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坦桑尼亚的气候特征及其与基本环流和海表温度的关系

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A Dissertation Submitted to Graduate School of China University of Geosciences in Partial Fulfillment of the Requirements for the Master's Degree

Climate characteristics in Tanzania and its relationship with general circulation and sea surface temperature (SST)

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Dedication

To my wife Fatma

坦桑尼亚的气候特征及其与基本环流和海表温度的关系

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摘 要

该论文研究坦桑尼亚南部高原地区（6°S-12°S，29°E-38°E）的气候特征，为确保研究的真实性，所用数据为来自坦桑尼亚气象局（TMA）的降水资料，全球海洋环境资料（包括海表温度 SST、海平面气压 SLP 的逐月格点资料）以及来自国家海洋和大气研究所（NOAA）地球系统研究实验室的纬向风分量（U）和经向风分量（V）数据。降水量资料用于建立标准化降水指数（SPI），来寻找降水与全球海洋环境的相关性，小波分析用来分析时间序列上的突变以及降水量的突出形态。

研究显示，该地区降水与印度洋海表温度存在相关关系，具体为当印度洋西部海温高（低）时，坦桑尼亚降水量多（少）。在较湿润（干旱）年份，弱（强）的赤道西风和赤道南部反气旋（气旋）式环流异常会减弱（加强）非洲东部方向的水汽输送。不仅如此，东北印度季风带来的水汽对坦桑尼亚地区的降水也存在显著地影响，在较湿润年份，强的东北向印度季风可到达坦桑尼亚的绝大部分地区，而在较干旱年份，东北向变为北向而不能到达该地区。另外，在较湿润（干旱）年份，来自几内亚海湾和刚果盆地的水汽增多（减少），会增加（降低）坦桑尼亚西部地区水汽的集中。

结果表明，坦桑尼亚最湿润年份为 1978/1979 年，属于“大涝”，最干旱的年份为 1999/2000 年，属于“中度干旱”。在研究中发现坦桑尼亚降水存在不同的周期模态，但是最显著的两个周期为 2 年和 7 年，与准两年震荡（QBO）和厄尔尼诺南方涛动(ENSO)相对应。而且，对降水有显著影响的两个海洋区域为印度洋 5°S-18°S，58°E-70°E 和大西洋 2°N-17°S，5°W-10°E 区域。

本文建议可以对关键区域海表温度变化作进一步研究，这将会有助于该地区年度降水量变化的预报。而且，政府的相关部门可以利用本实验结果，作为一个基准，来改善农业部门以及对于极端事件的警惕。

关键词：坦桑尼亚；主要周期模态；气候特征

Climate characteristics in Tanzania and its relationship with general circulation and sea surface temperature (SST)

Candidate : Mbululo, Yassin Adam Supervisor : Prof. Qin Jun

Abstract

This study was conducted to examine the climate characteristic of southern highland Tanzania (Latitude 6°S-12°S and Longitude 29°E-38°E). In order to meet the objectives of this study, monthly average rainfall data from Tanzania Meteorological Agency (TMA) and global marine environmental data, which consists gridded monthly sea surface temperature (SST), sea level pressure (SLP) and zonal (U) and meridional (V) wind components from National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory were used. The rainfall data was used to develop Standardized Precipitation Index (SPI) which was then used to find correlation with global marine environmental parameters. Wavelet method was used to analyze variations of power within the time series and dominant modes of rainfall variability

The study findings revealed that rainfall over the region is linked with SST over the Indian Ocean, where warmer (cooler) western Indian Ocean is accompanied by high (low) amount of rainfall over Tanzania. During wet (dry) years, weaker (stronger) equatorial westerlies and anticyclone (cyclonic) anomaly over the southern tropics act to reduce (enhance) the export of equatorial moisture away from East Africa. Not only that, but also moisture influx from the northeast Indian monsoon has significant influence on the rainfall over the region. During the wet years, strong northeasterly Indian monsoon is evident over most of Tanzania while during the dry year the northeasterly is seen to turn north hence denying moisture influx over Tanzania. In addition, increased (decreased) low level moisture influx from gulf of Guinea and Congo basin tend to occur during the wet (dry) seasons, leading to enhanced (reduced) low level moisture convergence over western part of Tanzania.

Results suggest the wettest season in record to be 1978/79 which can be classified as the "Severely wet" and the driest season in record to be 1999/00 which can be classified as "Moderate drought". Different dominant periodicity modes have been observed over the study period, but two of them seem to be more dominant over the whole study period. These modes of rainfall have been identified at time scale of 2 and 7 years which may be associated with the quasi biennial oscillation (QBO) and El Nino Southern Oscillation (ENSO) respectively. Moreover, key areas over the Ocean have been identified to be in between 5°S-18°S and 58°E-70°E for Indian Ocean and 2°N-17°S, 5°W-10°E for Atlantic Ocean.

The study recommends a closer follow-up on the local variation of SST over these key areas as they can help in forecasting year to year rainfall variability. Also responsible institutions in the government should make use of the findings from this study as a benchmark in improving agriculture sector and vigilance for extreme events.

Key words: Tanzania; Climate characteristics; Dominant periodicity mode

Table of content

List of Tables

List of Figures

List of abbreviations

AGCM	Atmospheric General Circulation Model
CIRES	Cooperative Institute for Research in Environmental Sciences
ENSO	El Nino Southern Oscillation
ERL	Environmental Research Laboratories
FEWS NET	Famine Early Warning System Network
GDP	Gross Domestic Product
GRR	Great Ruaha River
HEP	Hydro Electric Power
ICOADS	International Comprehensive Ocean Atmosphere Data Set
IOD	Indian Ocean Dipole
IODZMI	Indian Ocean Dipole Zonal Mode Index
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
MW	Mega Watts
NCAR	National Center for Atmospheric Research
NCDC	National Climate Data Centre
NCEP	National Centre for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NTP	National Trade Policy
QBO	Quasi Biennial Oscillation
QDO	Quasi Decadal Oscillation
SAGCOT	Southern Agricultural Growth Corridor of Tanzania
SLP	Sea Level Pressure
SO	Southern Oscillation
SOI	Southern Oscillation Index
SPI	Standardized Precipitation Index
SST	Sea Surface Temperature
SWMRP	Soil Water Management Research Programme
TANESCO	Tanzania Electric Supply Company Limited
URT	United Republic of Tanzania

CHAPTER ONE

§1.0 INTRODUCTION

§1.1 Background information

The United Republic of Tanzania is the largest country in East Africa with an area of about 945,087 square kilometers. It is situated between latitude 1° and 12° South, longitude 29° and 40° East and between the great East African lakes, namely lake Victoria in the North, lake Tanganyika to the West and lake Nyasa to the South. To the East, there is Indian Ocean and Zanzibar Island. The terrain consists of plains along the coast, a central plateau with highlands in the North and South. Tanzania's lowest point is at the floor of Lake Tanganyika, 358 meters below sea level and its highest point is Africa's highest peak, Mountain Kilimanjaro standing at 5,895 meters.

The economy of this country depends mainly on rain fed agriculture. The sector contributes about 50 percent to Gross Domestic Product (GDP) and 70 percent of earnings from merchandise exports. Furthermore, over 80 percent of the population lives in rural areas and their livelihood depends mainly on agriculture (NTP, 2003; Keenja, 2004; SWMRP, 2007). Therefore, the performance of agriculture is a major factor in determining wellbeing of country's economy. According to Census (2006), the total population of Tanzania during the most recent intercensal period of 14 years from 1988 to 2002 has increased from 23.1 million to 34.4 million, an increase of 11.3 million or 49.1 percent. The annual average growth rate during this period was 2.9 percent. By using this annual average growth rate, the population estimates by the end of the year 2011 stand to be 44.6 million. This increasing trend in population growth calls for improvement in agricultural productivity and hence understanding climate characteristics is of significant importance since rain fed agriculture is highly vulnerable to the amounts and distribution of rainfall.

§1.2 Climatology of Tanzania

Although the climate elements of region such as temperature, pressure, humidity etc vary, especially with altitude and distance from the sea of the specific region or location, in the tropics, the element with the highest variations in space and time is rainfall (Ogallo, 1993). This in turn determines the settlement patterns, population density and distribution and agricultural productivity over the region. Rainfall over Tanzania is also revealing high space and time variability (Basalirwa et al, 1999; Indeje and Semazzi, 2000; Matari, 2002; Reason and Kijazi, 2011) which make agricultural activities difficulty. This high variation in rainfall has been attributed by the complex topography and existence of large inland water bodies that have a unique mesoscale forcing influence. In East Africa and Tanzania in particular, climate classification schemes (e.g. Basalirwa et al, 1999; Indeje et al, 2000) have been based mainly on analyses of rainfall data. Knowledge of these spatial extents of regions which have similar rainfall characteristics is advantageous in planning and management of not only rainfall dependent agricultural activities, but also water resources.

