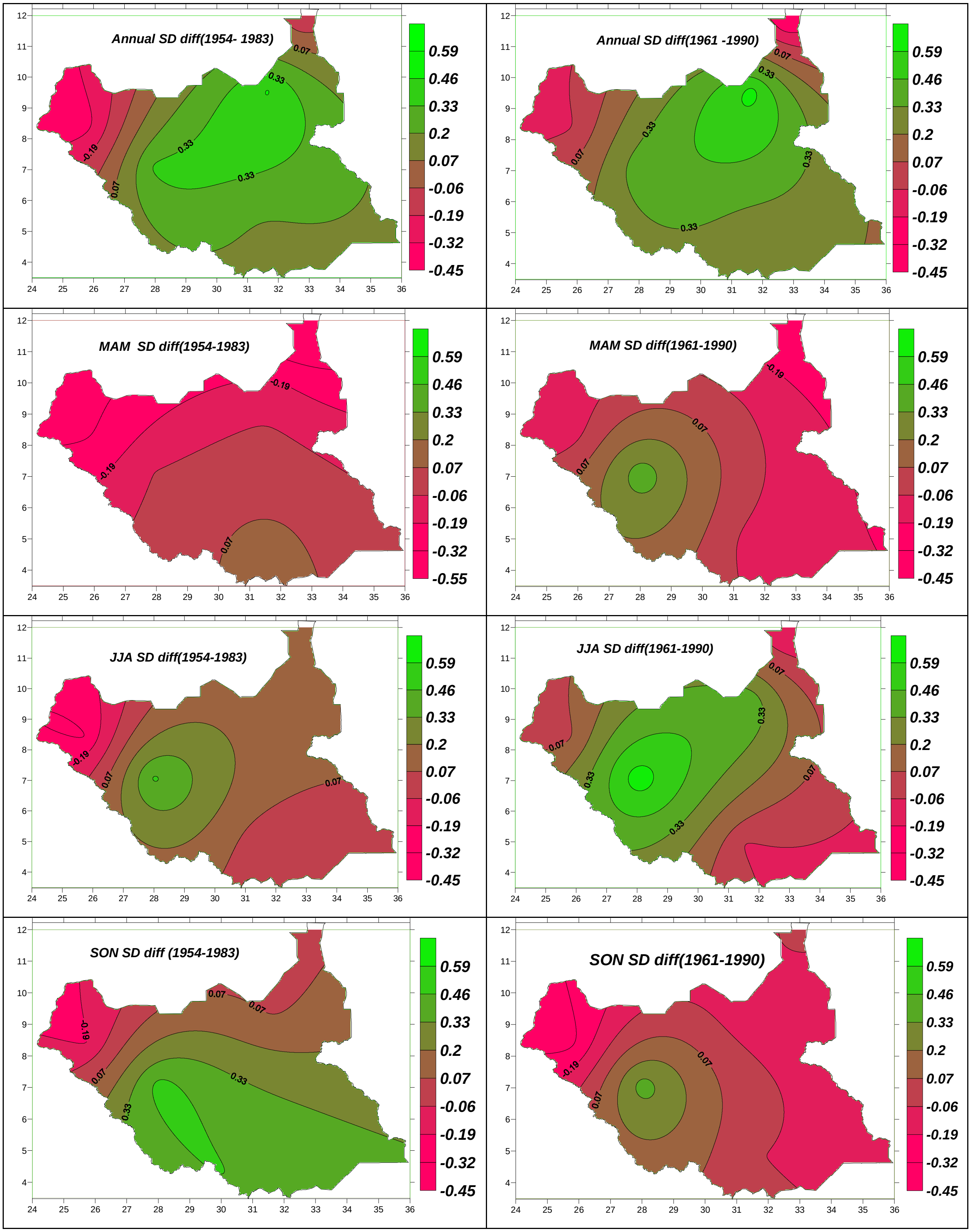


Figure 29: Observed variability in the current seasonal rainfall (1984-2013) relative to 1921-1951 (left panel) and 1952-1982 (right panel).

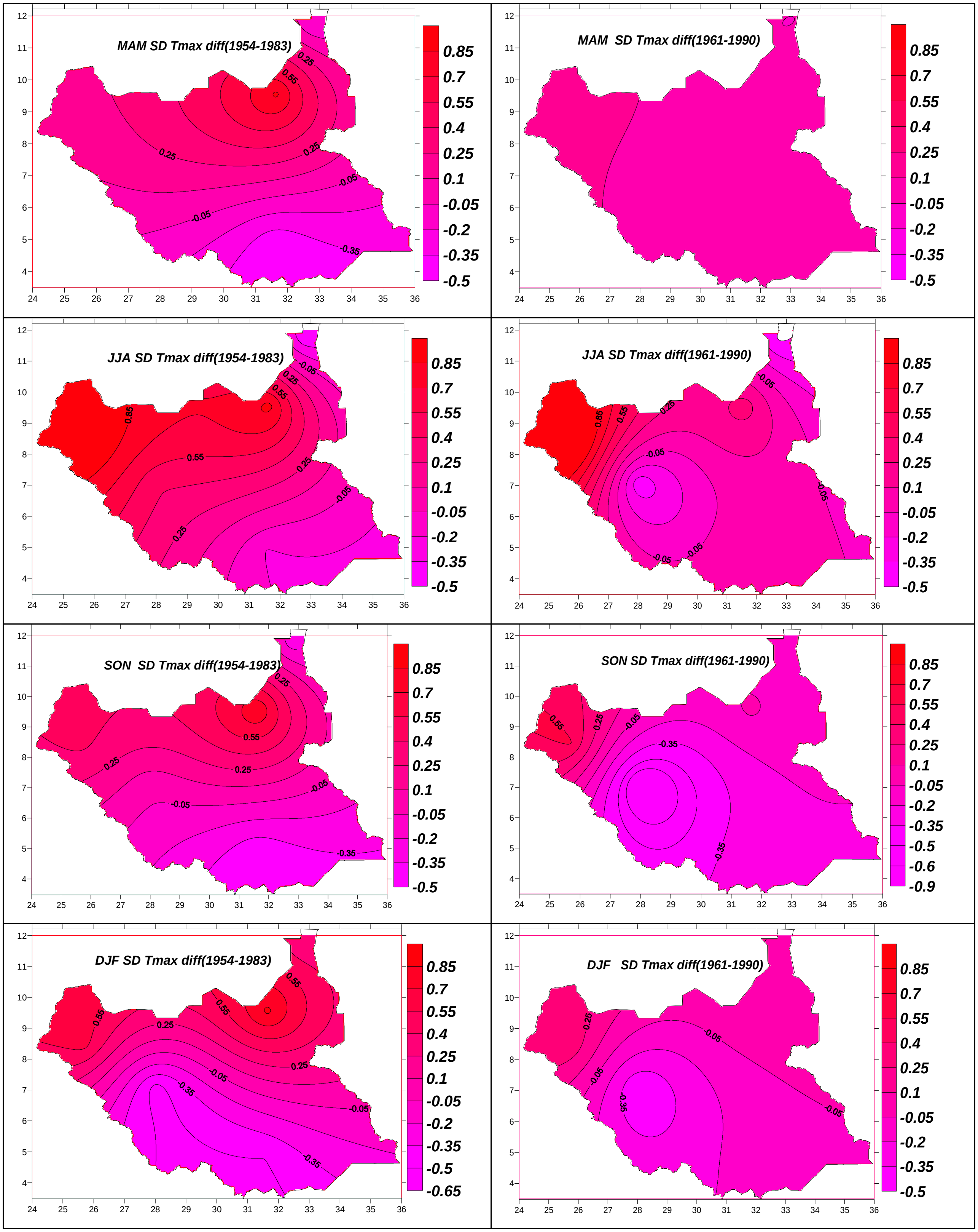


Figure 30: Observed variability current mean seasonal maximum temperature (1984-2013) relative to 1954-1983 (left panel) and 1961-1990 (right panel).

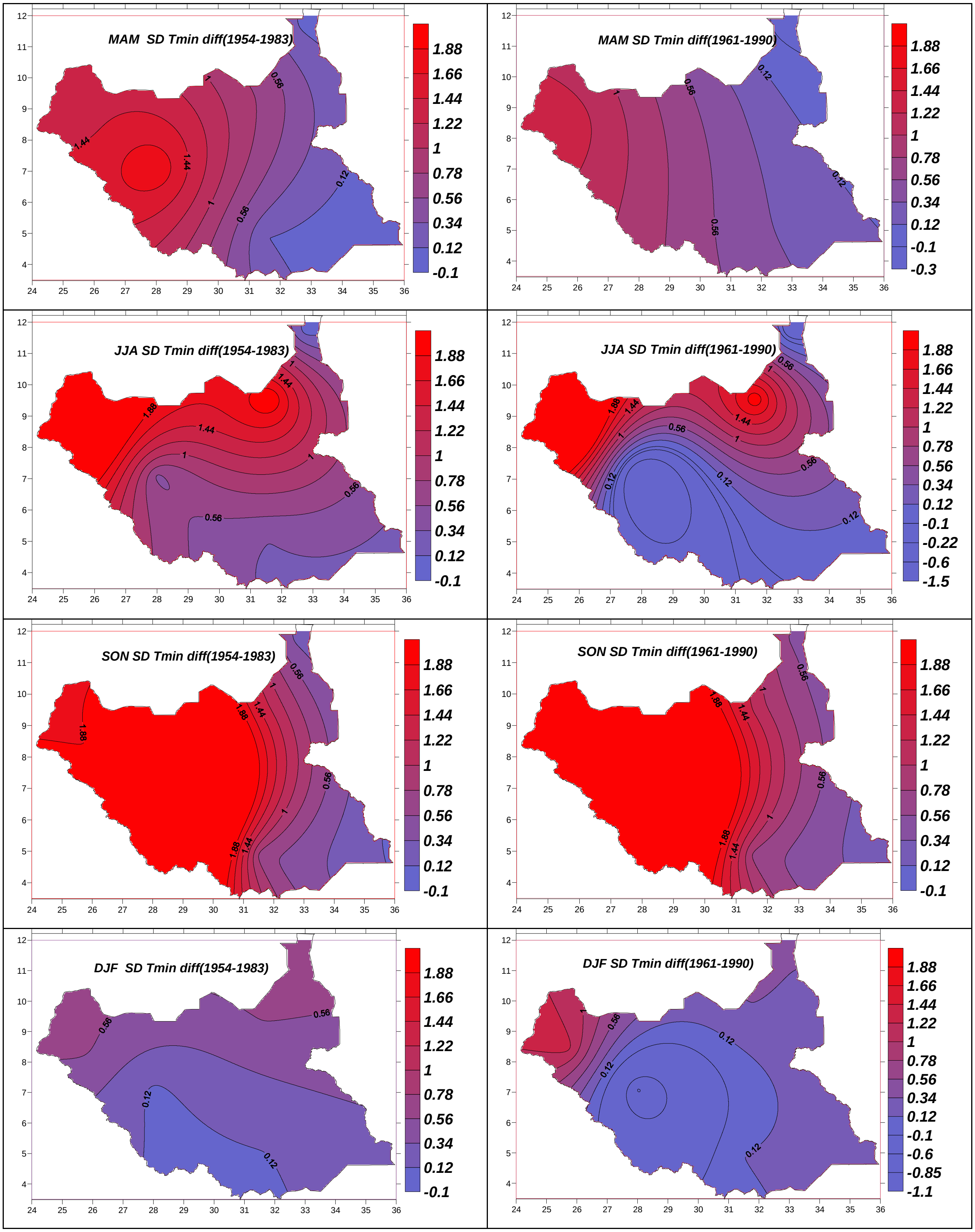


Figure 31: Observed variability current mean seasonal minimum temperature (1984-2013) relative to 1954-1983 (left panel) and 1961-1990 (right panel).

The impacts of variability and changes in maximum and minimum temperature can lead to negative or positive effects. For example the increase in maximum temperature can lead to increase in agricultural production up to an optimal value of air temperature beyond which any further increase would result in negative effects and a consequent decline in production and vice versa. In addition, there are other factors, which can accelerate the degree of negative /positive impacts of maximum and minimum temperature in any part of the world It is important to note that the increase in maximum temperature can only promote agricultural activities if rainfall trends over an area match temperature increases to keep the soil moisture content favorable for crop growth.

The increase/decreases in annual and seasonal rainfall variability during MAM, JJA and SON seasons can be linked to natural factors such as El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) among others. Several studies over east Africa have noted that ENSO effects are more pronounced during October – December season with a lesser influence on March - May and June – August seasons over east Africa region (Nicholson and Entekhabi, 1987; Mutai and Ward, 2000; Camberlin and Philippon, 2002). Other studies recommended that the IOD events appear to have a stronger impact on rainfall than ENSO (Black *et al*., 2003; Philippon *et al*., 2002). However, for south Sudan there is big gaps in such studies, therefore this study will investigate the linkage between those phenomena (ENSO and IOD) with the observed rainfall over South Sudan. Next subsection presents the spatial characteristics of observed annual and seasonal temperatures over South Sudan.

4.3.5 Probability distribution of rainfall and temperature in a changing climate extremes

This sub-section presents the results obtained from the Gaussian kernel distribution of rainfall, maximum and minimum temperatures long term means of two periods 1954-1983 and 1984-2013 for annual rainfall, March to May (MAM) maximum temperature and December to February (DJF) minimum temperature respectively for Renk, Malakal, Raja, and juba stations. The first one (Area shaded in coral pink) is long term mean for 1954-1983 and the second one (Area shaded in light sky blue) is long term mean for 1984-2013.

Figures 32 shows the results for rainfall distributions and shifting between past (1954-1983) and present (1984-2013) long term means (LTM). The results showed the existence of four main probability distribution either a simple shift of the entire distribution toward wettest/driest (floods /drought), effects of an increase in rainfall variability with no shift in the mean and effects of an altered shape of the distribution, such as a change in asymmetry toward the wettest/driest part of the distribution.

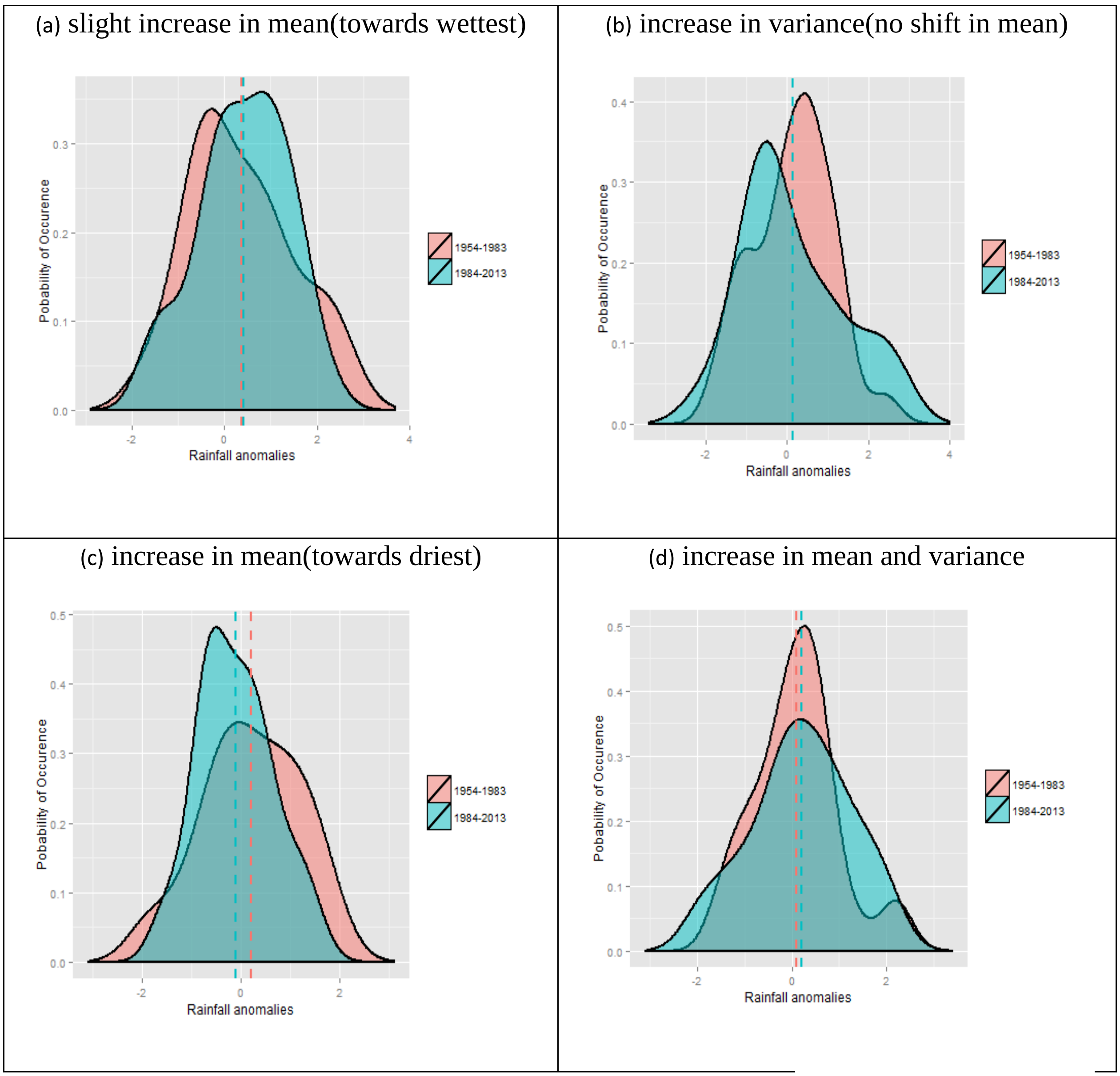


Figure 32: The effect of changes in Rainfall distribution on extremes: (a) Renk, (b) Malakal, (c) Raja, (d) Juba.

The long term mean for annual and MAM, JJA and SON seasonal rainfall, the distribution for 1984-2013 has slightly shifted to the right (i.e. towards wettest) such as situation in extreme north represented by Renk or shifted to the left (i.e. towards driest) like situation in northwest and central of country represented by Raja and Wau respectively or seem to be constant like situation in northeast of country represented by Malakal for 1954-1983 for all annual and seasonal maximum and minimum temperature at all locations considered in study. Also results showed shifting in long term mean to wettest/driest are different from what happens to the extremes at either end of the distribution, some extremes drought and floods increasing in recurrent with shifting of long term means toward wettest direction and driest direction.

Figures 33 shows the results for maximum temperature distributions and shifting between past (1954-1983) and present (1984-2013) long term means (LTM). The results for annual and MAM, JJA,SON and DJF seasonal maximum temperatures showed the distribution for 1984-2013 has shifted to the right (i.e. towards higher temperatures) from that for 1954-1983 for all annual and seasonal maximum and minimum temperature at all locations considered in study.

For a normally distributed variable such as temperature a small increase in long-term mean or variance, can produce substantial changes in the probability of occurrence of extreme heat waves (IPCC, 2007a, 2012, 2013a). All stations considered in study, observed shifting in long term mean of annual and seasonal maximum temperature anomalies which manifested the increase in mean, increase in variance and increase in mean and variance which resulted in substantial changes in the frequency of occurrence of extreme hottest waves events.