Tanzania is located in the tropical region therefore it experiences tropical climate with two major rainfall regions, that is unimodal (one long rainy season) and bimodal (two rainy seasons). The unimodal regions (southern, south-west, central and western) experience rainfall during November to April, the period which coincides with southern hemisphere summer. Within this period, the development over the western Indian Ocean of the northeastern monsoon and its transitions to and from the southwestern monsoon near the beginning and end of the rain season are important in determining the amount and distribution of rainfall of this region (Hastenrath et al, 1993; Mapande and Reason, 2005b). The rainfall peaks is associated with the maximum Intertropical Convergence Zone (ITCZ) induced convection over the southern hemisphere (Ogallo, 1993; Basalirwa et al, 1999; Slingo et al, 2004; Anyah et al, 2006) and the dry season normally coincides with the southern hemisphere winter (Mpeta, 2002). Study done by Matari (2002) suggests that, wind direction which is principally determined by the position of ITCZ and surrounding monsoons to be the most important factor on the distribution of moisture from the Congo basin. The basin receives moisture influx from the tropical Atlantic and it produces its own through evapotranspiration. Several studies (Ogallo, 1993; Mapande and Reason, 2005b) have associated rainfall over the western Tanzania with moist air mass from Congo basin while rainfall over parts of the coastal zone is associated with the East African low jet stream. Moreover, study by Anyah et al (2006) observed a substantial rainfall near all large water bodies as the result of land-sea/lake breeze effects.

In bimodal regions (north and northern coast) rainfall seasons are found on March to May and October to November. These are locally known as the 'long' or 'Masika' and 'short' or 'Vuli' rainfall seasons associated with the northward and southward movement of the Intertropical Convergence Zone (ITCZ), respectively (Ogallo, 1993; Kabanda and Jury, 1999; Mpeta, 2002; SWMRP, 2007; Sabiiti, 2008). Moisture for rainfall formation for these seasons is generally derived from the Indian Ocean by the monsoonal wind systems. The intermediate periods between these two rainy seasons are relatively dry.

In an equatorial region, rainfall would be associated with synoptic scale circulations. Rainfall over Tanzania is also controlled by synoptic and local factors, as well as global and regional teleconnection. Some of the synoptic scale features that affect rainfall include inland water bodies, ITCZ, Subtropical anticyclones, Tropical cyclones, Jet streams, westerly waves and many other global and regional systems that include El Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) among others. Hence, rainfall distribution characteristics in Tanzania results from interaction between the microscale features with both the synoptic and large scale systems (Indeje et al, 2000; Indeje and Semazzi, 2000; Sabiiti, 2008). Characteristics of some of these global, regional, synoptic and local systems and their influence on the climate of Tanzania and southern highland in particular are reviewed in the sub-sections below.

1.2.1 Inland water bodies

The presence of big lakes i.e. Lake Nyasa, Tanganyika and Victoria coupled with the complex physical features induces mesoscale circulation with a strong diurnal cycle over the surrounding areas. This is a result of existence of thermal contrast between land and water surfaces which initiates local circulations, including land-sea breeze. A good example of the local effect is observed over the Lake Victoria which has a vigorous circulation of its own (Ogallo, 1993; Indeje et al, 2000; Anyah et al, 2006; Sabiiti, 2008). The lake influence is due to its large body of water, the temperature contrasts between the lake and land during the day (night) resulting in a lake (land) breeze towards the land (lake) during the day (night). In general, the land-lake breeze phenomenon results in the lake basin region getting some rainfall almost throughout the year. The rainfall is however significantly enhanced during the main rainy seasons discussed above due to the passage of ITCZ. The characteristics of the ITCZ and how it affects the climate is reviewed in the next section.

1.2.2 Intertropical Convergence Zone (ITCZ)

The ITCZ is the boundary between inter-hemispheric monsoon wind systems where most of the enormous quantity of latent heat evaporated from the tropical oceans is converted into sensible heat. The ITCZ is the main synoptic scale system that affects the intensity, distribution and migration of seasonal rainfall over the equatorial East Africa. The onset and cessation of seasonal rainfall over the region depends mostly on the onset and withdrawal of the ITCZ (Sabiiti, 2008; Indeje et al, 2000; Mpeta, 2002). A number of Studies (Bates, 1970; Behera and Yamagata, 2001; Matari, 2002) observed ITCZ to be almost always situated away from the Equator, often as far away as 10 degrees or more. Moreover, its mean position varies with the season, advancing furthest from the Equator in the summer of each hemisphere. Over the oceans, the surface position of ITCZ nearly coincides with the region of highest SST and it is most stable in the eastern parts of the oceans, showing a marked tendency to migrate, break down into isolated disturbances and reform in the western parts. On the surface, ITCZ seeks regions of highest temperatures and wind confluence for its location. Furthermore, the presence of continental ITCZ between Tanzania and central Mozambique during December to February tends to coincides with the main rainy season (Behera and Yamagata, 2001). According to Sabiiti (2008) over East Africa, the ITCZ has two spatial components i.e. zonal and meridional arms. The zonal arm, which has an East-West orientation, is a zone of convergence between the northeast and southeast monsoons, while the meridional arm, which has a North-South orientation, is a zone of convergence between the westerlies from the Atlantic Ocean and the Easterlies from the Indian Ocean. The northward movement of the zonal arm of the ITCZ component is in response to the seasonal intensification (weakening) of the southeast (northeast) monsoon winds. Ogallo (1993) associated the two seasonal rainfalls, long rains (March to May) and short rains (October to December) in bimodal region with the double passage of the ITCZ over eastern Africa region. Moreover, study by Indeje et al (2000) on ENSO signals in East Africa rainfall seasons found that; short rainfall is influenced mostly by the East-West oscillation of meridional component of the ITCZ while the long rainy are more influenced by the North-South movement of the zonal arm of the ITCZ in the region. The effectiveness and depth of the ITCZ mainly depends on the intensity of the Subtropical anticyclones. These include the Arabian high to the northwest Indian Ocean, the Azores high to the northeast Atlantic Ocean, the Mascarene high to the southwest Indian Ocean and the St. Helena high to the southeast Atlantic Ocean. These anticyclones determine the characteristics of the monsoonal winds over East Africa. The characteristics of these subtropical anticyclones are reviewed below.

1.2.3 Subtropical anticyclones

These are semi permanent warm core, high pressure systems centered over the subtropical latitudes (approximately 30° N and 30° S) of the north and south Atlantic, and the Indian Ocean. These anticyclones create pressure differences between the equatorial regions and the subtropical regions necessary for driving the tropical trade winds. The anticyclones that influence the synoptic flow over East Africa are Mascarene, St Helena, Arabian, and the Azores high.

The moisture that comes into East African region depends on the location and strength of these anticyclones. For instance, the Mascarene anticyclone over the south western Indian Ocean determines the characteristics of the moist southeasterly monsoon flow over the Indian Ocean which influences rainfall over most of eastern Africa. Concomitantly, Xue et al (2004) found the intensification of Mascarene high to be main determinant of Somali jet intensification. The St. Helena anticyclone over southeast Atlantic Ocean is responsible for the pronounced middle level westerly flow (the Congo air mass) over the region. The Azores high causes subsidence of warm dry air over the Sahara and neighboring regions while the Arabian anticyclone sends dry continental northeasterly flow over most of the eastern parts of Africa (Cadet and Desbois, 1980;

Slingo et al, 2004; and Sabiiti, 2008). These systems are most intensive during winter seasons of each hemisphere and weaken during summer.