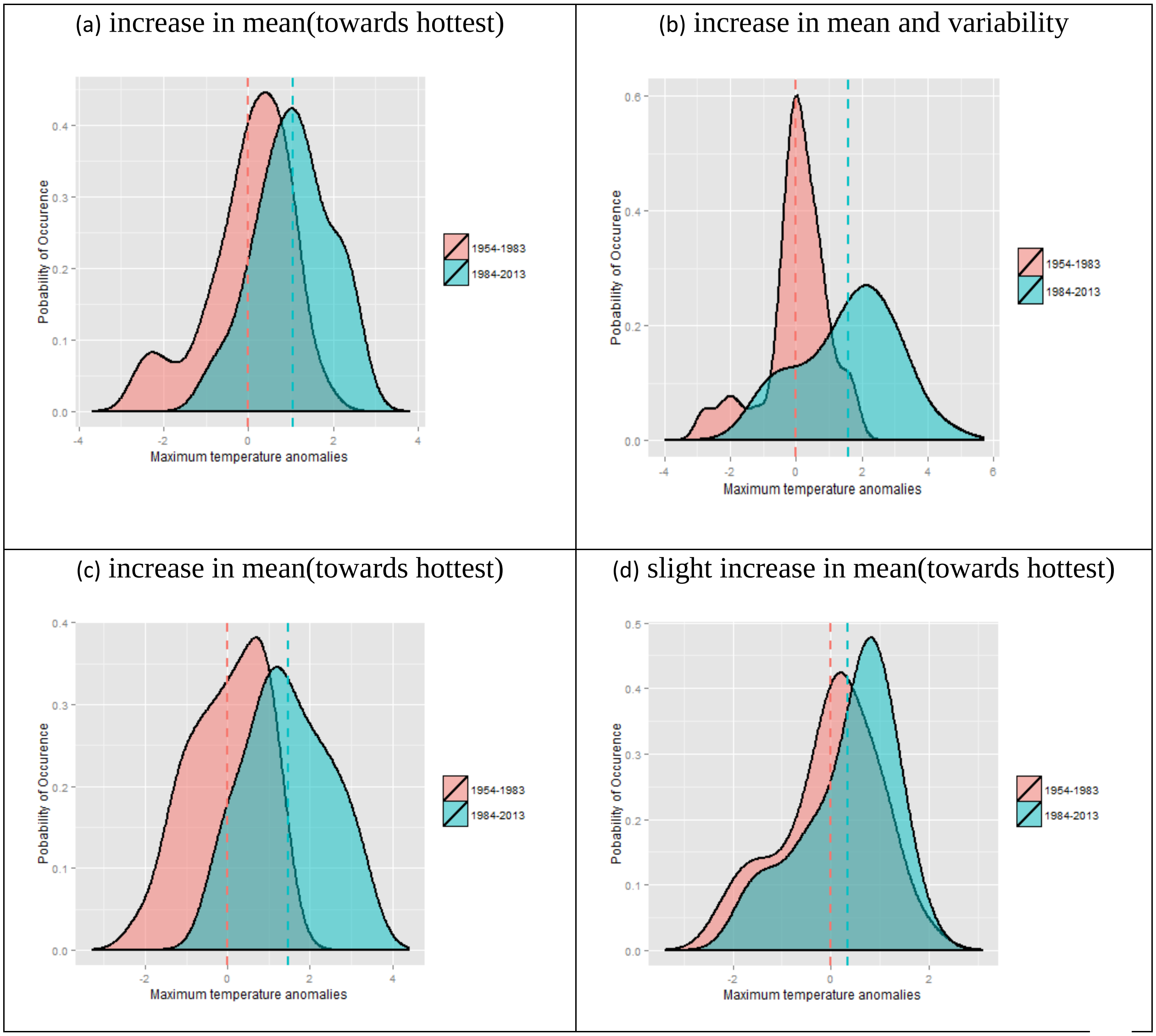


Figure 33: The effect of changes in MAM maximum temperature distribution on extremes: (a) Renk, (b) Malakal, (c) Raja, (d) Juba.

Figures 34 shows the results for minimum temperature distributions and shifting between past (1954-1983) and present (1984-2013) long term means (LTM). The results also showed existence four main probability distribution, either a simple shift of the entire distribution toward hottest minimum temperature, effects of increase minimum temperature variability with shifting in the mean or shape of the distribution, such as change in asymmetry toward the hotter part of the distribution.

In general the relationships between changes in mean rainfall and temperature and the corresponding changes in the probabilities of these extreme rainfall and temperature events are quite nonlinear, with relatively small changes in mean rainfall and temperature sometimes resulting in relatively large changes in event probabilities.

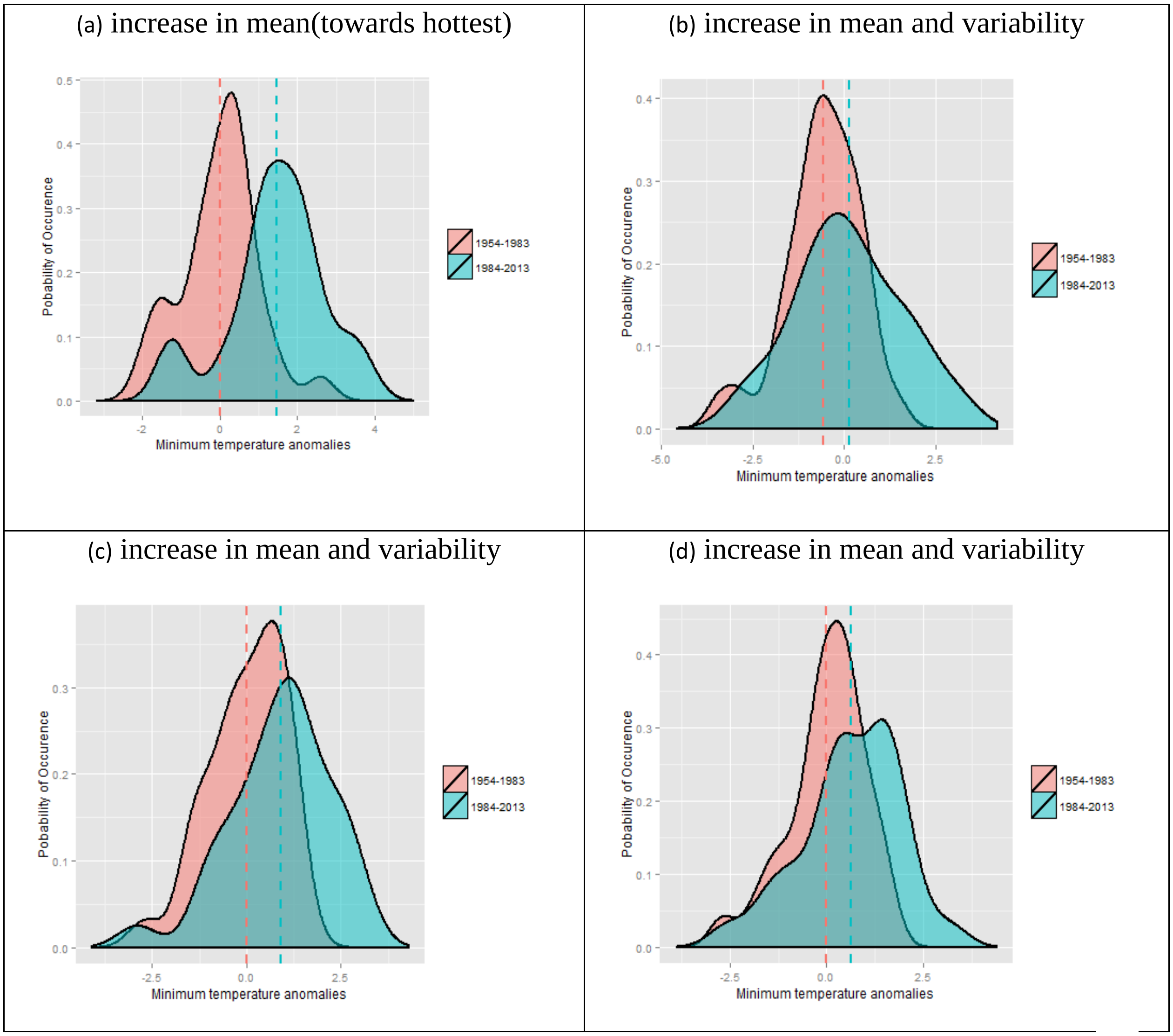


Figure 34: The effect of changes in DJF minimum temperature distribution on extremes: (a) Renk, (b) Malakal, (c) Wau, (d) Juba.

4.3.6 Spectral Analysis

This subsection presents the results obtained from spectral analysis of rainfall and maximum and minimum temperature for selected locations. The observed spectral peaks in the seasonal rainfall anomalies are presented in Figures 35 for selected representative stations and seasons. The results indicated that there is recurrent of spectral peaks in most of the stations considered in this study but not exceeding 3 significance spectral peaks at 95% confidence level.

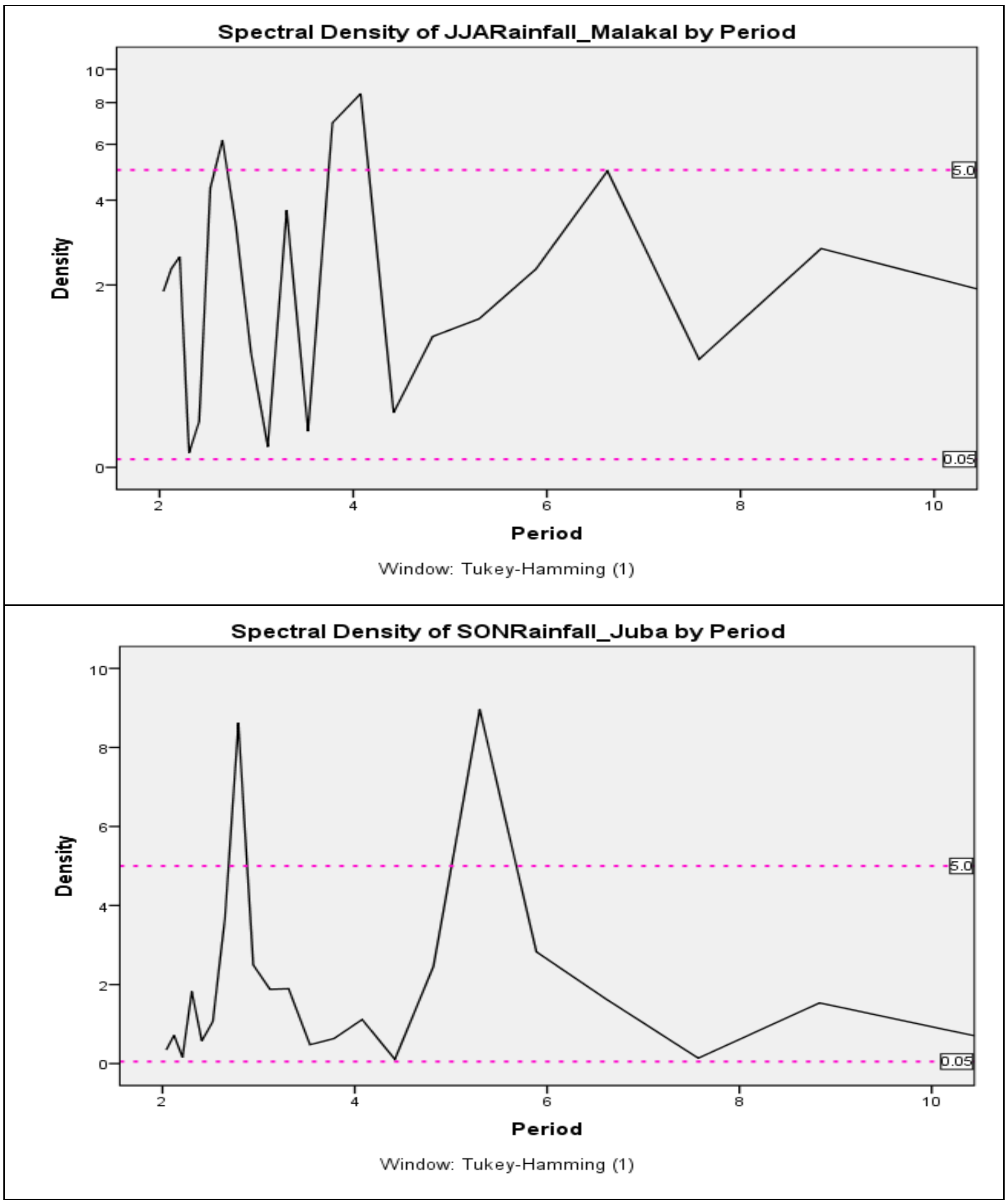


Figure 35: Observed spectral peaks in seasonal rainfall at selected stations (Malakal and Juba).

The proportion of the total rainfall variance accounted for by each spectral peak varied significantly from one region to another. Generally, the annual and seasonal rainfall spectral peaks occurred between 2 and 10 years. The period ranges of the two spectral peaks were centered on 2 to 7 years, and observed in most of stations considered in this study, especially in the southern parts of country represented by Juba. During the MAM, JJA and SON rainfall seasons, the one spectral peak ranging between 2 to 3 years and, two spectral peaks range between 4 to 6 years.

The observed spectral peaks in the seasonal maximum temperature anomalies are presented in Figures 36 for selected representative stations and seasons. The results indicated that there is recurrent of spectral peaks in most of the stations considered in this study but not exceeding 3 significance spectral peaks at 95% confidence level. Also the results revealed that there is recurrent of one spectral peak in most of the stations considered in study. The proportion of the total maximum temperature variance accounted for by each spectral peak varied significantly from season to season and one region to another. For mean annual maximum temperature all spectral peaks occurred between 2 and 5 years. The period ranges of the 2 spectral peaks were centered on 3 to 7 years, occursing in most locations. During the MAM rainfall season, most parts of country observed the spectral peaks ranging between 3 and 8 years, similar results were obtained for the JJA and SON rainfall seasons.

The observed spectral peaks in the seasonal minimum temperature anomalies are presented in Figures 37 for selected representative stations and seasons. The results revealed that there is recurrent of significance spectral peaks in minimum temperature anomalies at 95% confidence level in most of the stations considered in this study but not exceeding 3 peaks ranging between 2 and 7 years. The proportion of the total minimum temperature variance accounted for by each spectral peak varied significantly from one region to another.

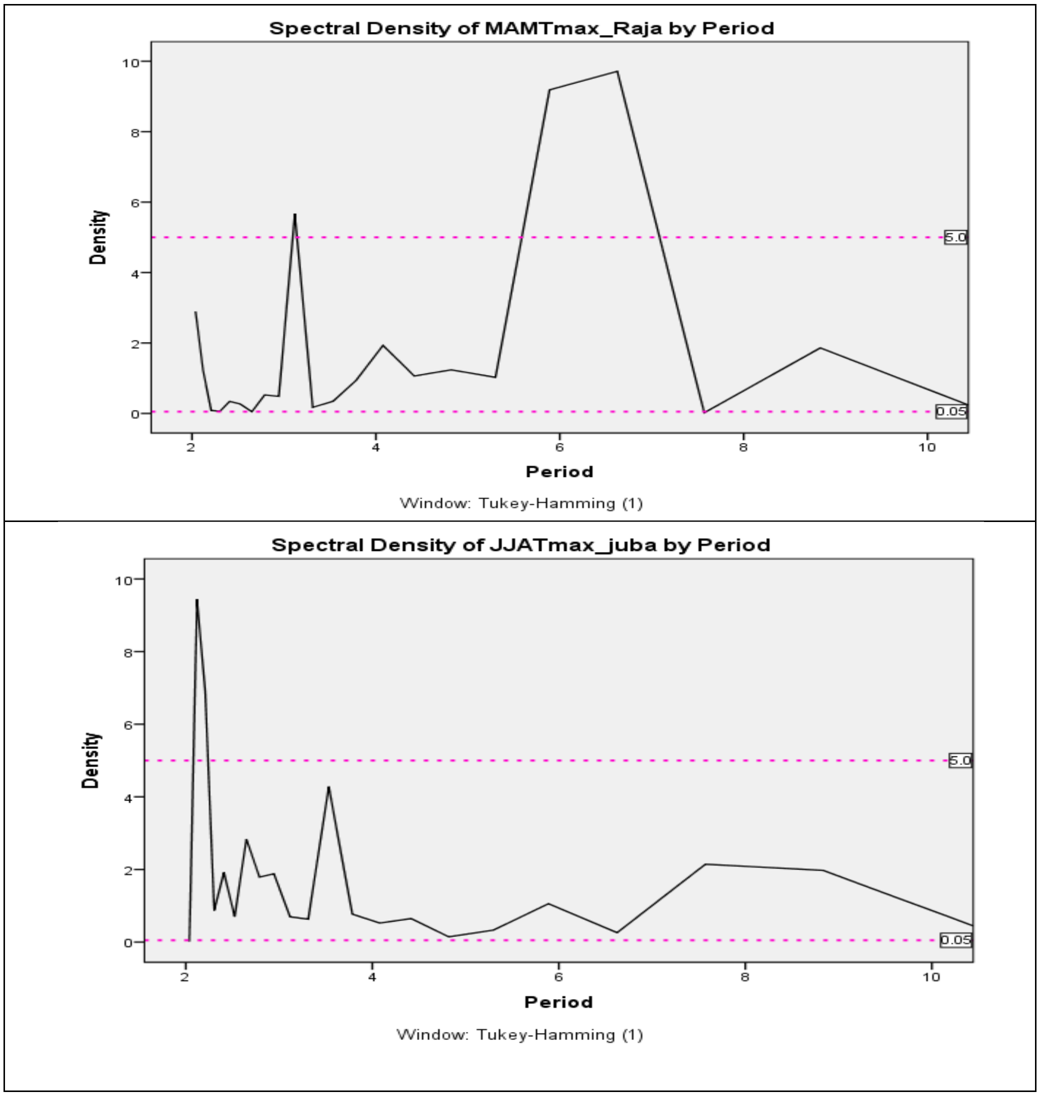


Figure 36: Observed spectral peaks in the annual and seasonal maximum temperatures at selected stations (Raja and Juba).

In general one spectral peaks in rainfall and maximum and minimum temperature occurs between 2 and 3 years. The period ranges of the 2 spectral peaks were centered on 3 and 7 years. During the periods 2 to 3 and 4 to 6 years, the spectral peaks were common in annual and seasonal rainfall and temperatures time series. Generally the most common spectral peaks in the south Sudan annual and seasonal rainfall and temperatures (maximum and minimum)) are centered around 2 to 3 years for all stations.

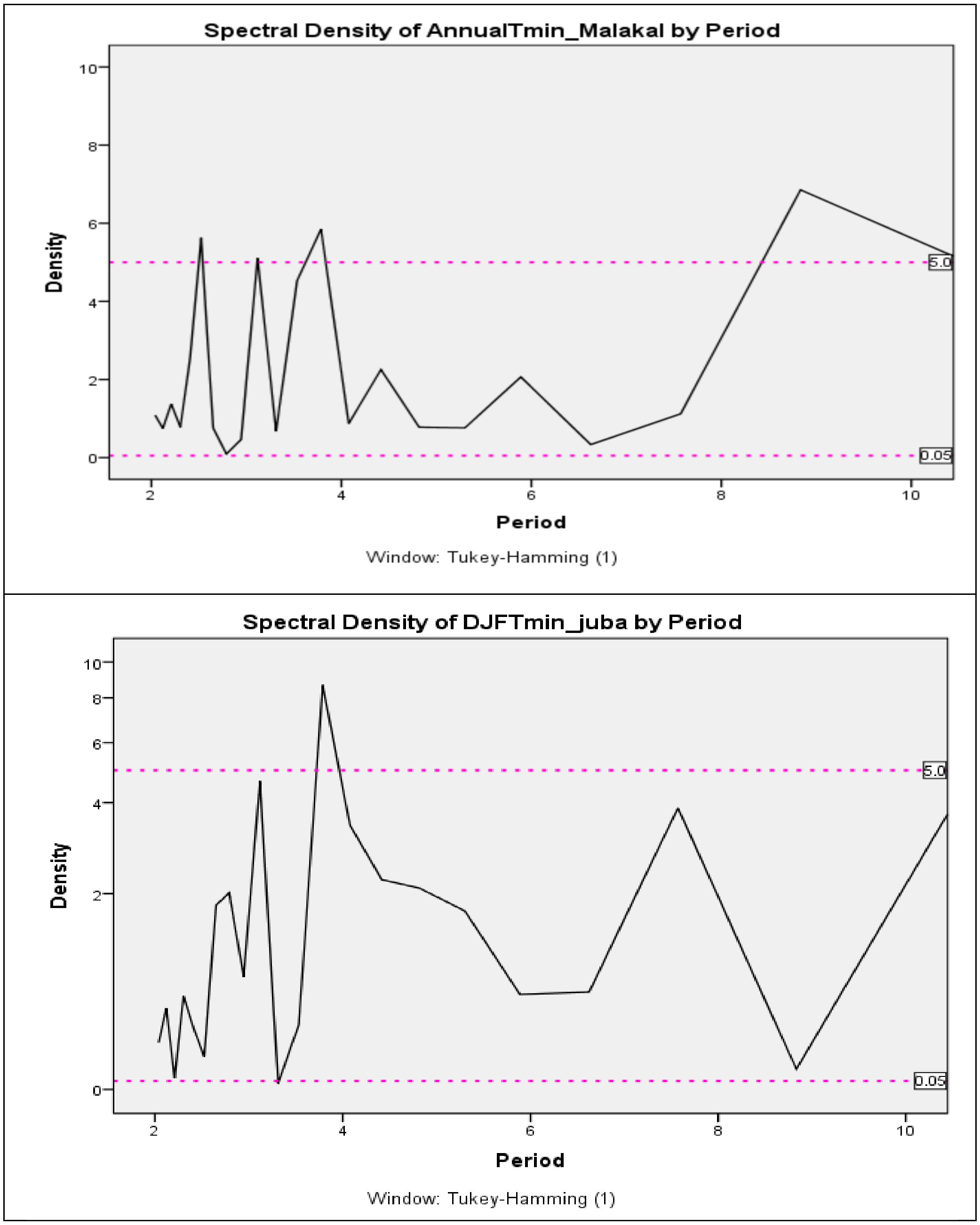


Figure 37: Observed spectral peaks in the annual and seasonal minimum temperatures at selected stations.

The observed fluctuations in the rainfall and temperatures can be attributed to some common large scale forcing mechanisms within atmosphere and ocean components such as Quasi-Biennial Oscillation (QBO) in the lower stratospheric zonal winds, El Niño and La Niña events especially those fluctuations occurring within periodicity of 2 to 3 years. Also, some local systems such as altitude, nearness to water bodies, local circulations such as meso-scale circulations of thermal or terrain origin can play some significant role in the spatial distribution of the rainfall variance (Ogallo 1982).

4.3.7 Standardized Precipitation Index (SPI)

In recent years hydro-meteorological disasters such as floods and drought are considered the major sources of losses of unknown percentage of the South Sudanese Gross Domestic Product (GDP) due to lack of documented information concerning the recurrence of these climatic extremes. In this section, Standardized Precipitation Index (SPI) was used to assess the recurrence of drought and floods in south Sudan. Figure 38, shows the SPI for three representative locations namely Malakal, Raja and Juba.

The results indicate that highest number and intensity of drought occurrences was experienced in the period 1980 - 1990 especially 1982 to 1985, while floods occurred in the 1960s. There is an increase in the rate of flood years from 2000s to the recent years over most parts of south Sudan. Standardized Precipitation Index (SPI) in Extreme north of country represented by El renk indicated no extreme drought but a severe drought occurred in 1971 and 1990 and a moderate one occurred in1983, 1984, 1987 and 1998. The recurrence of extreme floods occurred in 1963 and 1998, severe floods occurred in 1992, 2005 and 2007 and moderate floods occurred in 1961,1981,1989,1994, 1997, 1999 and 2006. The recurrence of extreme floods in El renk occurred in 1975, 1999, 2000 and 2007 and 2002 while severe ones occurred in 1996 and 2008 and moderate floods occurred in 1966,1967,1981,1989, 1995. Nine years out of the last 15 years in El renk, observed an increase in number of drought and floods events.

In the Northeast of the country represented by Malakal, extreme drought occurred in 2004 while severe drought occurred in 1965, 1969 and 2002 and a moderate one in 1977,1980,1982,1985, and 2005. The recurrence of extreme floods occurred in 1975, 1999, 2000 and 2007 and 2002 while severe cases occurred in 1996 and 2008 with moderate floods occurring in 1966,1967,1981,1989, and 1995. Nine years out of the last 15 years in Malakal, observed increases in the number of drought and flood events. Northwest of the country represented by Raja, had extreme drought in 1966 and 1969, severe one in 1987 and 1995 and moderate drought occurred in 1980 and 1983. The recurrence of extreme floods occurred in 1963, severe floods occurred in 1965, 1976 and 1997 and moderate floods occurred in 1961, 1968,1978,1996,2007 and 2013. Over raja, the 1960s had recurrences of drought and flood events. Central parts of the country represented by Wau, witnesses extreme drought in 2009 and 2010, severe drought in 1971, 1990,19994,2000 and 2011, and moderate drought in 1972, 1981, 1983 and 1986. The recurrence of floods was extreme in 1966 and 2013, severe in 1962, 1964 and 1997, and moderate in 1963, 1969, 1987, 1995, 2001 and 2006. Over Wau, the 1960s and 2000s had recurrence of drought and flood events.SPI analysis for southern parts represented by Juba, had extreme drought in 2004, severe drought occurred in 1965, 1969 and 2002 and moderate drought in 1977,1980,1982,1985, 2005. The recurrences of floods were extreme in 1962, 1967, 1988 and 1999, severe in 2002 and 2011 and moderate in 1996 and 2003. Nine out of the last 15 years in Malakal, observed an increase in the number of drought and flood events.

Extra-ordinary extreme rainfall (droughts and floods) have negative influences on socio-economic sectors, especially activities depended on rainfall. Therefore, adaptation measures such as improving crop varieties, water harvesting and conservation, will enhance resilience and reduce the risk of these extremes to agricultural related activities. However, the effect of these extremes in terms of losses in life, economy or GDP remains unknown due to lack of assessments and documented information resulting from long civil strife in South Sudan.

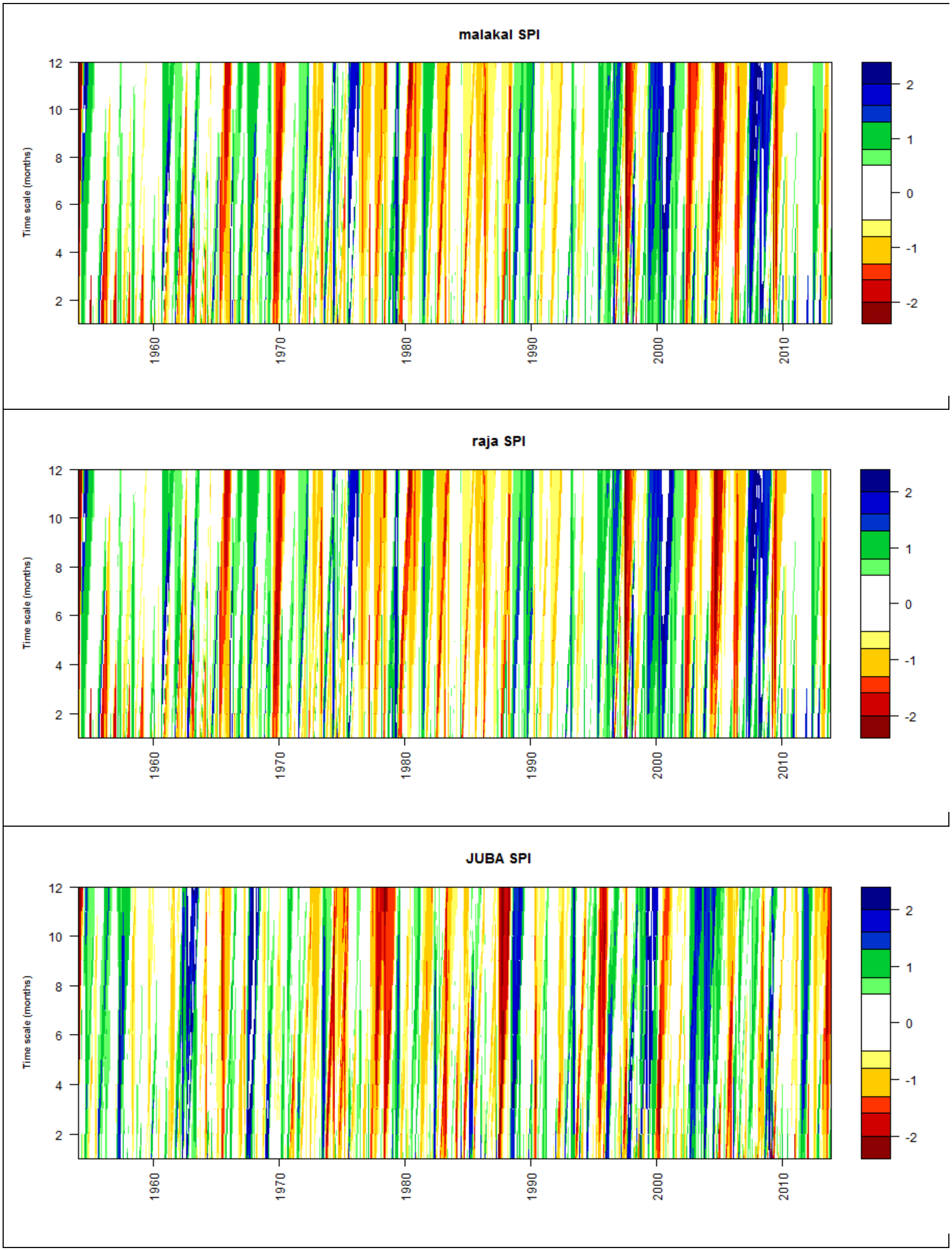


Figure 38: Standardized Precipitation Index (SPI) over south Sudan.

4.4 Analysis of teleconnection between rainfall and Indian Ocean dipole and ENSO events

This section presents the teleconnection between rainfall and Indian Ocean dipole (IOD) and El Niño Southern Oscillation (ENSO) indices. The results from teleconection between seasonal rainfall and IOD are presented first followed by the ENSO indices.

4.4.1 Linkages between the Indian Ocean Dipole and South Sudan Seasonal Rainfall Anomalies

This sub-section presents the teleconnection between rainfall anomalies and Indian Ocean dipole (IOD). The analysis based on three main rainy seasons (MAM, JJA and SON) and spatial rainfall anomalies patterns associated with DMI analogues for five locations considered in study.

4.4.1.1 Temporal patterns of SST anomalies over the Indian Ocean associated with IOD Phases

Figure 39 shows the inter-annual variability of the Dipole Mode Indices (DMI) during the initial phases of (MAM), JJA and peak phase (SON) seasons.

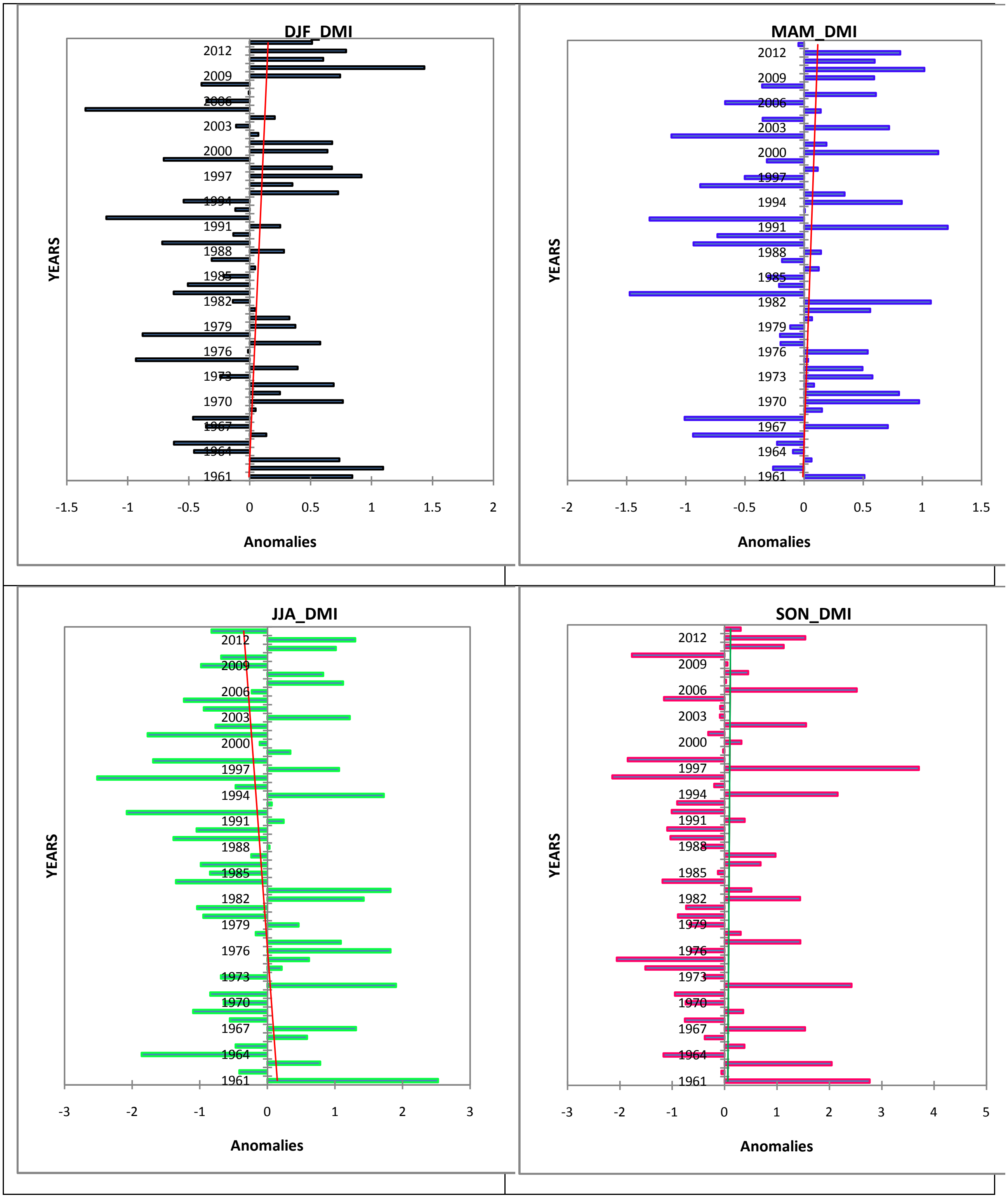


Figure 39: Interannual variability of the Dipole Mode Indices.

It is clear that there are recurrences of the years with positive and negative phases of the IOD events. The strength of DMI varies from year to year, season to season, and event to event. Dipole Mode Indices increase from DJF, MAM, JJA and peak in SON. In addition, Results shows that positive and negative dipole initiated clearly during MAM, and continued during JJA with a peak in SON season. For Sea surface temperature (SSTs) anomalies during September to November (SON), there are 15 positive IOD events (defined as years during which the DMI exceeds 0.5 standardized values) and 19 negative IOD events (defined as years during which the DMI exceeds -0.5 standardized values) occurred within the period 1961-2013.

The very strong positive phase of the dipole events (defined as years during which the DMI exceeds 2.0 standardized values) i.e. 1961, 1972 and 1997 and very strong negative IOD events (defined as years during which the DMI exceeds -2.0 standardized values) i.e. 1975, and 1996. It is very important to note that all strong positive IOD that occurred coincided with El Niño, while all strong negative IOD occurred coincided with La Niña. These results confirmed the work done by (Meyers *et al., 2007*) which found that positive (negative) IOD events often, but not always, coincided with El Niño (La Niña), and that a significant number of IOD events occur during neutral ENSO years. The Correlation analysis and rainfall patterns associated with these strong positive and negative IOD phases are discussed in the next subsections. There is increasing trends of DMI during DJF, MAM and decreasing in JJA and seem to be constant during SON season.

4.4.1.2 Correlation analysis between IOD and South Sudan seasonal rainfall anomalies

Figure 40 presents results obtained from Correlations between IOD and MAM, JJA and SON seasonal rainfall at Lag **0** and Lag **1** season. The results indicate most of locations at zero and one Lag season registered insignificat correlations at 0.05 level of significance except Raja and Juba at lag **1** and lag **0** for MAM and SON seasons, which registered positive significant correlation in respectively. Also negative significant correlation observed in Malakal and Wau stations at lag **1** during MAM and JJA seasons respectively. The spatial patterns of correlation confirmed the existence of weak association between Indian Ocean SST and rainfall anomalies over South Sudan. This means that extreme rainfall can occur either in absence or presence of strong positive or negative IOD events.

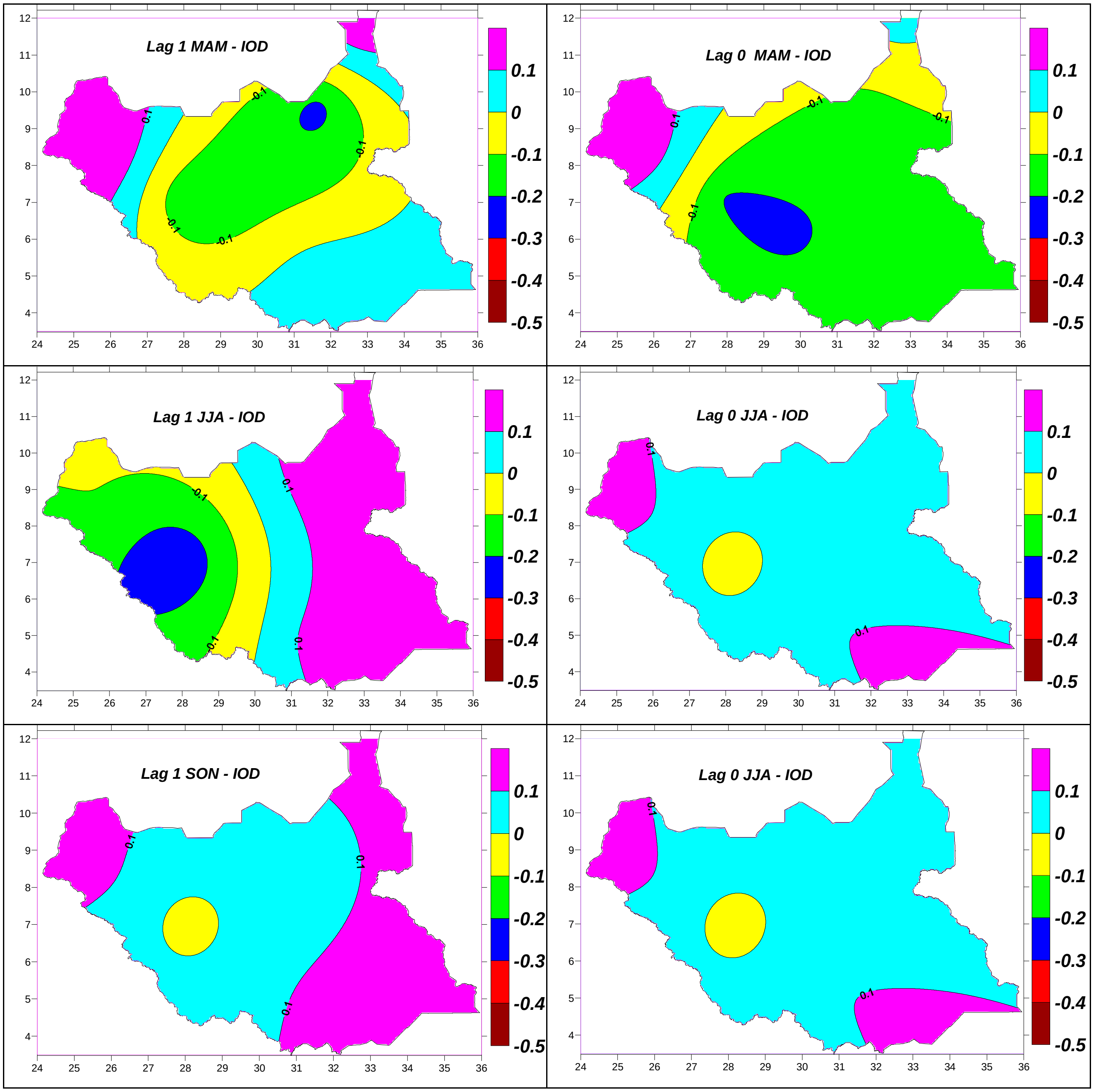


Figure 40: Correlations pattern between IOD and seasonal rainfall over South Sudan.