1.2.4 Tropical monsoons

Monsoon is a large scale perturbation of the trade wind circulation associated with the seasonal movement of the equatorial heat source, which converges into the circulation around the heat source on its equator ward side at low levels, producing a wave with two zones of precipitation and a zone of clearance in between, and a host of other characteristic changes in air mass properties, during its advance and retreat (Chao and Chen, 2001; Saha, 2009). Monsoon is one of the key elements of the global climate system and strongly affects agricultural and other human activities in monsoon regions. Since tropical monsoon constitutes a perturbation of the trade wind circulation that converges into the ITCZ, the seasonal movement of the ITCZ offers a practical means to identify the leading edge of the monsoon over a region at any time of the year. In other words, the region swept out by the ITCZ in the course of its movement between summer and winter constitutes the domain of the tropical monsoon in that region (Saha, 2009). The main rainy seasons in Tanzania are largely associated with one monsoonal wind current receding while another one advancing. During the short rains season (OND) in bimodal regions, the northeast monsoonal wind is advancing while the southeast monsoonal wind is receding. For the long rains season (MAM), the northeast monsoonal wind is receding while the southeast monsoonal wind is advancing. In both cases the low level monsoonal air current is topped by air due to easterly current which is generally dry (Zeng and Lu, 2003; Mapande and Reason, 2005b; Sabiiti, 2008; Saha, 2009). Nevertheless, there are some others facts which are of wealth to mention here apart from the literature which have been cited. East Africa and Tanzania in particular have several large water bodies, therefore thermal contrast which may arise between a landmass and these large water bodies can force a seasonal movement (circulation) of low pressure between land and water bodies. This can lead to local land-lake breeze as it has been discussed in subsection above.

1.2.5 Jet stream

Jet streams are fast flowing, narrow air currents found in both the upper and the lower levels of the atmosphere. The major jet streams on earth are westerly winds (flowing west to east). Their paths typically have a meandering shape (vertically and horizontally); it may start, stop, split into two or more parts, combine into one stream, or flow in various directions including the opposite direction of most of the jet. Findlater (1969) suggest that, since the jet streams have been located over very small islands in the Indian Ocean (e.g. St. Brandon), then they are not topographically generated, although large land masses such as Madagascar and eastern Africa do influence them. The jet streams that have been observed to influence weather over eastern Africa are Subtropical Jet, Tropical Easterly Jet (TEJ), African Easterly Jet (AEJ), Turkana Jet and East African Low Level Jet (Somali jet). Effects of these jets over East Africa climate have been widely discussed by several authors including those of Findlater (1969); Ardanuy (1979); Cadet and Desbois (1980); Kinuthia and Asnani (1982) among others.

1.2.6 El Nino Southern Oscillation (ENSO)

ENSO is a quasi periodic climate pattern that occurs across the tropical Pacific Ocean after every few years. It is characterized by variations in the temperature of the surface of the tropical eastern Pacific Ocean, warming known as El Nino while cooling known as La Nina. The two variations are coupled; warm oceanic phase, El Nino, accompanies high air surface pressure in the western Pacific, while the cold phase, La Nina, accompanies low air surface pressure in the western Pacific. The return period of El

Nino events is varied, ranging from two to seven years. The intensity and duration of the event are also varied yet predictable to some degree. Typically, it lasts anywhere from 14 to 22 months.

The Southern Oscillation (SO) is characterised by a seesaw in atmospheric pressure between the western and eastern regions of the Pacific Ocean (Behera and Yamagata, 2003), with one centre of action located at Australia and the other centre located near Tahiti. The Southern Oscillation Index (SOI), which is an index that measures the magnitude of SO is obtained by calculating the difference in atmospheric surface pressure anomalies between Tahiti and Darwin, Australia. As the SO and El Nino are closely linked with each other, they are collectively known as the El Nino Southern Oscillation, or ENSO (Hastenrath et al, 1993; Trenberth, 1997; Behera and Yamagata, 2003). ENSO events are those in which both the El Nino and Southern Oscillation occurs together (Torrence and Compo, 1998; Mpeta, 2002). Originally, it was thought to be a regional phenomenon that sea surface temperature (SST) temporarily rises in the equatorial eastern Pacific Ocean, but is now deemed a global episode entangling the earth system. A number of studies (Stewart, 2006; Heki and Morishita, 2008) reveal that, ENSO changes not only precipitation patterns in the equatorial Pacific area, but also imposes climate changes in remote areas by teleconnection.

In Tanzania, rainfall pattern is normally influenced by SST over the Indian Ocean. However, the SST over the Pacific Ocean which is associated with El Nino and La Nina event has also an influence in the rainfall pattern. El Nino event is normally associated with extremely high rainfall particularly in equatorial regions. Several studies (Nicholson and Selato, 2000; Mapande and Reason, 2005a; Indeje et al, 2000) observed above (below) normal rainfall in much of equatorial (south) eastern Africa during El Nino (La Nina) event. A very recent and memorable experience of devastating effect of El Nino event happened in 1997/98. This El Nino event was associated with catastrophic disruption of socioeconomic infrastructure such as roads, railways, farms and loss of life. An important note to be raised about El Nino is that, it can alter weather and seasonal climate on a global scale, but their impacts on the local climate are much affected by conditions in the local oceans where they originate.

1.2.7 Indian Ocean Dipole

The Indian Ocean Dipole (IOD) is a coupled ocean-atmosphere phenomenon in the Indian Ocean. It is normally characterized by anomalous cooling of SST in the south eastern equatorial Indian Ocean and anomalous warming of SST in the western equatorial Indian Ocean. It represents the dominant climatic mode found in the tropical Indian Ocean by Saji et al (1999) and its strength is measured through the IODZM index (IODZMI) which quantifies zonal gradients in the SST rather than the proper East-West dipole (Ashok et al, 2003; Manatsa et al, 2010). Associated with these changes the normal convection situated over the eastern Indian Ocean warm pool shifts to the west and brings heavy rainfall over the East Africa and severe droughts/forest fires over the Indonesian region (Saji et al, 1999; Iizuka et al, 2000; Ashok et al, 2001; Behera and Yamagata, 2001; Saji and Yamagata, 2003). A number of studies (Webster et al, 1999; Ashok et al, 2001; Yamagata et al, 2002; Ashok et al, 2003; Clark et al, 2003; Li et al, 2003) suggest that; even the 1997/98 ENSO events which have been mentioned in subsection above and attracted great public attention was the result of co-occurrence of strong El Nino event and positive IOD as presented in Table 5 below. Moreover, Behera et al (2005) notice that the influence of pure ENSO event on East Africa rainfall is quite different from the pure IOD event in term of distribution and intensity. The occurrence of pure IOD event is accompanied with more rainfall in most part of East Africa than during the pure ENSO event.

It is wealthier to acknowledge that the origin of IOD is unclear. This has led to a suggestion that IOD is a part of the ENSO phenomenon (Allan et al, 2001; Hendon, 2003). However, this seems unlikely due to an inverse relation between ENSO and IOD activity on decadal time scales, suggesting that decades of high ENSO activity co-occurred with decades of low IOD activity and vice versa. Not only that, but also there is significant proportion of IOD events occurred independent of ENSO and a significant proportion of ENSO events were independent of IOD. Interestingly, the group of IOD events that occurred in the absence of ENSO accounted for the larger share of variance in Indian Ocean variability than the group that co-occurred with ENSO (Iizuka et al, 2000; Ashok et al, 2001; Ashok et al, 2003; Saji and Yamagata, 2003). Due to aforesaid facts, it is logical to conclude that IOD event is independent from ENSO event even though its origin is unclear.

Therefore, this study wants to figure out the characteristics of rainfall and its relationship to general circulation and SST. So far several studies on rainfall variability have been done over Tanzania, mainly focusing on the bimodal rainfall regions and ignoring the unimodal rainfall regions. Some of the studies regarding variability of rainfall on bimodal regions are such as those of Kabanda and Jury (1999) on Interannual variability of short rains, Zorita and Tilya (2002) which was focusing on variability of long rain season and its links to large scale climate forcing, Reason and Kijazi (2011) on Intraseasonal variability of rainfall and associated circulation anomalies among others. The importance of these unimodal rainfall areas for Tanzania lies in the fact that the major cereal producing region and catchment areas for the rivers which have been tapped for hydroelectricity power generation are located in this area.

§ 1.3 Problem Statement

Tanzania has been experiencing unreliable and unpredictable rainfall patterns for the past few decades. This trend is an alarming problem to agricultural productivity and wellbeing of the country since the sector is the backbone of the country economy (Keenja, 2004; Kijazi and Reason, 2005). These trends have led to several other problems over the country ranging from food shortage, power crisis, destruction of infrastructures and environmental degradation. Furthermore, the country is experiencing a rapid increase in population growth (Census, 2006) which calls for improvement in agricultural productivity i.e. rain fed agriculture which is highly vulnerable to the amounts and distribution of rainfall. Sabiiti, (2008) suggested that for any given region to have sustainable development, there is a need to apply climate information into its socioeconomic strategic plans hence this study wants to supplement the climate information on developments plans. So far, little have been done to study ocean-atmosphere interaction and its effect on climate variability over the Indian Ocean as compared to Pacific and Atlantic oceans where internal modes of variability that lead to climatic oscillations have been recognized (Saji et al, 1999). This study therefore observed the gap in understanding the internal modes of variability over the Indian Ocean which determines rainfall patterns. However, relatively small changes in SST over Indian Ocean can have a large impact on atmospheric convection and circulation (Latif et al, 1999; Slingo et al, 2004). With regard to this problem, it signifies the need of studying climate characteristics in relation to SST and general circulation so as to be in a good position to forecast the near future and reduce the costs which may be caused by unpreparedness event.