4.4.1.3 Rainfall anomaly patterns associated with Indian Ocean dipole (IOD) analogues events

In this subsection, the space and time characteristics and composite analysis of rainfall anomalies during the various IOD phases are presented. Figures 41 illustrate the inter-annual variability of DMI with observed seasonal rainfall anomalies for three locations namely Malakal, Wau and Juba during MAM, JJA and SON seasons. Results revealed a clear and strong signal that dry and wet conditions are recurrent during strong positive or negative IOD phases. What was observed for all seasons (MAM, JJA and SON) seasons is that, some of the driest years that occurred coincided with some of the strong positive dipole and some of the wettest years that happened coincided with some strong negative dipole phases and Vice versa.

During peak the of IOD in September to November (SON) season, most of the extreme dry (drought) or wet (flood) cases do not coincide with some of the strong IOD events either positive or negative. There is a number of strong positive IOD cases that occurred and coincided with normal to above normal rainfall, for instance 1961 and 1997, while below normal rainfall that occurred in 1972 and 1994 coincided with strong positive dipole). In addition, evidence observed from results showed that there is a number of extra-ordinary flooding that occurred and coincided with negative IOD (1964), while Extra-ordinary drought occurred and coincided with strong negative IOD (1984). In another wards, the recurrences of wet and dry conditions in the country during positive or negative phases differ from region to region, event to event, and year to year. Therefore, some parts of the country received below normal rainfall (dry) in the same time others received above normal rainfall (wet) during strong positive or negative IOD events.

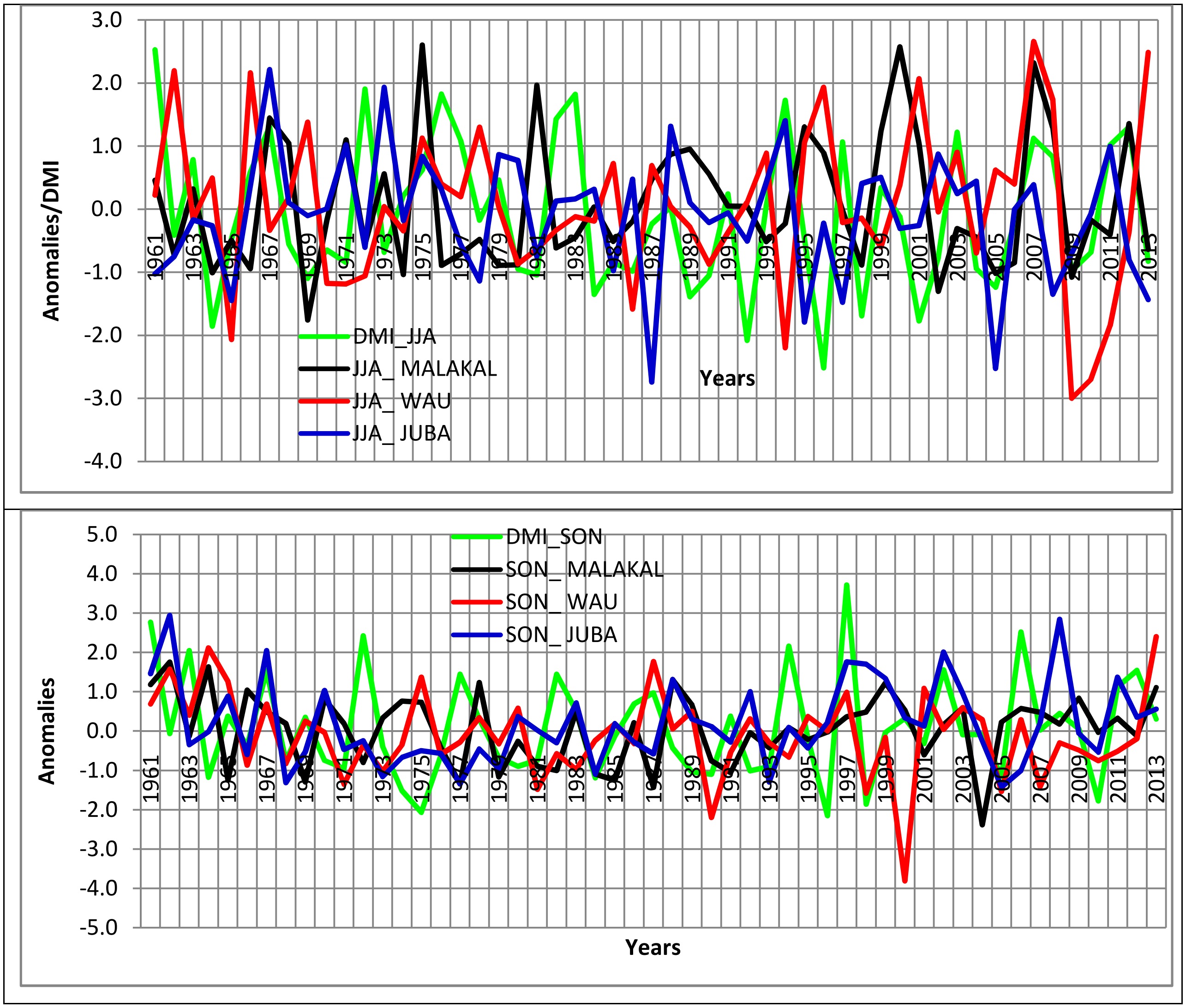


Figure 41: Interannual variability of DMI with seasonal rainfall anomalies over selected stations.

Figures 42 shows composites of the spatial rainfall anomaly indices associated with the IOD analogues during MAM, JJA and OND rainfall seasons. The years 1961, 1963, 1972, 1994, and 1997, 2002, 2006, 2011 and 2012 were used to develop composites for positive, while the years 1960, 1975, 1992 and 1996, 2005 and 2010 were composited for negative IOD phases used for analogue studies. The composite analysis was included in the study in order to further study patterns of associations between South Sudan seasonal rainfall anomalies and the IOD events. The results showed the probability of occurrence of extra-ordinary rainfall conditions to too low. Most of location observed normal rainfall during positives and negative IOD events. This not means the recurrences of extra-ordinary rainfall (drought and floods) during positive or negative are rarely to happen coincide with some IOD years.

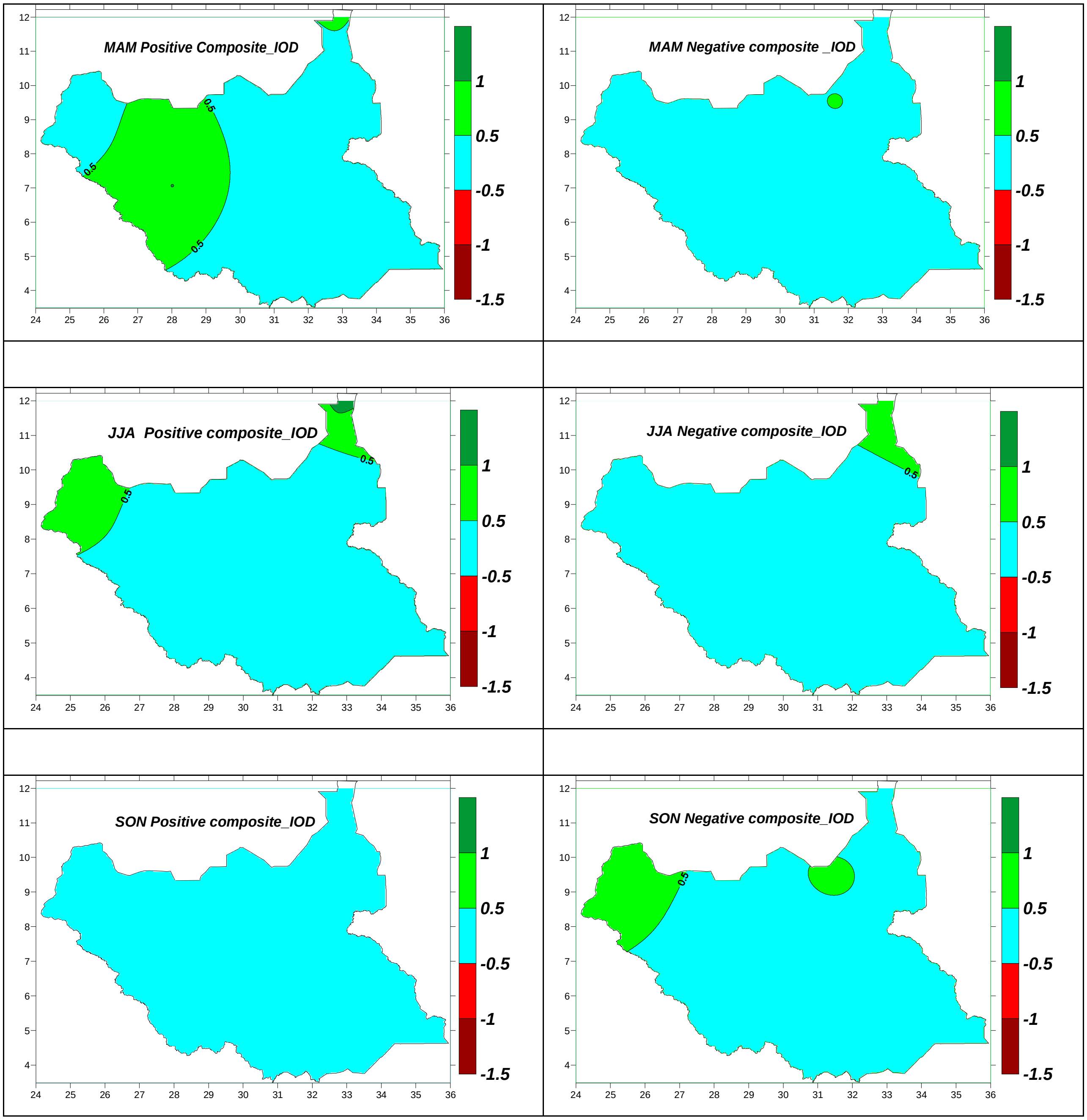


Figure 42: Composite of seasonal rainfall anomalies associated with the phases of the Indian Ocean dipole: left panel during positive phase (b) right panel during negative.

Normality of rainfall during IOD composited years may explain and conform the evidence of weak teleconnection of South Sudan rainfall to different phases of IOD either positive or negative phase. Also results showed the performance of rainfall during positive and negative phases of IOD are not showing association of above normal or below normal rainfall with positive or negative IOD. The normal differ from region to region, event to event, and year to year. Therefore, most parts of the country received normal rainfall during positive or negative IOD events**.** These results may suggest large variability of rainfall during positive and negative IOD phases explaining the weak linkages between the Indian Ocean Dipole and South Sudan Seasonal rainfall anomalies.

4.4.2 Linkages between the El Niño Southern Oscillation and South Sudan Seasonal Rainfall Anomalies

This subsection examined the teleconnections between South Sudan seasonal rainfall and El Niño Southern Oscillation (ENSO).

4.4.2.1 Temporal patterns of SST anomalies over Equatorial Pacific Ocean associated with ENSO phases

Examining the Temporal patterns of SSTs anomalies over the Niño 3.4 region play a key role in investigating the recurrence of Weak, moderate and strong ENSO events and the linkage between them and the observed rainfall anomalies over South Sudan. Figure 43 presents the inter-annual variability of sea-surface temperature anomalies over Niño3.4 region during the MAM, JJA and SON seasons.

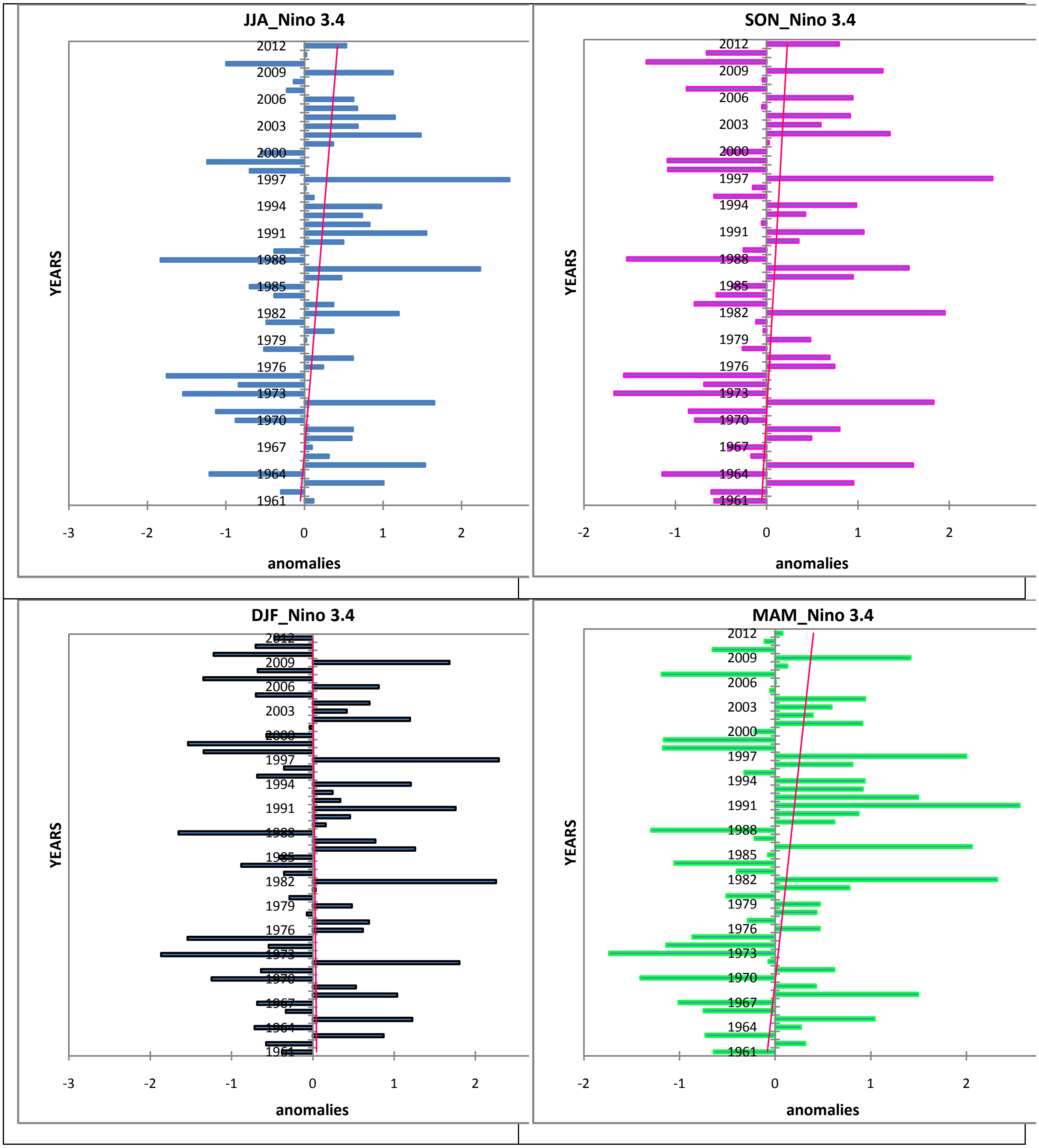


Figure 43: Interannual variability of sea-surface temperature anomalies over Niño3.4 region.

It is clear from the figures that there are recurrences of the years with warm and cold ENSO phases. These warm and cold ENSO events are classified into weak, moderate and strong El Niño and La Niña. Weak El Niño and La Niña events are defined as years, during which the sea-surface anomaly range between positive/negative 0.5- 0.75 standardized values. Moderate El

Niño and La Niña events are defined as years during which the sea-surface anomaly range between positive/negative 0.75- 1.0 standardized values.

Strong El Niño and La Niño events are defined as years during which the sea-surface anomaly exceeds positive/negative 1.0 standardized values. SSTs indices during September to November (SON) season for the period 1961-2013 shows that there is 20 warm ENSO (El Niño) and 18 cold ENSO (La Niña) events. Warm ENSO (El Niño) consisted of ten(10) strong El Niño events (1997,1982,1972,1965,1987,2002,2009,1991, 1994 and 1963) and five(5) moderate El Niño events (1986,2006, 2004, 1969 and 2012) and five(5) Weak El Niño events(1976,1977,2003,1968 and 1979). Cold ENSO (La Niña) comprised seven(7) strong La Niña events (1973,1975,1988,20101964,1999 and 1998), four(4) moderate La Niña events (1970,1983,1971 and 2007) , seven(7) weak La Niña events (2000, 1984,1961,1995, 1962 , 2011 and1974). The trend in SSTs over Niño 3.4 showing increasing in trends during MAM,JJA and SON while DJF season trend seem to be constant during SON season.

4.4.2.2 Correlation Analysis between ENSO Indices and South Sudan Rainfall

This subsection presents results obtained from correlation analysis between seasonal rainfall anomalies (MAM, JJA and SON) and the various Niño indices at **zero** Lag season (right pannel) and **one** Lag season(left pannel).

Figure 44 presents results obtained from correlation analysis between March to May (MAM) seasonal rainfall anomalies and various Niño indices (Niño 1+2, Niño 3, Niño 3.4 and Niño 4) at zero Lag season (right panel) and one Lag season (left panel) over South Sudan. The results indicate that most locations in South Sudan observed positive and negative insignificant correlations between MAM seasonal rainfall and all Niño indices(Niño1+2, Niño 3, Niño3.4 and Niño 4**)** especially the western and southwestern parts of country**.** The values of correlation coefficient (r) for all stations considered in the study do not exceed 0.3, which show weak linkage between rainfall anomalies and ENSO events.

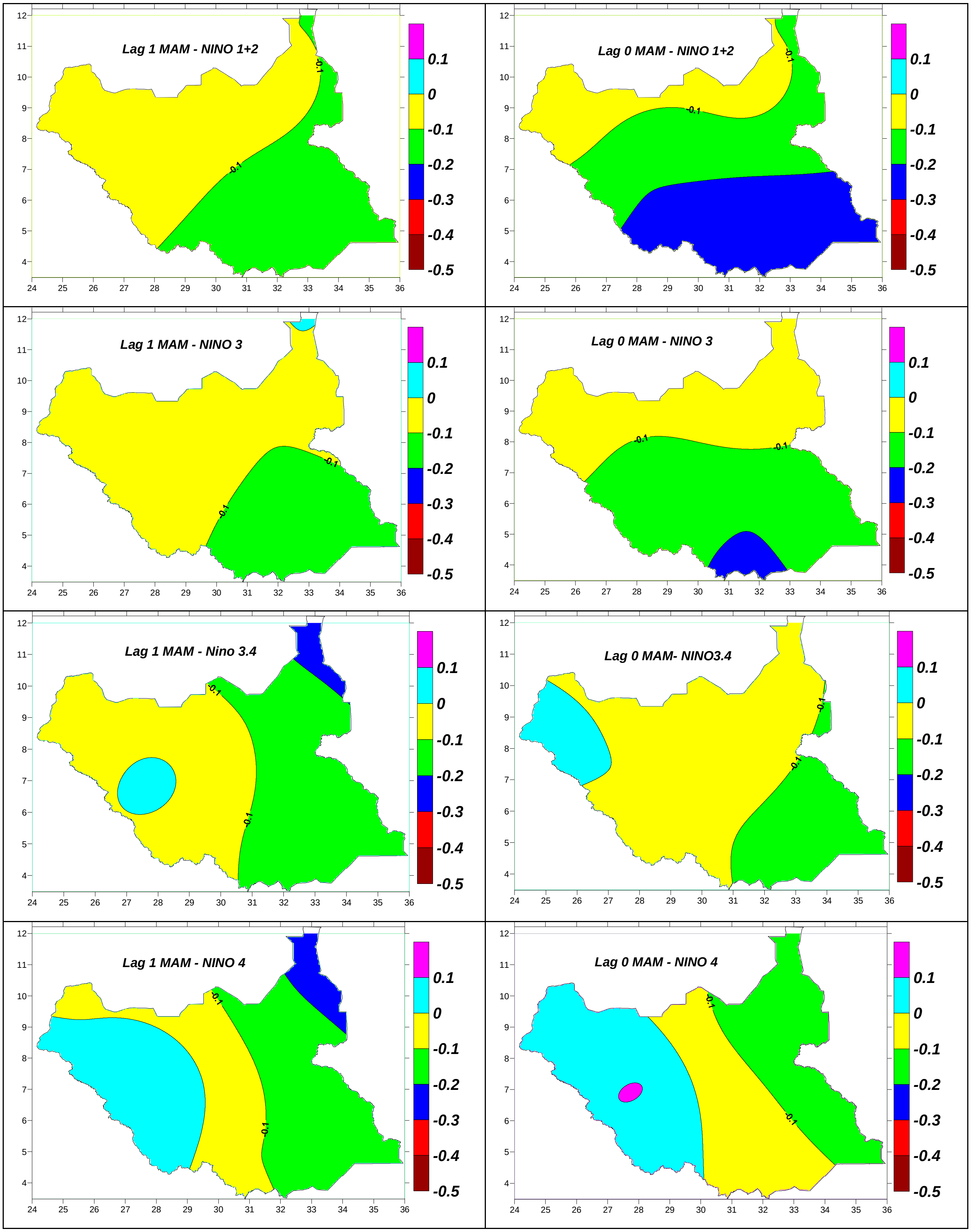


Figure 44: Correlations between ENSO indices and March to May rainfall over South Sudan

Figure 45 presents the results obtained from correlation analysis between June to Augast (JJA) seasonal rainfall anomalies and various Niño indices (Niño 1+2, Niño 3, Niño 3.4 and Niño 4) at Lag 0 and Lag 1 season. The results show enhanced correlation between rainfall and various Niño indices compared to March to May (MAM) season. High negative significant correlations were observed in the Southern and southeastern parts of the country for Niño 3 at Lag 0 and Niño 3.4 at Lag 1 season. Northeastern parts of country represented by Malakal station had good negative significant correlation compared to other parts of the country all the different Niño regions, while western parts observed insignificant correlation. The enhanced negative significant correlation in Malakal station explains the inverse relationship between ENSO and rainfall anomalies.

The strength of correlation coefficient decreasing from east to west of country, hence Wau and Raja stations registered insignificant correlation during all seasons (MAM, JJA and SON).The results agree qualitatively with previous study by Zaroug *et al*. 2014, who suggested enhanced correlation between the SSTs anomalies in the Niño 3.4 region during 3-month periods from January–February–March (JFM) to October–November–December (OND) seasons and the ensemble average rainfall anomalies over the upper Nile River catchment (Ethiopian highlands) during JJAS.

Figure 46 presents results obtained from correlation analysis between September to November (SON) seasonal rainfall and various four Niño regions (Niño 1+2, Niño 3, Niño 3.4 and Niño 4) at Lag 0 and Lag 1 season over South Sudan. The results showed enhanced negative correlation between rainfall and all the four Niño regions (Niño 1+2, Niño 3, Niño 3.4 and Niño 4) at Lag 0 and Lag 1 season compared to MAM and JJA seasons especially in northeastern parts represented by Malakal station that registered the highest negative significant correlation coefficients compared to the other study locations.

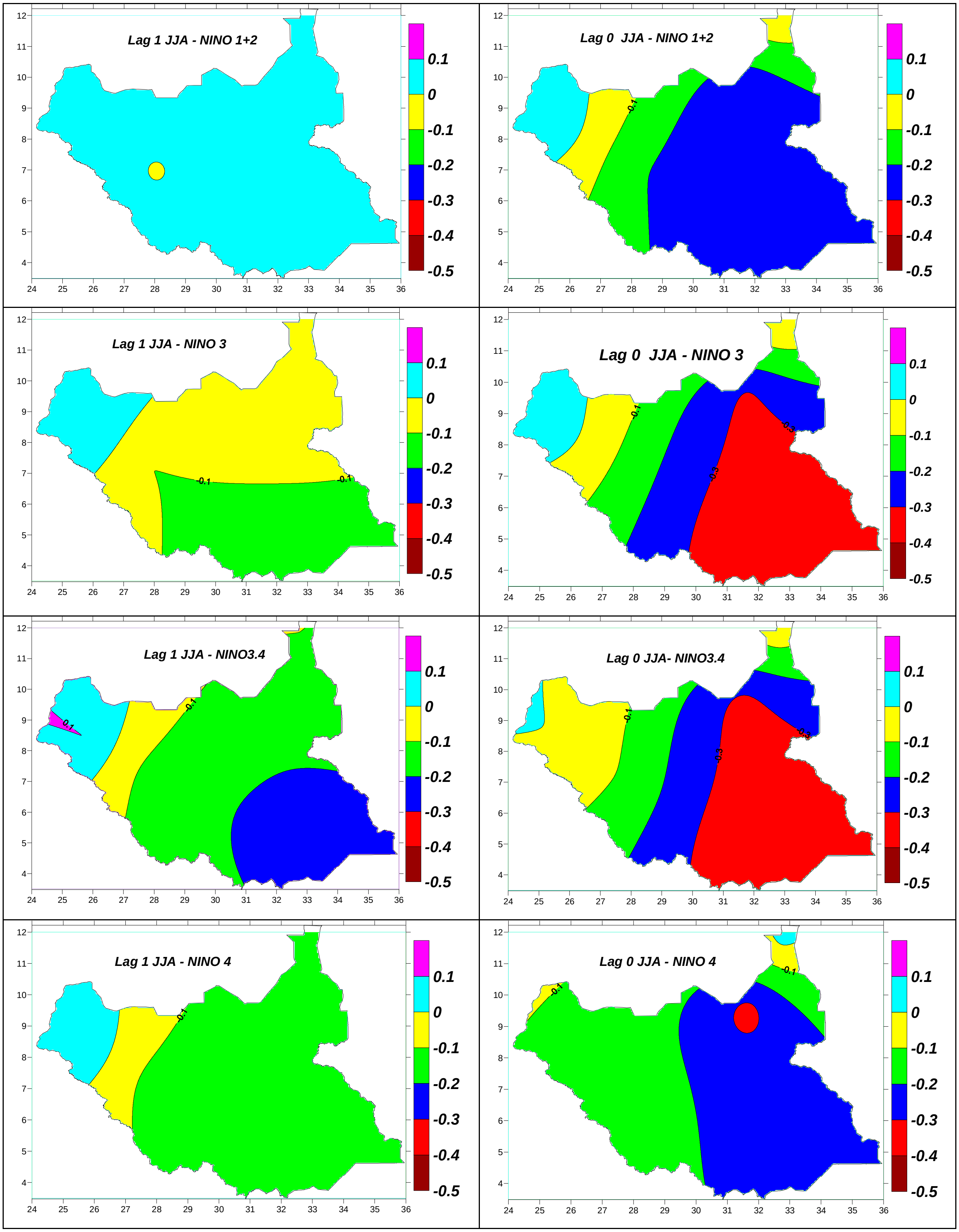


Figure 45: Correlations between ENSO indices and June to Augast rainfall over South Sudan

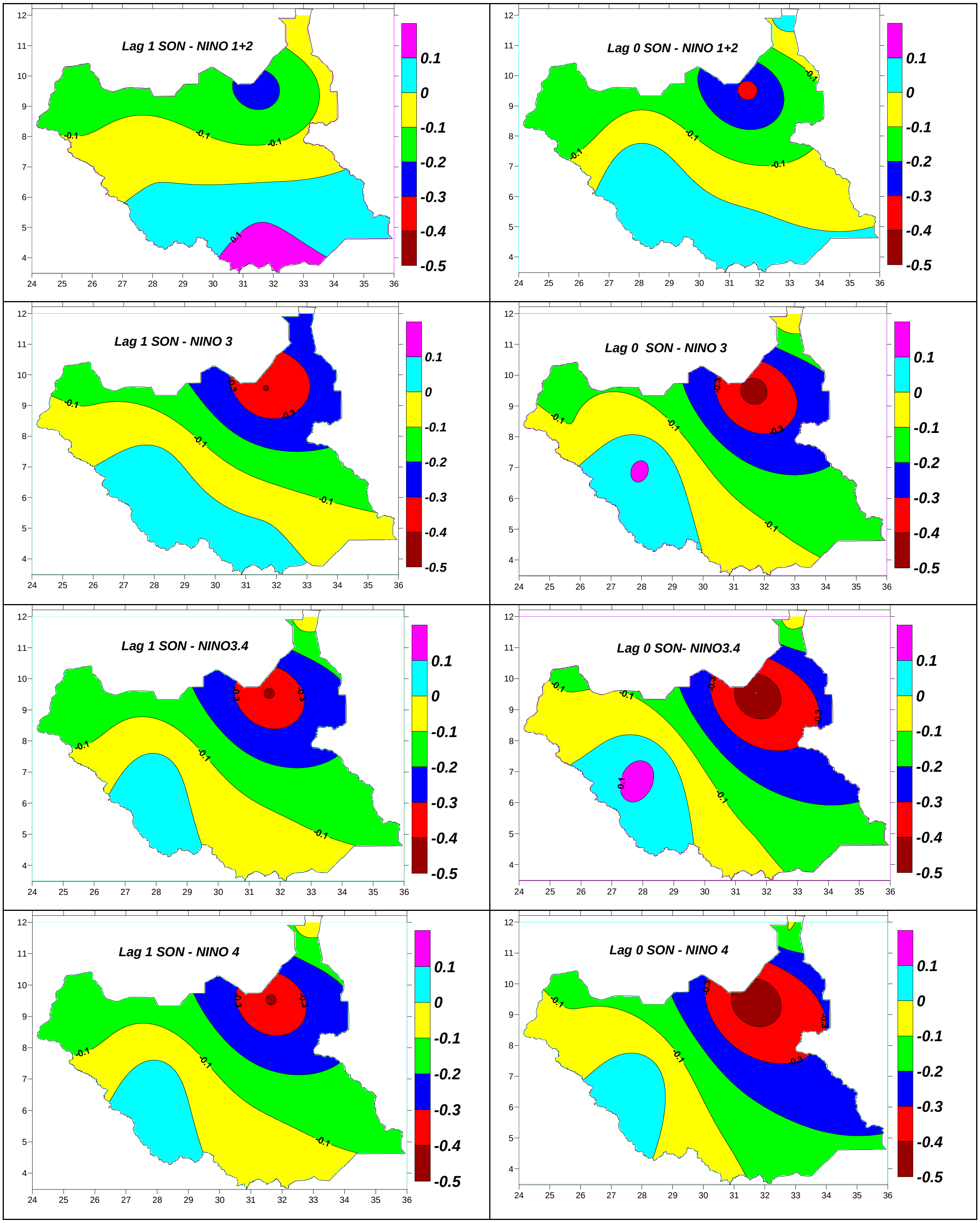


Figure 46: Correlations between ENSO indices and September to November rainfall over South Sudan.

For all seasons (MAM, JJA and SON), the correlations coefficient (r) did not exceed ±0.5 implying that the relationship between observed rainfall over South Sudan and all four Niño regions (Niño 1+2, Niño 3, Niño 3.4 and Niño 4) are not too strong. The correlations coefficient (r) between seasonal rainfall and different Niño indices obtained explained in clear manner, the weak effect or contributions of circulations and systems occurring in equatorial pacific and Indian oceans compared to circulations and systems occurs at Atlantic and Congo moist air mass appearing have strong teleconnection with rainfall in South Sudan. Therefore, all humid and semi humid areas in southwestern and southern parts registered weak correlation compared with the northeastern parts.

4.4.2.3 Rainfall Anomaly Patterns Associated with ENSO Analogues Events

The evaluation of rainfall anomalies over South Sudan during ENSO years is very important for risk assessment and damage associated with climate extremes. This helps in anticipating the type of risk associated with ENSO as part of early warning processes. The analysis is based on evaluation of rainfall performance corresponding to the timing of the ENSO and composite analysis of rainfall anomalies patterns corresponding to weak moderate and strong El Niño and La Niño events, to define areas characterized with wet and dry conditions during these episodes.

Figure 47 illustrate the inter-annual variability of Niño 3.4 indices with seasonal rainfall anomalies for three locations namely Malakal, Wau and Juba during MAM, JJA and SON seasons. The results shows the strong evidences that dry, wet and normal conditions are recurrent in all parts of South Sudan during weak, moderate and strong ENSO (El Niño and La Niña) events. Also results shows that some of the driest and wettest years over South Sudan coincide with weak, moderate and strong ENSO events.

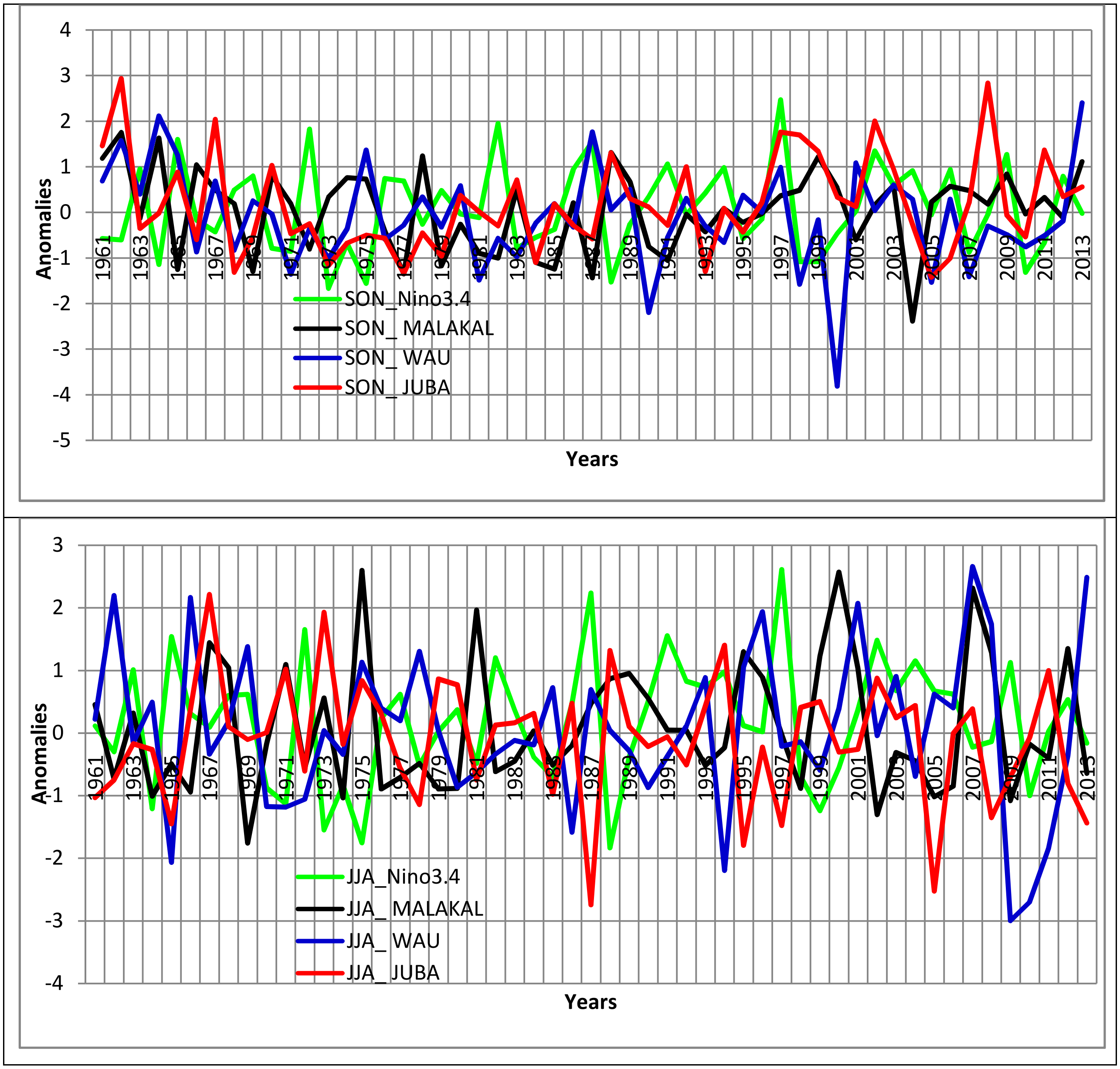


Figure 47: *Interannual variability of Niño 3.4 with seasonal rainfall anomalies over selected stations*

The recurrence of wet and dry conditions in the country during ENSO an event vary from location to location, season to season and doesn't depend on strength of ENSO event. Another important observation from the tables maps are most of driest conditions coincides with El Niño and some wettest condition coincides with la Niña and some occur in ENSO neutral phase. For example, the 1997/1998, 1982/1983 and 1991/1992 considered strongest El-Niño events, the 1997/1998 accompanied by rains above normal in most location while 1982/1983 and 1991/1992 El-Niño was accompanied by below normal in most locations in South Sudan. The 1973/1974, 1974/1975, 1988/1989 and 1999/2000 considered strongest El-Niño events accompanied by rains above normal in most location of South Sudan. This result agrees with previous study done by Osman and Shamseldin (2002), which suggested that driest years were associated with warm ENSO and Indian Ocean SST conditions in the tropical Indian Ocean.

There is also weak evidence on the linkage of recurrence of extreme drought and flooding events over South Sudan with ENSO events because the values of seasonal rainfall anomalies don’t exceed ± 1 for all location except SON season in Malakal during Strong La Niña years. Results also revealed that during ENSO episodes, some parts of country received normal to above normal rainfall, while other parts received normal to below normal rainfall. Most of the dry (drought) or wet (flood) cases do not coincide with some of the strong ENSO events, either El Niño or La Niña. There are a number of extreme wet and dry conditions that occurred in absence of El Niño and La Niña episode, and some of extreme wet and dry conditions occurred in presents of El Niño and La Niña episodes.

Composite analysis was included in the study in order to further study patterns of associations between South Sudan seasonal rainfall anomalies and the ENSO phases. Figures 48 shows composites of the spatial rainfall anomaly indices associated with the El Niño analogues during MAM, JJA and OND rainfall seasons. The years (1969-70, 1976-77, 1977-78, 2004-05, 2006-07),(1963-64, 1968-69, 1986-87, 1991-92, 1994-95, 2002-03, 2009-10) and(1965-66, 1972-73, 1987-88, 1982-83, 1997-98)were used to develop composites for weak, moderate and strong El Niño respectively. The results revealed that, the performance of rainfall during ENSO phases not different from what observed during IOD events. Most locations during weak, moderate and strong El Niño and La Niña phases observed normal rainfall. These not mean no extremes drought and floods occurred associated with some years within composited years. The results showed also most of El Niño phases coincided with positive IOD events. The results showed clearly the existence of weak teleconnection between the El Niño events and above or below normal rainfall (drought and floods) over South Sudan.