§ 1.4 Objectives of the Study

1.4.1 General Objective

The general objective of this research work is to study climate characteristics and its relationship with SST, general circulation and also to reveal the climate mechanism and its forecast method in Tanzania

1.4.2 Specific Objectives

i. To analyze the observed rainfall patterns over southern Tanzania during the recent past.
ii. To develop rainfall distribution Index for southern highland Tanzania.
iii. To examine the influence of general circulations and SST on rainfall pattern over Tanzania.

§ 1.5 Significance of the Study

This study will help to improve the general understanding of the rainfall characteristics over southern highland Tanzania. Moreover, the findings from this study will add knowledge on forecasting and therefore proper management and planning of different activities which are rainfall dependant such as agriculture and hydropower generation. As it has been mentioned earlier, Tanzania as a third world country, its economy is depending mainly on the rain fed agriculture which needs to be improved to cope with the increasing population. Over the last decade, the agricultural sector has grown at an annual average rate of 3.7 percent compared with annual population growth of 2.9 percent (Keenja, 2004; Census, 2006). In recent years, the sector has shown signs of increased rates of growth due to interventions by the government aimed at stimulating agricultural growth by introducing various programs such as Agriculture First (Kilimo Kwanza). Apart from the achievement which have been observed so far, fluctuations of rainfall over the region pose a serious problem to farmers, water resource managers and related industries. Farmers, water resource managers, economic planners and others would be well armed if they would know the characteristics of the rainfall in their region. In order to achieve this, there is a strong need to identify year to year rainfall characteristics over southern highland Tanzania and its relation to regional global meteorological parameters together with forcing mechanisms.

§ 1.6 Study area

This study will focus on the Southern highland Tanzania (latitude 6° and 12° S and longitude 29° and 38° E) particularly in four regions which are Iringa, Mbeya, Rukwa, and Ruvuma presented in Figure 1 below. The basis for selecting southern highland regions as the study area is that; this area has not widely studied despite of its significant contribution to the economy of the country. The area is potential for food crops which depend mostly on rainfall. The region also acts as the water catchment area for great Ruaha River (GRR) which is the lifeline of Ruaha National Park, the second biggest National Park in Tanzania after Serengeti National Park (Kashaigili et al, 2005). Moreover, TANESCO's largest hydropower complex, the Mtera and Kidatu dams, depend on the Great Ruaha River. The Mtera dam is the most important reservoir in the power system providing over year storage capacity and also, it regulates the outflows to maintain the water level for the downstream Kidatu hydropower plant (World Bank, 2004). Kadigi et al (2008) reveals that; the Mtera and Kidatu dam system has a total installed capacity of 284MW which is the largest installed capacity in Tanzania. The system provides more than 50 percent of the 559MW available in the national hydropower grid. Therefore, the study on climate characteristic within this region is essential for maintaining the potentiality of this region.

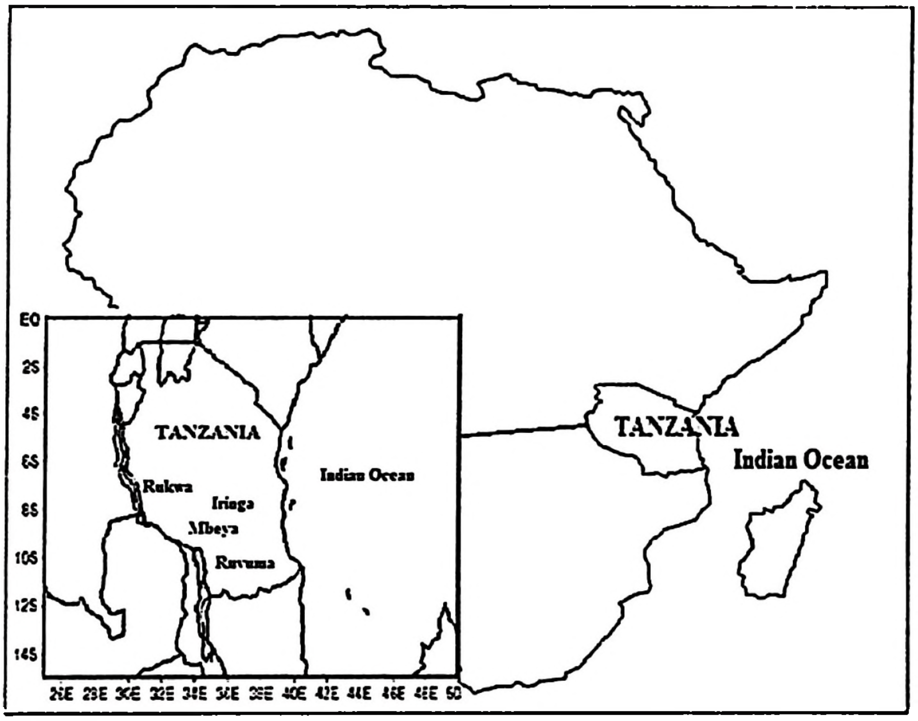


Figure 1: Map of Africa showing location of Tanzania and study area, Iringa, Mbeya, Rukwa and Ruvuma region

§ 1.7 Scope of the Study

This study confined itself to four regions which form southern highlands since it focused on climate characteristics of southern highlands Tanzania. These regions are the major cereal producing regions and experience unimodal type of rainfall. Taking into consideration of time and resources allocated in this particular study; only meteorological data will be used in this study. The findings are therefore specific to southern highlands Tanzania which exhibits unimodal type of rainfall and valid to specific study period and not necessarily valid for other regions within and outside Tanzania.

CHAPTER TWO

§ 2.0 LITERATURE REVIEW

§ 2.1 Weather and Climate

In common language, the concept of weather and climate are loosely defined. The term weather can be defined as the state of the atmosphere at a given time and space, with respect to variables such as temperature, precipitation, clouds, wind, pressure and other weather elements. Likewise, it is the result of rapidly developing and decaying weather systems such as mid latitude low and high pressure systems with their associated frontal zones, showers and tropical cyclones. The growth, movement and decay of these weather systems depends mainly on the vertical structure of the atmosphere, the influence of the underlying land and sea and many other factors which are not directly experienced by human beings. Moreover, weather has only limited predictability. Mesoscale convective systems are predictable over a period of hours only; synoptic scale cyclones may be predictable over a period of several days to a week. Beyond a week or two individual weather systems are unpredictable (IPCC, 2001). On the other hand, Climate refers to the average weather in terms of the mean and its variability over a certain time span and a certain area. Climate varies from place to place, depending on latitude, distance to the sea, vegetation, presence or absence of mountains or other geographical factors. Climate varies also in time; from season to season, year to year, decade to decade or on much longer time scales, such as the ice ages (Smith, 2001).

According to Hobbs (1997), the interest in atmosphere and awareness of its impact on human activities is nothing new since records shows that ancient Egyptians, Romans, Russians, Arabians, Greeks and Chinese were very much aware of weather and climate. During those days, they were interested in cause and effect which helps them to establish an order to existence. For instance, the Chinese thought of their environment in terms of the abundance or failure of rains and recorded variations in terms of rainfall that determine harvests and tax revenues.

§ 2.2 Rainfall variability

Over Tanzania, few studies on rainfall variability have been done mainly focusing on the bimodal rainfall areas (e.g. Kabanda and Jury, 1999; Latif et al, 1999; Behera et al, 2005; Zorita and Tilya, 2002; Reason and Kijazi, 2011) and ignoring the unimodal rainfall areas. The importance of these unimodal rainfall areas for Tanzania lies in the fact that the major cereal producing region (Mpeta, 2002) and catchment areas for the rivers which have been tapped for hydroelectricity power generation (Kadigi et al, 2008) are located in this area. Nevertheless, rainfall variability over the East Africa with relation to regional and remote atmospheric and oceanographic parameters have been studied by many researchers, among them are Hastenrath et al, 1993; Ogallo, 1993; Goddard and Graham, 1999; Latif et al, 1999; Webster et al, 1999; Indeje et al, 2000; Mpeta and Jury, 2001; Ntale and Gan, 2004; Behera et al, 2005; Mapande and Reason, 2005a.