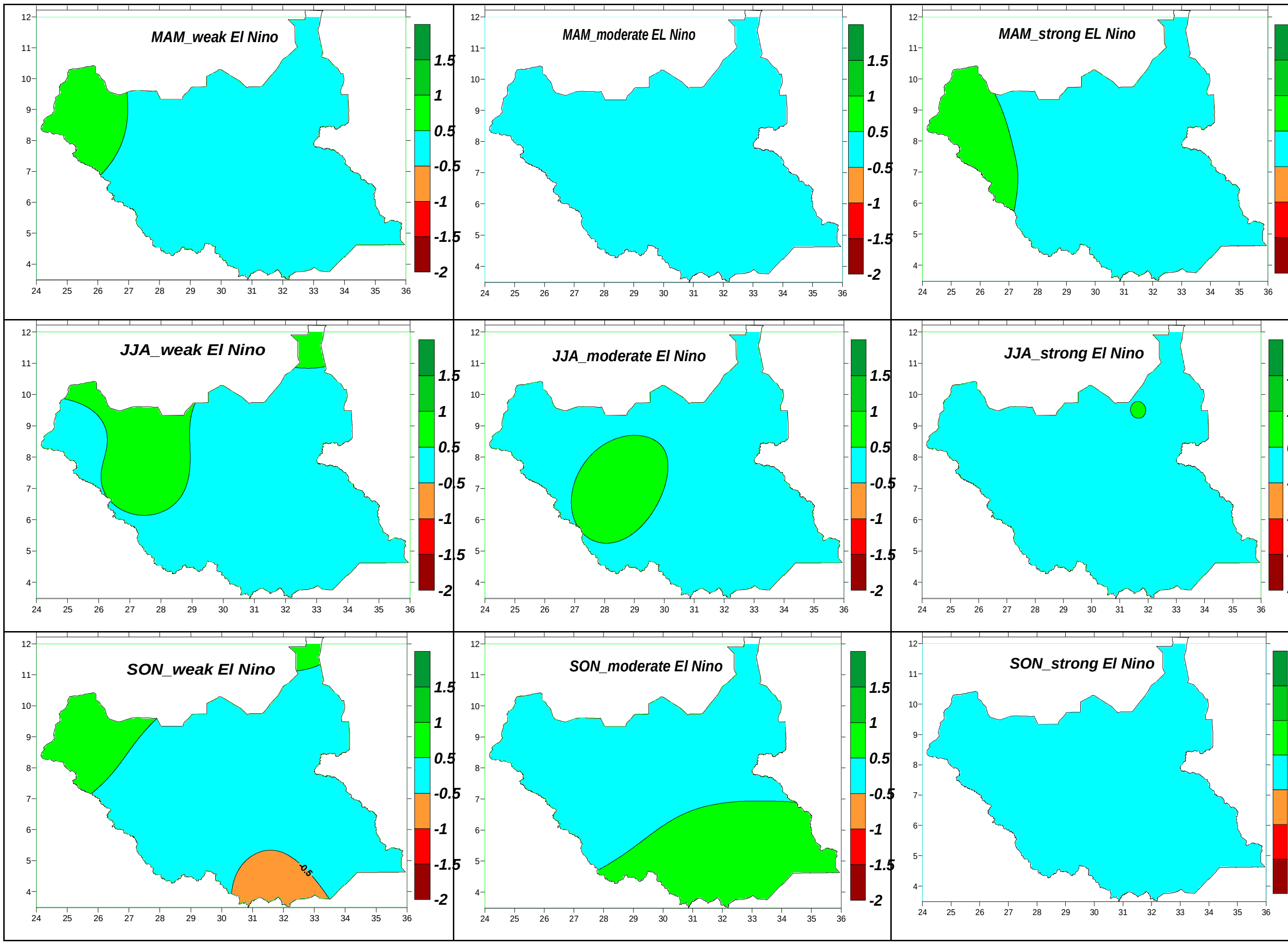


Figure 48: Composite of seasonal rainfall anomalies associated with the phases of the ENSO: left panel during weak, moderate and strong El Niño phases.

Figures 49 shows composites of the spatial rainfall anomaly indices associated with the La Niño analogues during MAM, JJA and OND rainfall seasons. The years (1964-65, 1971-72, 1974-75, 1983-84, 1984-85, 1995-96, 2000-01, 2005-06, 2008-09,2011-12),(1970-71, 1998-99 2007-08) and (1973-74, 1975-76, 1988-89, 1999-00, 2010-11) were composited for weak, moderate and strong La Niña phases respectively used for analogue studies. The results revealed that, the performance of rainfall during ENSO phases not different from what observed during IOD events. Most location during weak, moderate and strong La Niña phases observed normal rainfall. These also not mean no extremes drought and floods occurred associated with some years within composited years. The results showed also most of La Niña phases coincided with positive IOD events and La Niña phases coincided with negative IOD events. The results showed clearly the existence of weak teleconnection between the La Niña events and above or below normal rainfall (drought and floods).

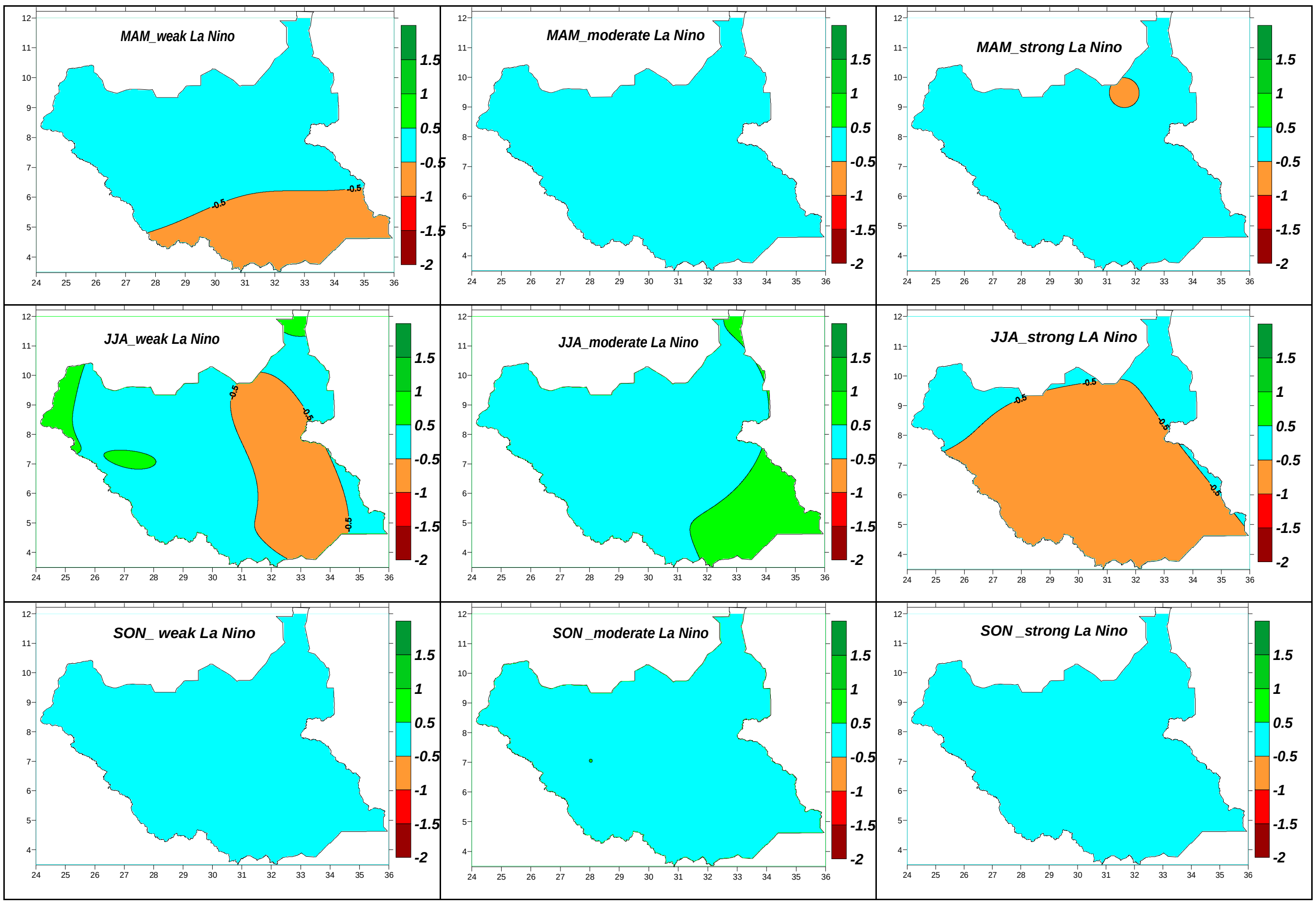


Figure 49: Composite of seasonal rainfall anomalies associated with the phases of the ENSO: left panel during weak, moderate and strong El Niño phases.

These results did not concur with what was concluded by most of studies carried out by scientists from East Africa, which found co-occurence of extra- ordinary extreme rainfall (floods and drought) in East Africa and ENSO (Ropelewski and Halpert, 1987; Janowiak, 1988; Ogallo, 1988, among others). Generally the El Niño was accompanied by some enhanced rainfall performance compared to La Niña events over South Sudan.

4.4.3 Results from Linear Regression Analysis

This sub-section presents results obtained after regression models were fitted between South Sudan seasonal rainfall anomalies and Indian Ocean dipole (IOD), Niño indices at lag one and zero. It should be noted that due to the low correlations obtained between the variables under correlation in most of the stations considered in the study, the constructed regression models were based only on stations that had the coefficient of determination greater than 10% of variability for Niño indices. For Indian Ocean dipole (IOD) correlations, stations that registered significant correlation only wzere considered in construction of regression models.

4.4.3.1 Lag Regression Models

Correlation coefficient between seasonal rainfall anomalies (MAM, JJA and SON) and IOD were weak, therefore the coefficient of determination(R Square) not exceeding 10 percent of variability for all stations considered in study. Raja station during March to May (MAM) season and Wau station during June to August (JJA) season at one Lag season registered significant correlation coefficient at confidence interval of 0.05, hence adopted for linear regression model.

Figure 50 illustrates the models constructed between seasonal rainfall and IOD at one Lag season. The results indicated the regression models constructed were far from being optimal and model not able to capture some peaks observed in the observed rainfall anomalies.

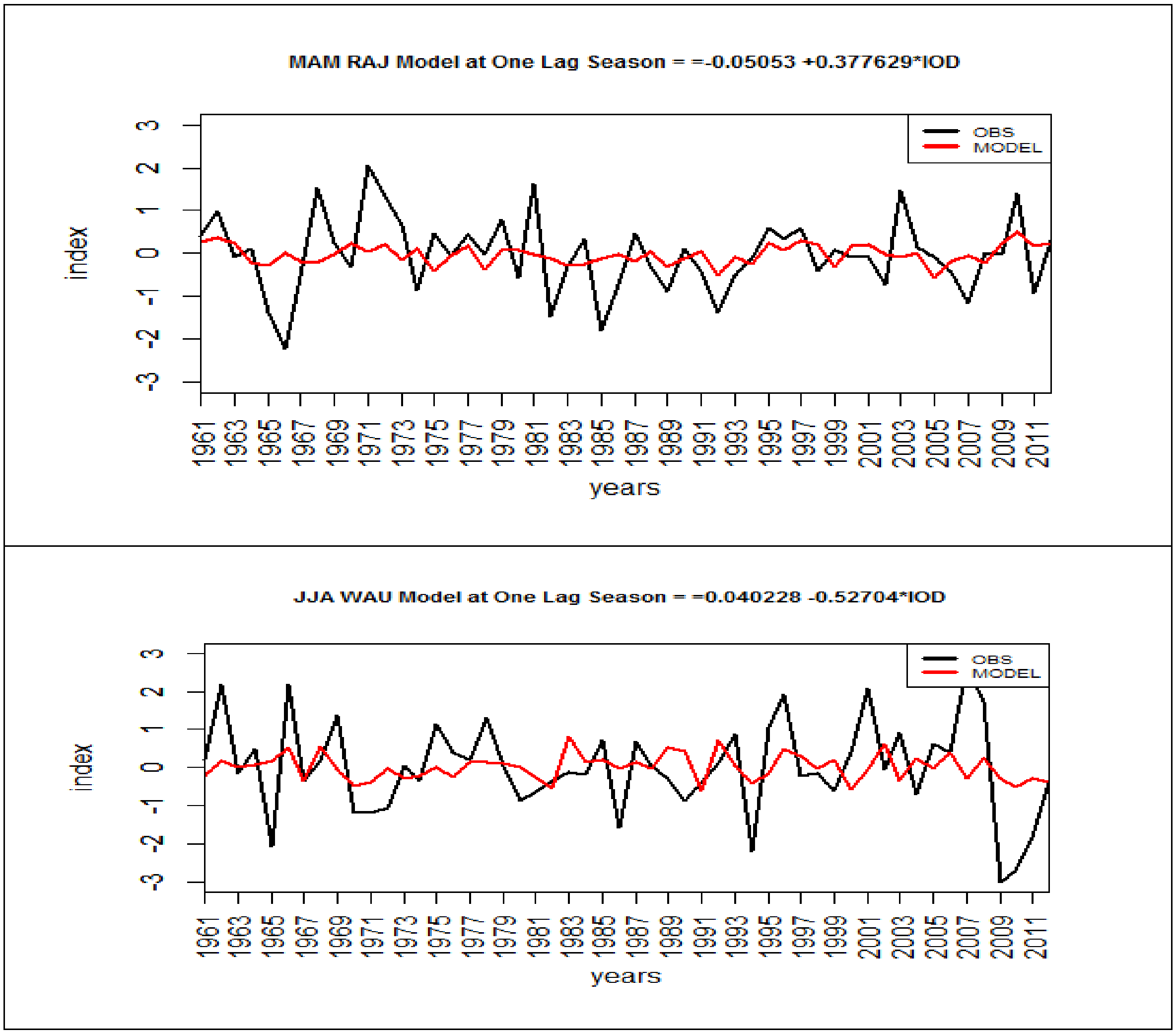


Figure 50: IOD Regression Model at One Lag Season for MAM and JJA

A part from construction of regression model for seasonal rainfall and IOD, the regression model for Niño indices at one and zero Lag season were also constructed in Figure 51. The results showed coefficient of determination performed much better than IOD especially over Malakal for several Niño indices (Niño 3, Niño 3.4 and Niño 4) during September to November (SON) season, which indicated a contribution greater than 20% of rainfall variability. Most of the regression models constructed were not far from optimal since the model was able to capture some peaks of the observed rainfall anomalies.

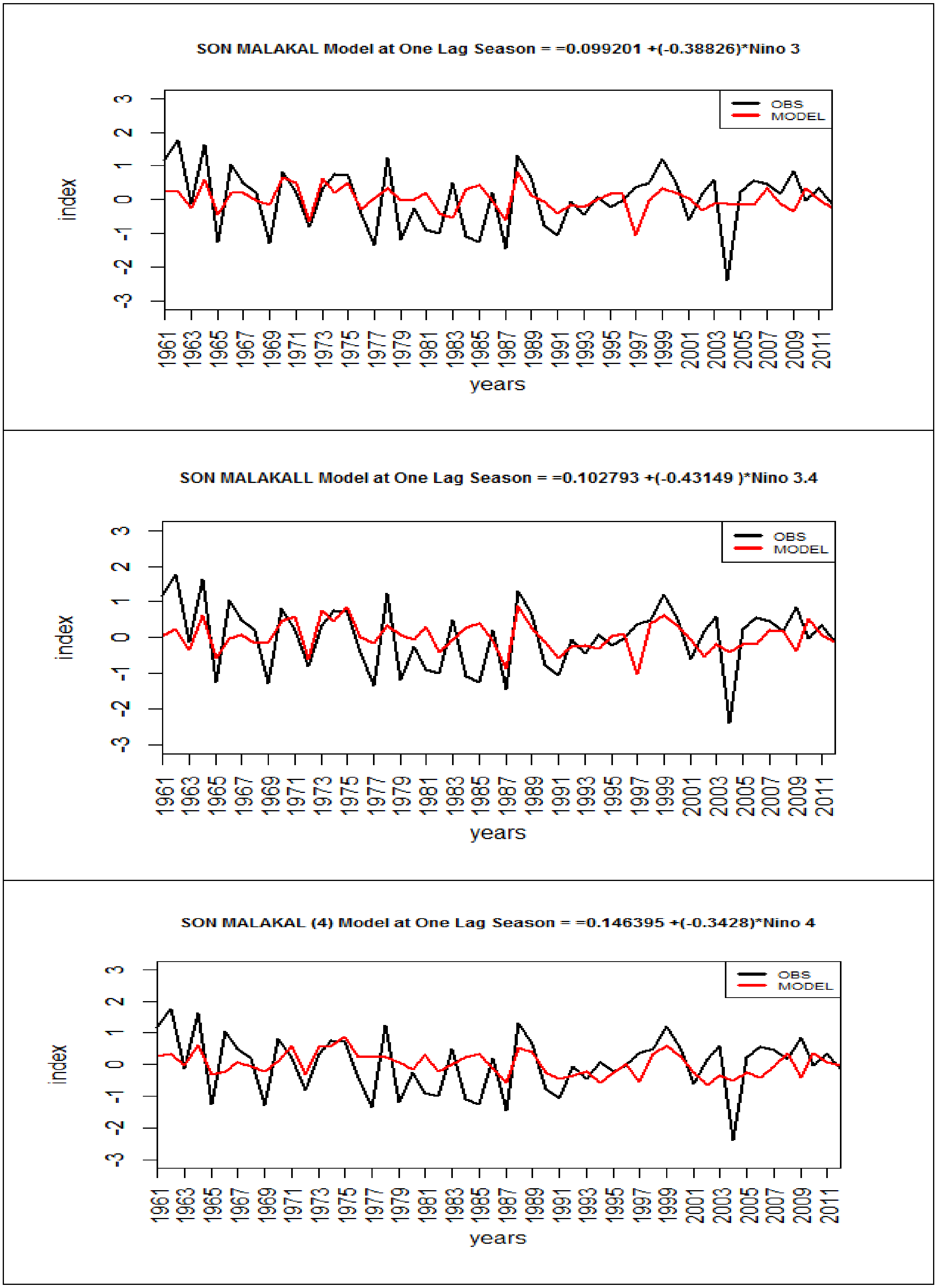


Figure 51: Niño indices Regression Model at one Lag Season for SON

Similar results for regression model for Niño indices at zero Lag season is presented in Figure 52.the results of Most of the regression models constructed at zero Lag season were not far from optimal since the model was able to capture some peaks of the observed rainfall anomalies.

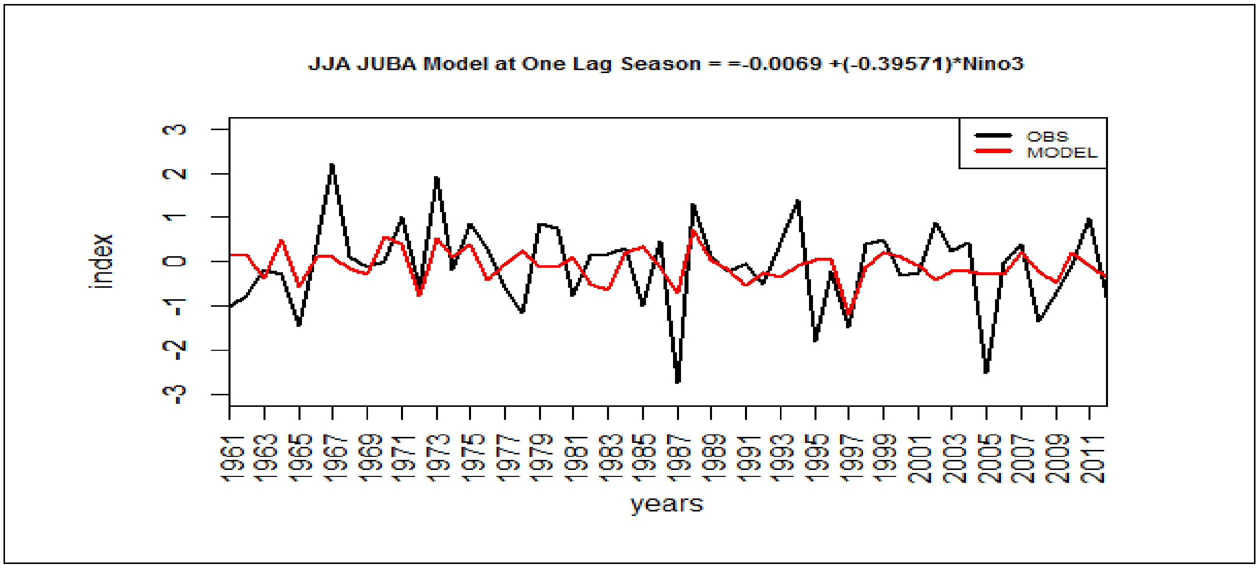


Figure 52*: Niño indices Regression Model at Zero Lag Season for SON*

CHAPTER FIVE

5.0 Summary, Conclusions and Recommendation

This chapter presents summary and conclusions drawn from the study and recommendations for further research and applications.

5.1 Summary and Conclusions

This study sought to assess the spatial and temporal characteristics of rainfall and temperature over South Sudan with a new better understanding of some mechanisms and physical processes responsible for the observed variability in the climate over South Sudan especially the teleconnections between Indian ocean dipole (IOD) , El Niño / Southern Oscillation (ENSO) and seasonal rainfall anomalies over the country.

Several statistical methods were employed in this study. These methods included data homogeneity test, Standard deviation, linear regression analysis, Mann Kendall Trend Test, Standardized Precipitation Index (SPI) and Spectral analysis, Probability of occurrence of extremes and Correlation Analysis among others.

Results from data homogeneity test and quality control for both rainfall and temperature (maximum and minimum) exhibited homogeneity and hence were suitable for use to assess the temporal and spatial characteristics of rainfall and temperature. Skewness and Kurtosis showed asymmetric distributions of dataset.

The temporal and spatial characteristics of rainfall and temperature over South Sudan, show that mean monthly rainfall are uni-modal, increase from northeast to southwest, peak in months of July and august. In terms of season, the June to August (JJA) considered as the main rainy season and contributes more than 50 - 60 % of annual rainfall. While maximum and minimum level of maximum and minimum temperatures observed in MAM and DJF season respectively.

The annual seasonal rainfall trend indicated that most locations in South Sudan experiencing insufficient statistical evidence of a significance decreasing trends, while maximum and minimum showed statistical significance evidence of increasing trends at 0.05 level of significant test. The variability and changes in annual and seasonal rainfall and temperature current period 1984-2013 relative to 1954-1983 and 1961-1990 revealed declined in amount of rainfall and increase in maximum and minimum, while variation in temperatures too small compared to rainfall which showed increasing variability in recent years.

Standardized Precipitation Index (SPI) results indicate highest number and intensity of drought occurrences experienced in the period 1980 - 1990 especially 1982 to 1985, while flood occurred in the1960s with an increase in rate from 2000s to the recent years. Also cyclical variations in rainfall and temperature indicated that there is recurrent of spectral peaks in most of the stations considered in study but not exceeding 2 significant peaks for rainfall and tow 3 peaks for temperatures (maximum and minimum) and all spectral peaks occurs between 2 up to 3, 4 to 6 years, which explains effect of Quasi-Biennial Oscillation (QBO), el Niño and la Niño events especially those fluctuation occurs within periodicity of 2 to 3 years. The Probability distribution of long term mean of rainfall and temperature distributions between past (1954-1983) and present (1984-2013), showed shift of the entire distribution toward driest for rainfall and a warmer climate for temperatures (maximum and minimum).

The relationships between seasonal rainfall in South Sudan and IOD events show, weak significant positive correlation in northwest and southern parts at one Lag season in raja during MAM and at zero Lag season during SON season. The Central and northeast observed significant negative correlation at one Lag season during MAM and JJA seasons. The relationships between seasonal rainfall in South Sudan and several Niño indices were also show the insignificant positive and negative correlation in northwest and southwest of country at one and zero lag season for all Niño regions (Niño 1+2, Niño 3, Niño 3.4 and Niño 4).The northeast of country observed significant negative correlation. The spatial rainfall patterns associated with IOD and Niño indices shows that the most of locations during IOD events registered insignificant positive correlation, while most of locations registered insignificant negative correlations during recurrent of ENSO events.

The spatial patterns of observed seasonal rainfall anomalies during strong positive and negative IOD, weak, moderate and strong ENSO (El Niño and La Niña) confirmed the existence of weak teleconnection. Some parts of the country received normal to above normal rainfall (wet), while at the same time others parts received normal to below normal rainfall (dry). Extra-ordinary flooding/drought events that occurred coincided with IOD and El Niño and La Niña, and some did not coincide with any.

The composite analysis was included in the study in order to further study patterns of associations between South Sudan seasonal rainfall anomalies and the positive and negative IOD, weak, moderate and strong El Niño and La Niño phases. The results showed the probability of occurrence of extra-ordinary rainfall conditions to too low, most of locations observed normal rainfall. This not means the recurrences of above/below normal during positive or negative are rarely to happen coincide with some IOD and ENSO phases. Normality of rainfall during IOD and ENSO for composited years may explain and conform the evidence of weak teleconnection of South Sudan rainfall to different phases of IOD either positive or negative phase.

The regression results show the Indian Ocean dipole (IOD) contributing less than 10% of variability in rainfall. The regression models constructed for Raja and Wau stations indicated that the regression models constructed were far from optimal since the model was not able to capture some peaks of the observed rainfall anomalies. While SSTs over Niño regions especially Niño 3, Niño 3.4 and Niño 4 are contributing around 20% of variability in rainfall especially northeast of country representing by Malakal. Also the regression models constructed for Malakal station indicated that most of the regression models constructed were not far from optimal since the model was able to capture some peaks of the observed rainfall anomalies compared to IOD regression models. In general IOD and ENSO contribute less than 20% of variability in rainfall over South Sudan.

5.2 Recommendation and Suggestion for further work

There are many factors contributing and leading to increased gaps and inaccurate climate information in different areas around the globe especially developing countries (Sene and Farquharson, 1998). These factors include lack of high-quality climatic data for spatial and temporal scales, lack of research solicitudes, capacity and political will, as well as political upset. All these factors influence the quality of scientific research and weather prediction. For example the few numbers of meteorological stations and luck of observed data in many states in South Sudan was the main obstacle to the process of extracting results which reflecting the reality of different climatological zones in South Sudan.

To enhancing and strengthen the ability of south Sudanese Scio-economic sectors to cope with climate variability and change stresses such drought and floods and to enhance the quality of scientific research and information for early warning system, The following recommendations and the way forward are made:

- The findings of the study will be useful to disaster risk reduction and climate change adaptation research scientists, weather and climate prediction research scientists, policy makers, National Meteorological and Hydrological Services (NMHS), and other professionals in all Scio-economic sectors that are affected by the climate such as water, agriculture, food security, industry, energy and among others.
- This study concluded that, the climate change and variability including recurrent of extremes rainfall and temperature are real in south Sudan, therefore the famers should switch into growing drought/drought tolerant crop, keeping climate tolerant livestock to minimize crop failure and death of livestock. Also government should develop a policy to conserve forest to reduce the deforestation.
- The findings of this study are based on historical observed rainfall and temperature (maximum and minimum) dataset for only five stations across the country. Some regions are not well represented due to inadequacy of meteorological stations, therefore results cannot be conclusive. There is an urgent need to establish new meteorological station networks in the different states.

- The results of the study were based on observed rainfall and temperature dataset; therefore further work may include satellite dataset to enhance the spatial representativeness of rainfall and temperature over the area of study.
- This Study concentrated on past and present characteristic of rainfall and temperature. Further work should concentrate on the projected future changes based on the global and regional climate model outputs.
- This study examined teleconnection between sea surface temperature (SSTs) over Indian Ocean and equatorial Pacific Ocean. Further research should include others factors affecting rainfall and temperature of South Sudan for instance SSTs in Atlantic Ocean, wind and pressure systems.
- Further research should be undertaken to assess the impacts of changes and variability in rainfall and temperature on socio economic sectors, livelihoods and coping strategies at household level.
- Government should work hardly to enhance the resilience of South Sudanese communities through mainstreaming and incorporate risks associated with climate variability and change into disaster risk management and sectoral development, policies and plans

6.0 REFERENCES

Abaje, I.B., Ishaya, and 3S.U. Usman,(2010): An Analysis of Rainfall Trends in Kafanchan, Kaduna State, Nigeria, Research Journal of Environmental and Earth Sciences **2(2):** 89-96, 2010 ISSN: 2041-0492.

Alexander, M. A., I. Blade, M. Newman, J. R. Lanzante, N. C. Lau, and J. D. Scott, (2002) : The atmospheric bridge: The influence of ENSO teleconnections on air-seainteraction over the global oceans. *Journal of Climate* **15,***2205-2231.*

AMS, (2010): American meteorological society (http://amsglossary.allenpress.com/glossary).

Anyah and F. H. M. Semazzi, (2005): Climate variability over the Greater Horn of Africa based on NCAR AGCM ensemble, Theor. Appl. *Climatol.* **86**, *39–62 (2006).*

Anyamba E. K., (1993): Short term climate variability in East Africa, Proc. *First International Conference of African Meteor. Soc.*, Nairobi, Kenya, 8-12, February *1993, 224-235.*

Anyamba, E. K (1984): On the monthly mean lower tropospheric circulation and anomalous circulation during the 1961/62 floods in east Africa*: MSc. Thesis, Department of Meteorology, University of Nairobi.*

Ariel Dinar, James Benhin, Rashin Hassan, Robert Mendelsohn(2008): Climate Change and Agriculture in Africa: Impact assessment and adaptation strategies.eath scan dunsan house,14A St gross street, London

Ashok, K., S. K. Behera, S. A. Rao, H. Weng, and T. Yamagata (2007b) : El Nin˜o Modoki and its possible teleconnection, *J. Geophys. Res., 112, C11007, doi:10.1029/2006JC003798*.

Ashok, K., H. Nakamura, and T. Yamagata (2007a): Impacts of ENSO and IOD events on the Southern Hemisphere storm track activity during austral winter, J. Clim., **20**, *3147 – 3163.*

Barkhordarian, A., H. Von Storch, and E. Zorita, (2012b): Anthropogenic forcing is a plausible explanation for the observed surface specific humidity trends over the Mediterranean area. Geophysical Research Letters, **39**(19).

Barkhordarian, A., J. Bhend, and H. von Storch, (2012a): Consistency of observed near surface temperature trends with climate change projections over the Mediterranean region. Climate Dynamics, **38**(9-10), *1695-1702.*

Battisti D. S.,Naylor R. L. (2009): Historical warnings of future food insecurity with unprecedented seasonal heat. Science 323, 240–244. (doi:10.1126/science.1164363)

Behera, S. K., J.-J. Luo, S. Masson, P. Delecluse, S. Gualdi, A. Navarra, and T. Yamagata, (2005): Paramount impact of the Indian Ocean dipole on the East African short rains*: A CGCM study, J. Climate, 4514-4530.*

Behera, S. K., R. Krishnan, and T. Yamagata, (2003): Unusual oceanatmosphere conditions in the tropical Indian Ocean during 1994, Geophys. Res. Lett., **26**, *3001-3004, 1999*. Behera, S., and T. Yamagata, Influence of the Indian Ocean dipole on the southern oscillation, *J. Meteorol. Soc. Jpn,* **81**, *169-177*.

Biggs, R., E. Bohensky, P.V. Desanker, C. Fabricius, T. Lynam, A.A. Misselhorn, C. Musvoto, M. Mutale and Co-authors, (2004): *Nature Supporting People: The Southern African Millennium Ecosystem Assessment Integrated Report*. Millennium Ecosystem Assessment, Council for Scientific and Industrial Research, Pretoria, 68 pp.

Black E, Slingo J and Sperber K.R (2003): An observational study of the relationship between excessively strong short rains in coastal East Africa and Indian Ocean SST. *Mon Wea Re*v,131, 74-94.

Burg, J.P. (1972): The relationship between maximum entropy and maximum likelihood spectra. Geophy. **37:** *375-376.*

Camberlin, P. and Philippon, N. (2002): The East African March-May rainy season: Associated atmospheric dynamics and predictability over the 1968-97 period. *J. Climate*, **9**, 1002-1019.

Camberlin P (1995): June–September rainfall in north-eastern Africa and atmospheric signals over the Tropics: a zonal perspective. Int J Climatol **15**:*773–783.*

Cannarozzo M, Noto LV, Viola F (2006): Spatial distribution of rainfall trends in Sicily (1921–2000). *Phys Chem Earth 31:1201–1211*

CDKN, (2013): The IPCC's Fifth Assessment Report/What's in it for Africa? http://cdkn.org/wp-content/uploads/2014/04/AR5_IPCC_Whats_in_it_for_Africa.pdf

Challinor AJ, Wheeler TR(2008): Crop yield reduction in the tropics under climate change: processes and uncertainties. Agric Forest Meteorol 2008;148:343–56.

Chan (2011): Assessment climate variability and change impacts on livelihood and coping strategies in upper Nile state of south Sudan, *MSc Dissertation , University of Nairobi*

Chang H., Knight C.G., Staneva M.P,(2002):Water resource impacts of climate change in southwestern Bulgaria Geol J, 57 (2002), pp. 159–168.

Chiang, J.C.H., and Sobel A.H.,(2002) : Tropical tropospheric temperature variations caused by ENSO nad thire influence on remote tropical climate. *Journal of climate* **15**, *2616-2631*.

Clark, C. O., P. J. Webster, and J. E. Cole, (2003): Interdecadal variability of the relationship between the Indian Ocean Zonal Mode and East African coastal rainfall anomalies, *J. Clim.*, **16,** *548–554*,.

Collins, J.M., (2011): Temperature variability over Africa. Journal of Climate, 24(14), 3649-3666.

Cooley, J.W., Lewis, P.A.W. and Welch, P.O. (1967) : Historical notes on the Fast Fourier Transform. IEEE, 79-84.

Costa A. C.,(2011): Local patterns and trends of the Standard Precipitation Index in southern Portugal (1940–1999),Adv. Geosci., **30**, *11–16, 2011*

David.W.Sabo(2003):Probability and statistics for Biological sciences(*http://commons.bcit.ca/math/faculty/david_sabo/apples/math2441/section3/variability/variability.htm)*

De Luís M, Raventós J, González-Hidalgo JC, Sánchez J. R, Cortina J (2000): Spatial analysis of precipitation trends in the region of Valencia (East Spain). *Int J Climatol* **20***:1451–1469.*

Dockerty T., A. Lovett, K. Appleton(2006). Developing scenarios and visualisations to illustrate potential policy and climatic influences on future agricultural landscapes Agric Ecosyst Environ, 114 (2006), pp. 103–120.

Dockerty T., A. Lovett, G. Sunnenberg(2005): Visualising the potential impacts of climate change on rural landscapes Comput Environ Urban Syst, 29 (2005), pp. 297–320.

Easterling, D. R., J. L. Evans, P. Ya. Groisman, T. R. Karl, K. E. Kunkel, and P. Ambenje, 2000: Observed variability and trends in extreme climate events: A brief review. *Bull. Amer. Meteor. Soc., 81, 417–425.*

Easterling, D. R., and Coauthors, 1997: Maximum and minimum temperature trends for the globe. *Science*, **277***, 364–367.*

Edward.A. Ashiek(2011): Indicators of Climate Change in Upper Nile State, South Sudan, A Case study of Malakal and El Renk Counties, Upper Nile State, South Sudan, *MSc. Dissertation, Sudan academic of science* .

Enos Peter, (2013): El-Niño Southern Oscillation (ENSO) and its influence on rainfall over Tanzania, *PGD Dissertation University of Nairobi-Department of Meteorology*

Food Agriculture Organization of the United Nation (FAO), 2008: Crop and food supply assessment mission report, FAO office, Sudan

Funk, C., J. Michaelsen, and M. Marshall, 2012: Mapping recent decadal climate variations in precipitation and temperature across Eastern Africa and the Sahel. In: Remote Sensing of Drought: Innovative Monitoring Approaches. *Wardlow, B.D., M.C. Anderson, and J.P. Verdin (eds.)]. CRC Press, Boca Raton, FL, USA, pp. 331-358.*

Funk C., and Williams, A.P.,(2011): A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa. *Climate Dynamics, **37**(11-12), 2417-2435.*

Gezahegn W., Girma (2001): predicting Ethiopian rainfall using ENSO indices, PGD Dissertation: Department of Meteorology, University of Nairobi ed.; 2001.

Gitau Wilson, Ogallo laban , Pierre Camberlin, Okoola Raphael,(2013): Spatial coherence and potential predictability assessment of intraseasonal statistics of wet and dry spells over Equatorial Eastern Africa, International Journal of Climatology. **33(12)**:2690–2705. DOI: 10.1002/joc.3620.

Gitau Wilson (2005): characteristics of the wet and dry spells during wet seasons over Kenya, MSc. Dissertation Thesis: Department of Meteorology, University of Nairobi ed.; 2005.

Gonzalez-Hildago JC, De Luís M, Raventos S, Sanchez JR (2001): Spatial distribution of seasonal rainfall trends in a western Mediterranean area. Int J Clim Int J Climatol **21**:843 860.

GOSS, (2011): South SudanDevelopment Plan 2011-2013, Government of the Republic South Sudan.

Griffith, J.F (1972): Climates of Africa survey of climatology. Vol. 10. Edited by Landbergy, H.E. Elselvie Publishing Co. Amsterdam-London-New York.

Hall J. D., Matthews A. J. and Karoly D. J., (2001): The modulation of tropical cyclone activity in the Australian region by the Madden – Jullian Oscillation (MJO), *Mon. Wea. Rev.*, 129, **12**, 2970-2982.

Halpert, M.S. and Ropelewski, C.F. (1992): Surface temperature patterns associated with the Southern Oscillation', J. Climate, 5,577–593.

Hammer, R. M., (1973): Application and consequences of precipitation observations in the Republic of Sudan in view of the nomadic life and economy. *Geoforum*, **14,** 11-18.

Harle K.J.,. Howden S.MHunt, L.P(2007): The potential impact of climate change on the Australian wool industry by 2030 Agric Syst, 93 (2007), pp. 61–89.

Helsel, D. R. and R. M. Hirsch(2002): Discussion of "Applicability of the t-test for detecting trends in water quality variables" by R.H. Montgomery and J.C. Loftis, Water Resources Bulletin, 24, *201-204, 1988.*

Hendon, H., C. Zhang, and J. Glick, (1999): Interannual variation of the Madden-Julian Oscillation during Austral summer. *J. Climate, **12,** 2538-2550.*

Herrera P. M. and K.M. Hiscock (2008):The effects of climate change on potential groundwater recharge in Great Britain Hydrol Process, 22 (2008), pp. 73–86.