Goddard and Graham (1999) experiment on Atmospheric General Circulation Model (AGCM) suggests the Indian Ocean sea surface temperature (SST) to be exerting a greater influence over the East and Central Africa rainfall than the Pacific ocean. They also found a considerable modification of convective activities over equatorial Africa and the tropical Indian Ocean to be directly linked by the Pacific Ocean. Study by Clark et al (2003) demonstrated the strong correlation which exists between Indian Ocean

SST and East African short rains. The authors ascribe the pattern to reoccurring coupled ocean atmosphere phenomena (IOD) as described in pioneer study of Saji et al (1999). Kijazi and Reason (2005) examined the intraseasonal oscillations responsible for short term rainfall variability along the Tanzanian coast during ENSO years. From their study, they observed rain seasons starting earlier and ending considerably late during wet years while during the dry years, the rain seasons tend to start late and end earlier. Mapande and Reason (2005b) analysed the link between rainfall variability on intraseasonal scales over western Tanzania and the associated regional circulation. In their study, they found strong links between regional circulation patterns and rainfall over the unimodal area of western Tanzania.

In terms of interannual and seasonal scales, it has long been established that ENSO influences Tanzanian climate mainly during the October to December (OND) season (Kabanda and Jury, 1999; Indeje et al., 2000; Kijazi and Reason, 2005). Hastenrath et al (2007) found East African rainfall during the OND season to be related to the strength of the equatorial surface westerlies over the Indian Ocean and the zonal pressure gradient over the basin. Saji et al (1999) showed an East-West dipole mode in the Indian Ocean sea surface temperature (SST) anomalies that is coupled to the atmospheric zonal circulation. They also found IOD to have significant correlation with East African rains where the rainfall is increased during a positive event and decreased during a negative event.

Several other studies (e.g. Basalirwa et al, 1999; Indeje et al, 2000) have tried to delineate homogeneous rainfall region over East Africa and Tanzania in particular. Basalirwa et al (1999) performed principal component analysis and delineate Tanzania into 15 homogeneous rainfall regions based on the network of 150 widely distributed rainfall stations. Indeje et al (2000) performed another principle component analysis and simple correlation analyses using a network of 136 rainfall stations over East Africa.

Their analyses yielded 8 homogeneous rainfall regions over East Africa, among them, 5 were found in Tanzania.

Nicholson and Entekhabi (1986) have demonstrated the interannual variability of rainfall in much of Africa to be characterized by strong quasi periodic fluctuations in 2.2-2.4, 2.6-2.8, 3.3-3.8 and 6.0-6.3 years spectral bands. The author acknowledges the presence of other distinct quasi periodicities which are evident throughout equatorial and southern Africa. Study by Indeje and Semazzi (2000) found rainfall oscillates in East Africa to have dominant periodicity of between 1.7-2.5 years and 4-5 years, which appear to be related to quasi biennial oscillations and ENSO events respectively.

Study by Mpeta (2002) found that the convergence of the moist southeast and northeast trade winds which forms part of monsoon system of the western Indian Ocean to be the main determinant of rainfall over the tropical highlands of East Africa. Moreover, Sabiiti (2008) suggested that, westerlies from the Atlantic Ocean to have influence on rainfall over western part of East Africa. The author suggest the observed winds and rainfall over East Africa to be dependent mainly on the relative strength of the subtropical marine high pressure systems while the thermodynamic state of the adjacent Atlantic and Indian Oceans tend to determine the moisture flux.

§ 2.3 Impact of rainfall variability

Rainfall is the main source of water that is most vital for human life. In Tanzania, most of the economic activities depend directly or indirectly on it. It is an essential parameter in agriculture, climatology, hydrology, energy, transportation and recreation. It is also a major factor for planning and management of water resource project and agricultural production. Subsection below take a closer look on some of these sectors.

2.3.1 Agriculture sector

Agricultural sector which is the backbone of the economy of the country depends mainly on rain fed agriculture (Keenja, 2004; Kijazi and Reason, 2005), so unpredictability of rainfall has significant devastating effect to the economy of the country. Indeed, the sector is the major source of foreign exchange followed by tourism sector (Kweka, 2004). Report by Famine Early Warning System Network (FEWS NET, 2006) reveals that; poor rainfall distribution of 2005/06 season in unimodal areas of southern, southeast, central and western areas of Tanzania was the main cause of poor agricultural production. This poor season rainfall has also thwarted pasture growth and availability of pasture hence livestock sector also faced some difficulties. It has been estimated by Karekezi et al (2009) and SAGCOT (2011) that, the cost associated to this drought was about 1 percent of country GDP. Therefore, whenever there is unpredictable rainfall, the economy of the country tends to suffer severely.

2.3.2 Energy sector

Energy is essential ingredient for economic growth and social development of any nation. The growth of energy demand is often driven by several factors namely, population growth, economic growth, urbanization, rural energization programmes, increasing penetration of energy intensive appliances and industrialization. In Tanzania, energy sector depends heavily on Hydro Electric Power (HEP) generation and by the year 2008; over 50 percent of generated electricity was from Hydro (Karekezi et al, 2009). The country has installed Hydro electricity generation capacity of 561 MW (URT, 2007) but in recent years the turbines are not working in full capacity due to persistent drought which leads to power shortages. For instance, Karekezi et al (2009) reported the drop of 17 percent in hydropower generation in Mtera dam as the result of drought in the year 1997. Furthermore, the study which was done by Malley (2011) reveals that in between the year 1990 and 2008 there was water shortage in Mtera reservoir which led to electric power shortage. According to Matiku et al (2011) the worse scenario happened in 2006 where the threats of going into completely power blackout were clearly seen. During this time, the country was subjected to power rationing of up to 18 hours a day (Sosovele, 2010) as the result, country economy was halted due to leapfrogging price of goods and services. As the response to this emergency and to reduce the impacts of the national power crisis, the government opted into the exercises of hiring expensive alternative power sources. This process was followed by public criticism and attracted Matiku et al (2011) to make a follow-up on the whole process. The authors found indication of the process to be completely corrupt and involving some highly placed government officials. Up to now, the country is in debt burden which constrain the government budget for the socioeconomic development activities.

2.3.3 Tourism sector

Weather and climate have an important influence on the global tourism sector. For tourists, weather and climate are an intrinsic component of the vacation experience. Study by Scott et al (2008) reveals that, weather and climate is the central motivator in an individual's choice of holiday destinations and timing of travel, and can also be a salient factor in tourism spending and holiday satisfaction. In Tanzania where almost one third of its land is allocated to Natural Park, tourism is one among essential sector in economic growth given its ability to generate foreign exchange and employment (Kweka, 2004). Tourism impacts on the economy through tourist's expenditure on different goods and services. Thus, the tourist expenditures may be regarded as an inflow of foreign exchange that can lead to appreciation of exchange rate hence reduction of the domestic price of exports, which acts as a disincentive to exporters.

§ 2.4 Precipitation Index

So far there are several indices which have been developed and adopted to quantify wetness and dryness. Generally, most of them are based on the deviation of precipitation of a given period of time from the historically established mean. Among those indices, mostly used are Percent of Normal, Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Crop Moisture index (CMI) and Precipitation Temperature Index (PTI).

2.4.1 Percent of Normal

The Percent of Normal index is calculated by dividing actual precipitation, which is typically considered to be a 30 year mean and multiplying by 100 (Bordi et al, 2001) to get the percentage. Manatsa et al (2010) substantiate the index to be mostly used in the southern African countries as the monitoring tool of drought despite of its shortfall on effectively representing the earlier identified important drought magnitude. Computation of the index can be done in different time scale ranging from a single month to a particular season, or to a couple of years. The normal condition of precipitation for a specific area is considered to be 100 percent, while values less (greater) than 100 percent mean a dry (wet) condition.

2.4.2 Palmer Drought Severity Index (PDSI)

The Palmer Drought Severity Index was originally developed by Palmer in 1965 (Guttman, 1998; Lloyd-Hughes and Saunders, 2002), as a measure of dry and wet spells. It differs from the others indices which are based on precipitation data only, because it takes into account temperature, evapotranspiration, soil water moisture and runoff. The index computation needs the knowledge of precipitation and temperature monthly means as well as the temperature long term mean (usually calculated over 30 year period) and the soil water capacity. Abnormal wetness (positive values) as well as dryness (negative values) can be measured by the index ranging between +4 and -4 (Bordi et al, 2001) while persistently normal precipitation and temperature theoretically resulting in an index of zero in all seasons in all climates (Heim, 2002).