Hirsch, R. M., J. R. Slack, and R. A. Smith (2002): Techniques of trend analysis for monthly water-quality data, *Water Resources Research, **18**, 107-121, 1982.*

Howden S.M.,'Leary G.J. O (1997): Evaluating options to reduce greenhouse gas emissions from an Australian temperate wheat cropping system Environ Modell Software, 12 (1997), pp. 169–176.

IFAD. (2009): Republic of The Sudan - Country strategic opportunities programme. Rome: International Fund for Agricultural Development (IFAD).Retrieved from:www.ifad.org/gbdocs/eb/96/e/EB-2009-96-R-42-Rev-1.pdf.

Indeje M, and Semazzi F.H.M (2000): Relationships between QBO in the lower equatorial stratospheric zonal winds and East Africa seasonal rainfall *Meteorol Atmos Phy* **73**:227-244.

Ininda J.M, Muhati F.D, Opijah FJ.,(2007): Relationship between ENSO parameters and the trends and periodic fluctuations in east African rainfall. J Kenya Meteorological Soc 2007;1:20-43.

IPCC (2014): Climate Change 2014, Impacts, Adaptation, and Vulnerability. *Chapter 22. Africa (p.3).*

IPCC, (2013a): Climate Change 2013a: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.

Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]: Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC.(2012): Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), 2012, http://ipcc-wg2.gov/SREX/ 40-43.

IPCC, (2007a): The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

IPCC, (2007b): Working Group II Report "Impacts, Adaptation and Vulnerability" Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

IPCC, (2001b) Climate change 2001: Synthesis report. A contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Watson, R. T. and the Core Writing Team, Eds. Cambridge, UK: Cambridge University Press, 398 pp.

Janowiak, J. (1988): An investigation of Interannual rainfall', *J. Climate, 1, 240–255.*

Jenkins, G.M. and Watts, D.G. (1968) Spectral Analysis and Its Applications. Holden-Day, California, USA.

Karanga F.K.(2007): keyna adaptation to climate change in arid lands(kaccal):institutional Capacities for Climate Management. Final Project Component Report, University of Nairobi, December, 2007.

Kendall, M. G.(1975): Rank Correlation Methods, 4th ed., Charles Griffin: London, 1975.

Kostopoulou, E. and Jones, P. D., (2005): Assessment of climate extremes in the Eastern Mediterranean, *Meteorol. Atmos. Phys., 89, 69–85.*

Kunkel, K. E., S. A. Pielke Jr., and S. A. Changnon, 1999: Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. Bull. Amer. *Meteor. Soc.,* ***80****, 1077–1098.*

Lamb P.J (1978a): Large-scale tropical Atlantic surface circulation patterns associated with Subsaharan weather anomalies. *Tellus* **30***:240–251*.

Lamb P.J (1978b): Case studies of tropical Atlantic surface circulation patterns during recent Subsaharan weather anomalies: 1967 and 1968. *Mon Wea Rev* **106:***482–491*.

Lange A. (2014): Spatio-temporal patterns of recent and future climate extremes in the eastern Mediterranean and Middle East region, Nat. Hazards Earth Syst. Sci., **14**, *1565–1577*.

Lexer M.J., Honninger K., Scheifinger H.(2007): The sensitivity of Austrian forests to scenarios of climatic change: a large-scale risk assessment based on a modified gap model and forest inventory data For Ecol Manage, 162 (2002), pp. 53–72.

Li, L., S. Yang, X. Zhu, Z. Wang, H. Tang, (2010): Evidence of warming and wetting climate over the QinghaiTibet Plateau. – Arctic, Antarctic, and Alpine *Res.* **42**, *449– 457.*

Livia .B et al., (2009): VIA Module Vulnerability and Climate Change Impact Assessments for Adaptation, IEA Training Manual An integrated environmental assessment and reporting training manual p2-5.

Lloyd-Hughes, B. and Saunders, M. A (2002): A drought climatology for Europe, *Int. J. Climatol.,* **22,** *1571–1592.*

Lomuro, Martin Elia (2006): GOSS Agriculture and Forestry Policy Framework for the MAF 2006. Juba.

Lyon, B. and DeWitt D.G., (2012): A recent and abrupt decline in the East African long rains. Geophysical Research Letters, 39(2).

Magadza C.H.D,(2000): Climate change impacts and human settlements in Africa: prospects for adaptation, Environ Monit Assess, 61 (2000), pp. 193–205.

Mann, H. B.,(1945): Non-parametric test against trend, *Econometrica,* ***13****, 245-259, 1945.*

McKee, T. B., Doesken, N. J., and Kleist, J(1993): The relationship of drought frequency and duration to time scales, Preprints, 8th Conference on Applied Climatology, 17–22 January, Anaheim, California, Amer. *Meteor. Soc., 179–184.*

Mendelsohn, R., A. Dinar and A. Dalfelt, (2000): Climate change impacts on African agriculture. Preliminary analysis prepared for the World Bank, Washington, District of Columbia, 25 pp.

Michael D. Mastrandrea & Claudia Tebaldi & Carolyn W. Snyder & Stephen H. Schneider(2011): Current and future impacts of extreme events in California, Climatic Change DOI 10.1007/s10584-011-0311-6

Michaelides S.C, Tymvios FS, Michaelidou T (2009): Spatial and temporal characteristics of the annual rainfall frequency distribution in Cyprus. *Atmosph Res* **94(4):***606–615.*

Microsoft {computer software]. (1996): Excel.Redmond,WA: Microsoft Corporation.

Mojwok.O. Modo(2008): The effect of rainfall fluctuation on rain-fed agricultural production over el renk county, Upper Nile State, south Sudan, *MSc. Dissertation: Environmental science , university of Khartoum, Sudan.*

Mutai, C. C. and Ward M. M (2000): East African rainfall and the tropical circulation/convection on intra-seasonal to inter-annual timescales. *J. Climate*, **13(22)**, 3915–3939.

Mutemi J.N (2003): climate anomalies over eastern Africa associated with various ENSO evolution phases, *PhD Thesis: Department of Meteorology, University of Nairobi ed.; 2003.*

Muthama J.N., Manene MM, Ndetei CJ, (2008): Simulation of Decadal Precipitation over Nairobi in *Kenya.J.Scie.,* ***13****,43-54pp*

Ngaina and Mutai (2013): Observational evidence of climate change on extreme event over east Africa, *Global Meteorology;* **2***:e2.*

Ngongondo C, Xu C.Y, Gottschalk L, Alemaw B (2011): Evaluation of spatial and temporal characteristics of rainfall in Malawi: a case of data scarce region. *Theor Appl Climatol.* doi:10.1007/s00704-011-0413-0.

Niang, I., O.C. Ruppel, M.A. Abdrabo, A. Essel, C. Lennard, J. Padgham, and P. Urquhart, (2014): Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

Nicholson, S.E., D.J. Nash, B.M. Chase, S.W. Grab, T.M. Shanahan, D. Verschuren, A Asrat, A.-M. Lézine, and M. Umer, (2013): Temperature variability over Africa during the last 2000 years. *Holocene*, **23(8***), 1085-1094.*

Nicholson S.E. (1996): A review of climate dynamics and climate variability in Eastern Africa. In Johnson TC, Odada EO (eds). The Limnology, Climatology and Paleoclimatology of the East African Lakes. *Gordon and Breach: Australia; 25–56.*

Nicholson, S. E. and Entekhabi, D. (1987): Rainfall variability in Equatorial and Southern Africa: Relationship with sea surface temperatures along the Southwestern coast of Africa, *Journal of Climate and Applied Meteorology,* **26(5),** *561-578*.

Ning Baoying, Yang Xiaomei, Chang Li (2008): Changes of Temperature and Precipitation Extremes in Hengduan Mountains, Qinghai-Tibet Plateau in 1961–2008.

Norwegian People's Aid(2011):The New Frontier: A Baseline Survey of Large-scale land-based investment in Southern Sudan" (PDF). Norwegian People's Aid. 2011. Retrieved 2012-01-15.

Nsubuga F. N. W. and J. M. Olwoch and C. J. deW. Rautenbach and O. J Botai,(2013): Analysis of mid-twentieth century rainfall trends and variability over southwestern Uganda, *Theor Appl Climatol* **115***:53–71*.

Oakland Institute (2011):Understanding Land Investment Deals in Africa Country Report: South Sudan(http://www.oaklandinstitute.org/sites/oaklandinstitute.org/files/OI_country_report_south_sudan_1.pdf).

Ogallo L.J (1988): Teleconnection between seasonal rainfall over East Africa and Global Sea Surface Temperature Anomalies." Meteorological Society of Japan.

Ogallo, L.J,. Jonawiak J.E, and. Halpert M.S, (1988): Teleconnections between seasonal rainfall over East Africa and Global sea surface temperature anomalies*", J. Meteor. Soc. Japan,* **66,** *807-822.*

Ogallo L.J, Suleiman KA (1987): Rainfall characteristic in East Africa during the El-Niño year. Proc 1st Tech Conf Meteor Res East South Afr, Nairobi, p 76–80.

Ogallo, L.J. (1982): Quasi-periodic patterns in the East African rainfall records, *Kenya Journal of Science and Technology (A) (1982)* **3:** *43 – 54.*

Ogallo L.J (1981): Trend of rainfall in East Africa." *Kenya Journal of Science and Technology.;(A)(1981-2):83-90.*

Ogallo, L.J. (1980): Rainfall variability in Africa'*, Mon. Weather Re6., 107, 1133–1139.*

Okoola R.E. (1999): A diagnostic study of the Eastern Africa monsoon circulation during the Northern Hemisphere spring season. *International Journal of Climatology* **19:** *143–168.*

Okoola, R.E (1996): Space-Time characteristics of the ITCZ over equatorial eastern Africa during Anomalous Years. *PhD. Thesis, Department of Meteorology, University of Nairobi.*

Oludhe, C., (2010): Methods for seasonal Climate Prediction in the GHA region. First Evaluation Meeting on the training programme for Statistics in Agricultural Climatology (SIAC) in Africa, *2nd - 13th September 2002, Reading University, UK.*

Oludhe C. (2002): Step by step procedures in seasonal climate forecasting:Preforum Capacity Building training workshop for the GHA region. *14th – 30th August, 2005, ICPAC, Nairobi, Kenya*

Omondi.P.A (2005): Potential causes and predictability of the space - time patterns of the decadal rainfall variability modes over east Africa, *MSc. dissertation: Department of Meteorology, University of Nairobi.*

Osman YZ, Shamseldin AY (2002): Qualitative Rainfall prediction models for central and southern Sudan using El Nino Southern Oscillation and Indian sea surface temperature indices. *Int. J. Climatology* **22:***1861–1878.*

Otom,A.O (2011): assessment of the accuracy of the PRECIS-regional climate model in simulating climate extremes over equatorial east africa, *MSc. dissertation: Department of Meteorology, University of Nairobi ed.; 2011.*

Owiti Z.O , Laban.A. Ogallo, Joseph Mutemi (2008): Linkages between the Indian Ocean Dipole and East African Seasonal Rainfall Anomalies. *J. Kenya Meteorol. Soc.,* **2(1)** *3 –17.*

Owiti Z.O (2005): Use of the Indian Ocean dipole indices as a predictor of east African rainfall anomalies, *MSc. Dissertation Thesis: Department of Meteorology, University of Nairobi ed. 2005.*

Palmer TN (1986): Influence of the Atlantic, Pacific and Indian Oceans on Sahel rainfall. *Nature 322:251–253.*

Philippon N., Camberlin P. and Fauchereau N. (2002): Empirical predictability study of October–December East African rainfall, Quart, Roy. Met. Soc., 128, 2239–2256.

Räisänen, J. and L. Ruokolainen, (2008): Estimating present climate in a warming world: a model-based approach. *Climate Dynamics*, **31**, 573-585.

Rasmusson, E.M. and Carpenter, R.D. (1983): Variation in the tropical sea surface temperatures and sea wind fields associated with the Southern Oscillation/El-Nin˜o’, Mon. *Weather Re6.,* **110,** *354–384.*

Reynolds R. W and Smith, T. M., (1998): A high-resolution global sea surface temperature climatology for the 1961–90 base period. *J. Climate*, **11,** 3320–3323. Short rains over East Africa. *J. African Met Soc.,* **3,** *127-138.*

Reynolds, R. W., (1993): Impact of Mount Pinatubo aerosols on satellite-derived sea surface temperatures. *J. Climate,* **6,** *768–774.*,

Ropelewski, C.F. and Halpert, M.S. (1987): Global and regional scale precipitation patterns associated with the El-Nin˜o/Southern Oscillation', *Mon. Weather Re6.,* ***115,*** *1606–1626.*

Sabiiti Geoffrey(2008): Simulation of Climate Scenarios over the Lake Victoria Basin using the PRECIS Regional Climate Model, *MSc. dissertation, Department of Meteorology, University of Nairobi.*

Saji, N.H., and Yamagata, T., (2003): Structure of SST and surface wind variability during Indian Ocean dipole mode events: COADS observations, *J. Climate,* ***16,*** *2735-2751.*

Saji, N. H., Goswami, B. N., Vinayachandran, P. N., and Yamagata,T(1999): A dipole mode in the tropical Indian Ocean, *Nature,* **401,***360–364.*

Salinger, M. J., Renwick, J. A., and Mullan, A. B., (2001): Interdecadal pacific oscillation and southpacific climate', *Int. J. Climatol.* **21,** *1705–1721.*

Salinger, M. J., Stigter, C. J., and Das, H. P., (2000): Agrometeorological adaptation strategies to increasing climate variability and change', Agric*. Forest. Meteorol.* **103**, *167–194.*

Salinger, M. J., Desjardins, R., Jones, M. B., Sivakumar, M. V. K., Strommen, N. D., Veerasamy, S., and Lianhai, W., (1997): Climate variability, agriculture and forestry: *An update, WMO Technical Note 199, Geneva.*

SCOR (Scientific Committee on Oceanic research) (1983): Prediction of El Niño. Proceedings No. 19 Paris. Annex VI, *SCOR WG* **55** *47-51*.

Sene K.J, Farquharson FAK (1998): Sampling errors for water resources design: the need for improved hydrometry in developing countries. *Wat Res Manage* **12:***121–138.*

Tayanç, M., Doğruel İm, U., and Karaca M., (2009): Climate change in Turkey for the last half century, *Climatic Change,* **94,** *483–502,.*

Tilya Faustine Fidelis (2007): Characteristics of Wet and Dry Spells in Tanzania during the Rainy Seasons, MSc. dissertation, Department of Meteorology, University of Nairobi.

Turks M (1996): Spatial and temporal analysis of annual rainfall variations in Turkey. *Int J Clim* **6:***1057–1076.*

U.S. Census Bureau (2011): The 2011 Statistical Abstract: International Statistics.

UNDP Empowered lives, (2012): Resilient nations. Annual report (http://www.ss.undp.org/content/dam/southsudan/library/Reports/UNDP-SS-Annual-Report-2012-Web.pdf)

UNEP. (2007): Sudan post-conflict environmental assessment. Nairobi, Kenya: United Nations Environment Programme. Retrieved from *http://www.unep.org/sudan/post conflict/*.

USAID. (2007): Southern Sudan environmental threats and opportunities assessment: biodiversity and tropical forest assessment. Washington, DC: International Resources Group. Retrieved from *http://pdf.usaid.gov/pdf_docs/PNADL108.pdf*.

USGCRP (2009): United Stated Global Climate Change Impacts in the United States . Karl, T.R., J.M. Melillo, and T.C. Peterson (eds.). United States Global Change Research Program. Cambridge University Press, New York, NY, USA.

Van Rooy, M.P. (1965): A Rainfall anomaly index (RAI) independent of time and space. *Notos, 14, 43 – 48.*

Vincent, L.A., E. Aguilar, M. Saindou, A.F. Hassane, G. Jumaux, D. Roy, P. Booneeady, R. Virasami, L.Y.A. Randriamarolaza, F.R. Faniriantsoa, V. Amelie, H. Seeward, and B. Montfraix, 2011: Observed trends in indices of daily and extreme temperature and precipitation for the countries of the western Indian Ocean, 1961-2008. Journal of Geophysical Research D: Atmospheres, 116(10).

Vizy, E.K. and K.H. Cook, (2012): Mid-twenty-first-century changes in extreme events over northern and tropical Africa. *Journal of Climate*, **25***(17), 5748-5767.*

Wilby R.L,(2005):Uncertainty in water resource model parameters used for climate change impact assessment Hydrol Process, 19 (2005), pp. 3201–3219.

Williams, A.P., C. Funk, J. Michaelsen, S.A. Rauscher, I. Robertson, T.H.G. Wils, M. Koprowski, Z. Eshetu, and N.J. Loader, (2012): Recent summer precipitation trends in the Greater Horn of Africa and the emerging role of Indian Ocean Sea surface temperature. *Climate Dynamics*, **39***(9-10), 2307-2328.*

Williams, A.P. and C. Funk, 2011: A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa. Climate Dynamics, 37(11-12), 2417-2435.

Yun Kyung Sook , Ki-Young Heo, Jung-Eun Chu , Kyung-Ja Ha , Eun-Jeong Lee, Yumi Choi , and Akio Kitoh(2012) : Changes in Climate Classification and Extreme Climate Indices from a High-Resolution Future Projection in Korea, *Asia-Pacific J. Atmos. Sci.,* **48***(3), 213-226*

Zaroug.M. A. H. F. Giorgi1 , E. Coppola1 , G. M. Abdo3 , and E. A. B. Eltahir(2014): Simulate the connections of ENSO and the rainfall regime of East Africa and the upper Blue Nile region using a climate model of the Tropics, Hydrol. *Earth Syst. Sci.,* ***18****, 4311–4323.*

Zhang Q, Xu C-Y, Zhang ZX, Chen X, Han Z (2010): Precipitation extremes in a karst region: a case study in the Guizhou Province,southwest China. *Theor App Climatol* **101***:53–65*.

Zhang Q, Xu C-Y, Becker S, Zhang ZX, Chen YD, Coulibaly M(2009c): Trends and abrupt changes of precipitation maxima in the Pearl River Basin, China. *Atmosph Sc Lett* **10:***132–144.*

Zhang Q, Xu C-Y, Zhang Z, Chen YD, Liu C-L (2009b): Spatial and temporal variability of precipitation during 1951–2005 over China. *Theor App Climatol* **95***:53–68.*

Zhang Q, Xu C-Y, Zhang ZX (2009a): Observed changes of drought/ wetness episodes in the Pearl River basin, China, using the standardized precipitation index and aridity index. *Theor Appl Climatol* **98***:89–99.*

Zhang Q, Xu C-Y, Chen YD, (2008): Spatial and temporal variability of extreme precipitation during 1960–2005 in the Yangtze River basin and possible association with large-scale circulation. *J Hydrol* **353:***215–227. doi:10.1016/j.jhydrol.2007.11.023.*

ACKNOWLEDGMENT

First, I am grateful to the Almighty for His guidance, mercies and blessings, throughout my entire life. Glory Be To His Holy Name. Amen.

My special appreciations goes to the University of Nairobi Staff both teaching and non-teaching staff, especially staff at the Department of Meteorology, the IGAD Climate Prediction and Applications Centre (ICPAC) staff, South Sudan Meteorological Department; especially Director of Department, Mr. Mojwok Ogawi Modo for providing an enabling environment to conduct this research work. I also want to appreciate ICPAC for the financial support as well as providing me with the computational resources that enabled the completion of this research.

My sincere appreciation and special thanks go to my dear University Supervisors, Prof. Laban. A. Ogallo, Dr. Christopher Oludhe and Dr. Wilson Gitau for their guidance and humble and incisive approach on all aspects of this dissertation.

Last but not least, the golden medals go to my family members, especially my wife Rebecca Anthony, my daughter Chajwok for having endured the absence of her daddy for all the time I was away in pursuit of this research.