2.4.3 Crop Moisture index (CMI)

The Crop Moisture Index was developed by Palmer in 1968 to monitor week to week crop conditions using a procedure within the calculation of the PDSI (Bordi et al, 2001). It is based on the mean temperature and the total precipitation for each week. According to Heim (2002) the index was specifically designed as an agricultural drought and depends on the drought severity at the beginning of the week and the evapotranspiration deficit or soil moisture recharge during the week. It measures both evapotranspiration shortage (drought) and extreme wetness. Bordi et al (2001) suggest that, since the index was designed to monitor short term moisture conditions, the CMI may provide misleading information if used for long term conditions.

2.4.4 Precipitation Temperature Index (PTI)

More recently, Zhang et al (2011) have managed to develop PT index for southern China. The index measures the normalised difference between area averaged precipitation, temperature and normalised by their corresponding mean (Precipitation and Temperature) and their standard deviations. When the PT index value is high, it signifies that the year was dominated with high winter precipitation and low surface temperature, while low PT index value signifies that the year was dominated with low winter precipitation and high temperature.

2.4.5 Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) is the probability index which was developed by McKee et al (1993) to give better representation of abnormal wetness and dryness (Guttman, 1999). Since its development, the index have gained increasing acceptance in the United States and other parts of the world as a valuable tool for monitoring drought. It is currently being used by the U.S National Drought Mitigation Center, the Western Regional Climate Center, as well as the Colorado Climate Center (Edwards et al, 1997; Bordi et al, 2001; Manatsa et al, 2010). The index uses only precipitation data thus making the analysis possible even in the absence of other parameters.

The SPI is essentially a standardizing transform of the probability of the observed precipitation. It can be computed for a precipitation total observed over any duration desired by a user (1 month SPI, 3 month SPI, 6 month SPI, 12 month SPI , 24 month SPI etc); short term durations of the order of months may be important to agricultural interests while long term durations spanning years may be important to water resources management purpose because of the slow inherent responses in water bodies to rainfall changes (Guttman, 1998; Bordi et al, 2001; Heim, 2002; Manatsa et al, 2010). The method is capable of returning essential parameters after the analysis such as severity, magnitude, and frequency of the drought. Heim (2002) suggest that, although index was developed purposely for use in Colorado, the SPI can be applied universally to any location. Furthermore, Manatsa et al (2010) reveals the index to be temporarily and spatially comparable, independent of geographical and topographical differences, and even relevant in regions with diverse rainfall patterns.

CHAPTER THREE

§ 3.0 RESEARCH METHODOLOGY

§ 3.1 DATA AND METHODOLOGY

3.1.1 Data

Station rainfall data from Tanzania Meteorological Agency (TMA), gridded Kaplan SST anomaly, SST data from ICOADS, together with sea level pressure, zonal and meridional winds from NCEP/NCAR were used to study climate characteristics over southern highland Tanzania. The period 1970 to 2010 was chosen for the study because it was found that prior to 1970 there were few numbers of stations which were operating and many missing data were found on station rainfall data for existing stations. For climatological studies, this 41 years period is acceptable. A short description of the data follows in the next section.

3.1.1.1 NCEP/NCAR data

Kinematic and thermodynamic reanalysis data were downloaded (http://www.esrl.noaa.gov/psd) from the National Centre for Environmental Prediction (NCEP). The reanalysis project which is a joint project between National Center for Atmospheric Research (NCAR) and NCEP (Kalnay et al, 1996) aimed at producing a 40 year record of global atmospheric fields. The project involved recovery of land surface, ship, rawinsonde, pibal, aircraft, satellite and other data; quality control and assimilating the data with a system that was kept unchanged over the reanalysis period. This type of approach eliminates perceived climate jumps associated with changes in the data assimilation system. The data set were stored on a 2.5° latitude x 2.5° longitude boxes and consists of monthly mean from 1948 to date. Monthly mean zonal and meridional winds and sea level pressure (Table 2) were retrieved at two levels, i.e. 850 hPa and 200hPa from 1970 to 2010 to match with station rainfall data. NCEP/NCAR data has been used in numerous climatological studies in Tanzania, such as those of Mpeta (2002); Zorita and Tilya (2002); Mapande and Reason (2005a, b); Reason and Kijazi (2011) among others and yielded promising results.

3.1.1.2 Kaplan SST anomaly

Global analyses of monthly sea surface temperature (SST) anomalies was produced by taking the United Kingdom Meteorological Office Historical Sea Surface Temperature (MOHSST5) version of the Global Ocean Surface Temperature Atlas (GOSTA) data set as the input SST data set to various processing steps (Kaplan et al, 1998). These steps include EOF projection, Optimal Interpolation (OI), Kalman Filter (KF) forecast, KF analysis, and an Optimal Smoother (OS). Thus these techniques filled in any missing data using both spatial patterns derived from the data that exists together with time interpolation. The data set was stored on a 5° latitude x 5° longitude boxes and consists of monthly anomalies from 1856 to date. SST anomaly from 1970 to 2010 was retrieved to match with the station rainfall data obtained from TMA.

3.1.1.3 International Comprehensive Ocean Atmosphere Data Set

The International Comprehensive Ocean Atmosphere Data Set (ICOADS) is an extensive collection of surface marine gridded month data available for the world ocean extending from 1800 to date. ICOADS is a result of a continuing cooperative project in the National Oceanic and Atmospheric Administration (NOAA) specifically, its Environmental Research Laboratories (ERL), National Climate Data Centre (NCDC), and Cooperative Institute for Research in Environmental Sciences (CIRES, conducted jointly with the University of Colorado) and the National Science Foundation's National Centre for Atmospheric Research (NCAR). The parameter obtained from this data set was sea surface temperatures (SST). Mean enhanced monthly statistics were extracted from the Indian and Atlantic Oceans globally for the period 1970 to 2010 to match with rainfall station data obtained from TMA. In order to increase coverage, marine observations from ships, fishing vessels and surface oceanographic measurements were combined. The data was accumulated into 2° latitude x 2° longitude boxes from which interannual patterns were extracted for the Atlantic and Indian Oceans.

3.1.1.4 Station rainfall data

Station average monthly rainfall data of four regions (Iringa, Mbeya, Rukwa and Ruvuma) for 41 years (January 1970 to December 2010) were collected from Tanzania Meteorological Agency (TMA). The regions have 20 meteorological stations but only 16 stations which have been presented in Table 1 below were used in this study. Others stations have been omitted because of their limitation in number of time series and many missing data. Station monthly rainfall data were used to develop rainfall index and to study rainfall characteristics over the study area. The developed rainfall index which represents latitude 6°S-12° S and longitude 29°E-38° E was used to find correlation with the gridded SST, sea level pressure, zonal and meridional wind component.

§ 3.2 Methodology

In order to study rainfall characteristics over an area and at the same time to capture mechanisms which cause that characteristic, an index was developed to define rainfall over southern highland Tanzania. As it has been elaborated in chapter 2 above, SPI is one among the indices which have been widely accepted. By using this index, numbers of data are reduced and features associated with dry and wet situation throughout the study can be discovered. In order to understand the spectral characteristics of the resulting time series a wavelet analysis was done. Statistical association was also analysed using regression analysis. These methods are further described in the following section.

3.2.1 Standardized Precipitation Index (SPI)

The first step in calculating the SPI was to determine a probability density function that describes the long term time series of precipitation observations. The series can be for any time duration i.e. running series of total precipitation for 1-month, 2-months, 6-months, 12-months, 24-months, etc. Once the probability density function is determined, the cumulative probability of an observed precipitation amount is computed. The inverse normal (Gaussian) function, with mean zero and variance one, was then applied to the cumulative probability. The result is the SPI (Guttman, 1999). The departure from zero (positive or negative) is a probability indication of the severity of the wetness (positive value) or dryness (negative value) that can be used for risk assessment. The time series of the SPI can be used for drought monitoring by setting application specific thresholds of the SPI for defining drought beginning and ending times. Accumulated values of the SPI can be used to analyze drought severity.

3.2.1.1 Mathematical details of Standardized Precipitation Index (SPI)

The mathematical computation of SPI may be found in Guttman (1999), Bordi et al (2001) and Lloyd-Hughes and Saunders (2002) among others. Nevertheless, to make this study self-contained, the main steps for computation will be summarized. The SPI computation for a specific time scale and location requires a long term monthly precipitation record with 30 years or more and for this study, 41 years data were used. The probability distribution function is determined from the long term record by fitting a gamma function to the data. The gamma distribution is defined as

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \qquad \text{for } x > 0 \qquad (1)$$

Where

$\alpha > 0$ is a shape parameter,

$\beta > 0$ is a scale parameter,

x is precipitation amount and

$\Gamma(\alpha)$ is the gamma function.

The parameters of the gamma probability density function may be estimated from the data sample by means of a maximum likelihood method for each station, for each time scale of interest and for each month of the year. Thus, the following equation is obtained

$$\tilde{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right),$$

$$\tilde{\beta} = \frac{\bar{x}}{\tilde{\alpha}}, \qquad (2)$$

Where

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}, \qquad (3)$$

Here n is the number of observations in which some precipitation has occurred. Moreover $\bar{x}$, given a particular month, is the mean of the cumulative precipitation computed over all the same month in the record.

The resulting parameters are then used to find the cumulative probability of precipitation for the given month and time scale for the station considered. The cumulative probability, letting $= x/\tilde{\beta}$, becomes incomplete gamma function

$$G(x) = \int_0^x g(x)dx = \frac{1}{\Gamma(\tilde{\alpha})}\int_0^x t^{\tilde{\alpha}-1} e^{-t}dt \tag{4}$$

Since the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeros, the cumulative probability becomes

$$H(x) = q + (1 - q)G(x) \tag{5}$$

Where q is the probability of zero precipitation

$H(x)$ is then transformed into a normal variable Z by means of the following approximation

$$Z = SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right)$$

For $0 < H(x) \leq 0.5$ (6)

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right)$$

For $0.5 < H(x) \leq 1$

where

$$t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)} \quad \text{for } 0 < H(x) \leq 0.5 \tag{7}$$

$$t = \sqrt{\ln\left(\frac{1}{(1.0 - H(x))^2}\right)} \quad \text{for } 0.5 < H(x) \leq 1.0$$

And $c_0, c_1, c_2, d_1, d_2, d_3$ are the following constants

c_0=2.515517 d_1=1.432788

c_1=0.802853 d_2=0.189269 (8)

c_2=0.010328 d_3=0.001308

Hence, the SPI represents a Z-score variable and is normalised. At a given time, the SPI may be computed for different scales, say one month or longer, just computing the cumulative probability at a given location for the time scale selected. For the purpose of brevity of this study, a 'black box' software package was downloaded (http://www.drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx) and used for computation for which the input was rainfall data time series and the output was the SPI.

3.2.2 Regional SPI

To calculate the Regional SPI, aerial average stations 6-month scale SPI values for the month of April was taken. This 6 month scale counts from November of the previous year to April of the current year. Therefore, the first SPI to be obtained will be that of 1971 because it will start counting the 6 month from November of 1970 and ends at April of 1971. Specifically, Regional SPI is defined by

$$\text{Regional SPI}_y = \left(\frac{1}{N}\right)\sum_{i=1}^{N} SPI_y$$

Where N is the number of the regional stations operating in the year y (in this case N=16 and y=1971, 1972........2010). SPI values, Percentage of occurrence and nominal class descriptions have been presented in Table 3 below.

§ 3.3 Wavelet Method

Wavelet transform (WT) is an analysis tool which is appropriate for the study of multi scale, non-stationary processes occurring over finite spatial and temporal domains (Lau and Weng, 1995). This analysis is becoming a common tool for analysing localized variations of power within a time series. Therefore, with the ability of WT to resolve a time series within a time-frequency space, one is able to determine dominant modes of variability and how those modes vary in time (Torrence and Compo, 1998). A number of studies (Matari, 2002; Mpeta, 2002; Behera and Yamagata, 2003; Saji and Yamagata, 2003) have used this technique and have produced some interesting results. In this study therefore, Mexican hat wavelet analysis was used to decompose a number of time series into time frequency space. Time score from rainfall were analyzed to determine the dominant modes of variability and how these modes vary in time. The time-frequency space might provide a better picture in understanding the frequency and amplitude modulation within the period of measurement for parameter.

3.3.1 Mathematical details of Wavelet method

In this study, Mexican hat wavelet was used and below is the mathematical computation of it

$$\varphi(t) = (1-t^2)\exp(-t^2/2) \qquad (1)$$

Its Fourier transform is $\varphi(w) = \int_{-\infty}^{\infty} \varphi(t) e^{-iwt} dt$, the continuous wavelet transform of time series $f(t)$ is:

$$W_{a,b}(f) = \int_{-\infty}^{\infty} \varphi_{a,b}(t) f(t) dt \qquad (2)$$

Where, a is the Telescopic scale, b is the Translation factor, $W_{a,b}(f)$ is the Wavelet function. It can be proved that $\varphi(t) = -\frac{d^2 g(t)}{dt^2}$, at this point:

$$W_{a,t} = W_a f(t) = f \cdot \left[\sqrt{a^3} \frac{d^2 g_a}{dt^2} \right](t) = \sqrt{a^3} \frac{d^2}{dt^2}(f \cdot g_a)(t) \qquad (3)$$

In formula (3), $g_a(t) = 1/\sqrt{a}\, g\left[\frac{t}{a}\right]$, t is equivalent to b. Inverse wavelet transform can be written as:

$$f(t)=\frac{1}{C_r}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left[W_{a,b}(f)\cdot\varphi_{a,b}(t)/a^2\right]dadb \qquad (4)$$

Where C_r is constant. The relationship between the Disturbance scale (periods or wavelength) T and Telescopic scales (wavelet resolution scale) a is given by $T=3.974a$, and the relationship between Time scale L and Telescopic scale a is given by $L=a\pi/\sqrt{2}$. The wavelet variance:

$$W_a(P)=\int_{-\infty}^{\infty}\left|W_{a,b}(P)\right|^2 db \qquad (5)$$

This makes the trend of the coefficients of Mexican hat wavelet transform fit with the analyzed signals. The Wavelet transform for this case will be presented in contour map.

Table 1: Table showing names, station number and geographical position of sixteen meteorological stations found in between latitude 6°- 12° S and longitude 29°-38° E which have been used in this study to develop regional Standardized Precipitation Index (SPI).

No	Station Name	Station Number	Latitude (S)	Longitude (E)
1	Iringa Met Stn (Nduli)	9735013	7.60°	35.80°
2	Ludewa bomani	10034021	10.00°	30.40°
3	Njombe bomani	9934001	9.30°	34.80°
4	Iringa Experimental Stn	9735015	7.46°	35.41°
5	Kyela boma	9933010	9.35°	33.51°
6	Tukuyu Agric	9933002	9.10°	33.35°
7	Mitalula	9933017	9.23°	33.37°
8	Mbimba Coffee Research	9932005	9.40°	32.58°
9	Mbarali Irr. Scheme	9834008	8.40°	34.15°
10	Mbeya Met	9833001	8.56°	33.28°
11	Mpanda Boma	9631005	6.20°	31.50°
12	Kisanga hydromet	9736008	7.18°	36.47°
13	Namanyere-Nkansi	9731018	7.31°	31.30°
14	Sumbawanga Agric Stn	9731000	7.57°	31.36°
15	Tunduru Agriculture	10137000	11.60°	37.22°
16	Songea Airfield	10035010	10.40°	35.35°

Table 2: Table showing the parameters which have been used in this study to find correlation analysis with rainfall. Rainfall observed over an area is strongly influenced by these parameters and therefore they are the most important factor in studying climate of an area.

Parameter	Level used	Units
Sea Surface Temperature (SST)	Surface	°C
Sea Level Pressure (SLP)	Surface	hPa
Zonal wind (U)	850hPa and 200hPa	ms^{-1}
Meridional wind (V)	850hPa and 200hPa	ms^{-1}

CHAPTER FOUR

§ 4.0 RESULTS AND DISCUSSION

§ 4.1 Rainfall characteristics of Southern highland Tanzania

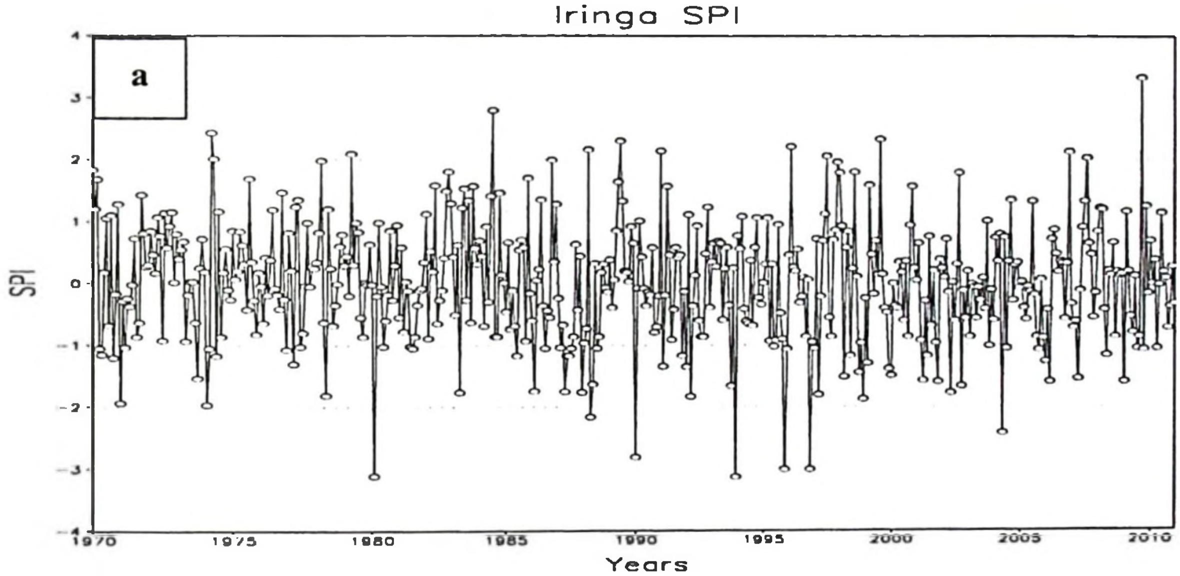
Rainfall characteristics in this study were done by the analysis of rainfall pattern through determination of Standardized Precipitation Index (SPI) over southern highland Tanzania. Figures 2 a, b, c and d below show the Standardized Precipitation Index (SPI) for one month for Iringa, Mbeya, Rukwa and Ruvuma region respectively. Observational study on these SPI figures shows substantial interannual variability of rainfall for each station. Moreover, some degree of persistence in rainfall anomalies can be seen from each station. To analyze this SPI results, a wavelet analysis was done for each region as described below.

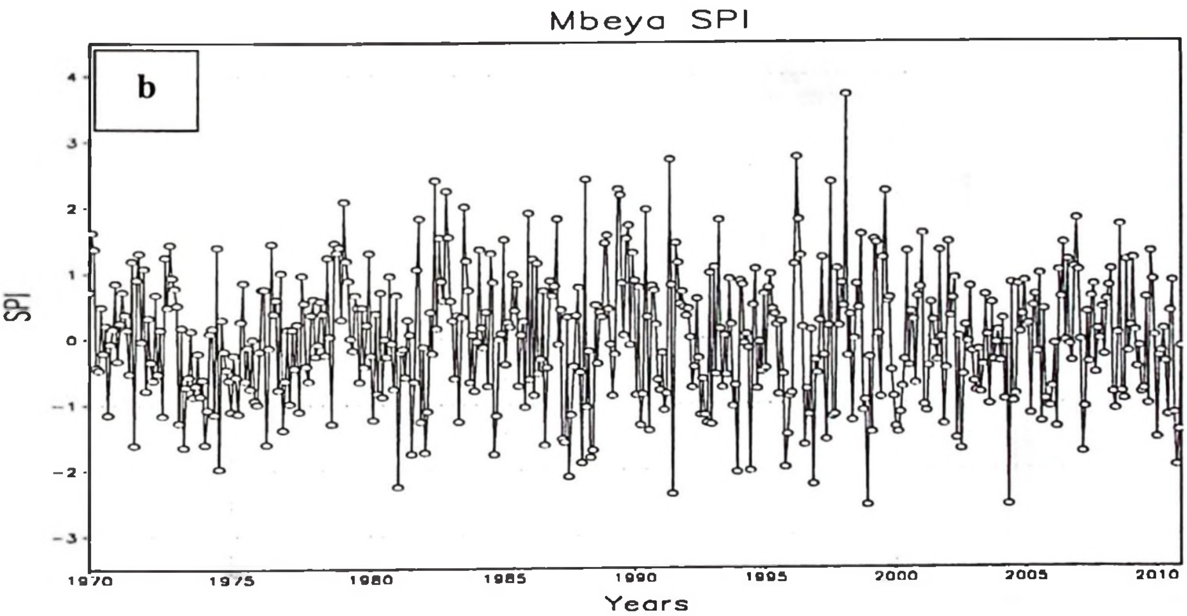
Figure 3a below is the wavelet representation of Iringa region SPI and the analysis shows the largest power at the time scale of 10 to 30 month particularly in the 1990s to 2000s, and also at 50 to 100 month throughout the record. In figure 4a which is also representing Iringa region wavelet analysis, there is series of purple (shaded) and white (unshaded) bands. The purple band represents rainfall of above normal while the white band represents rainfall of below normal. From figure 4a, it can be clearly seen that, the dominant periodicity mode of rainfall of above and below normal to be at the time scale of 2 and 7 years. The previous mode can be the result of the quasi biennial oscillation (QBO) and the latter mode can be the result of the El Nino Southern Oscillation (ENSO).

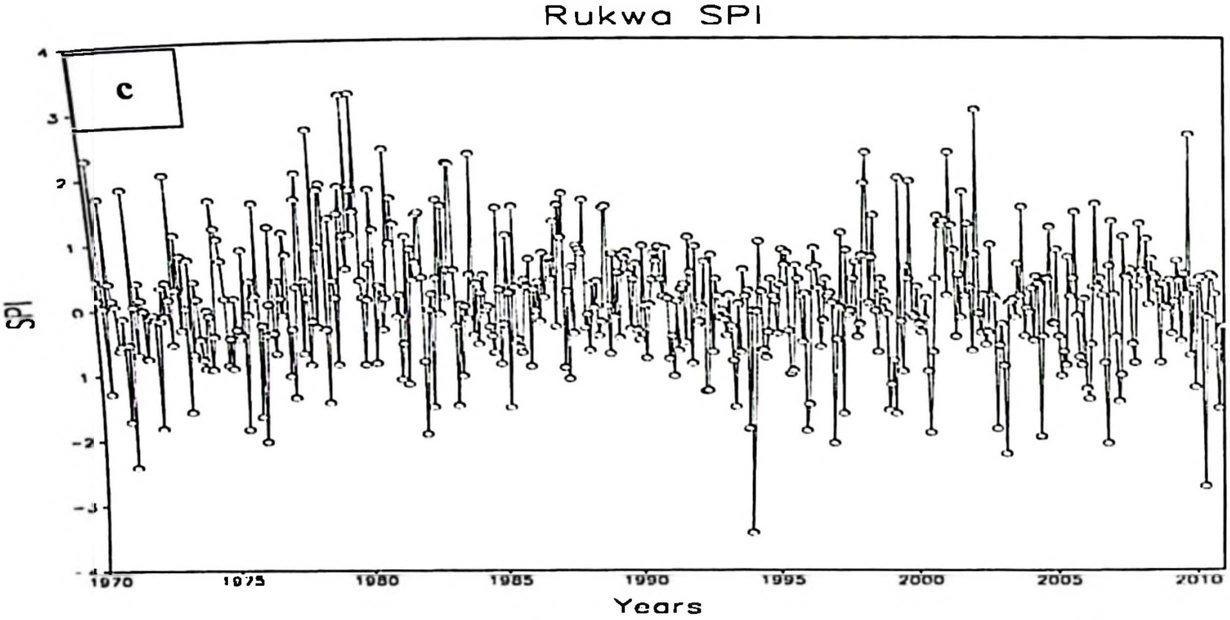
For the case of Mbeya region (Figure 3b) the largest power can be seen at the time scale of 10 to 40 month particularly in the 1975s to 1985s and 1995s to 2000s and also at the time scale of 60 to 80 month particularly in 1970s to 1990s. Figure 4b which is also Mbeya region wavelet analysis, there is series of purple (shaded) and white (unshaded) bands. The purple band represents rainfall of above normal while the white band represents rainfall of below normal. The dominant periodicity mode of rainfall of above and below normal can be seen at time scale of 3, 6 and 10 years. The main reason for this observed mode can be as the result of QBO, ENSO and quasi decadal oscillation (QDO) respectively.

The wavelet analysis for Rukwa region (figure 3c) reveals the largest power at the time scale of 10 to 40 month in the 1975s to 1985s and in the 1995s to 2005, and also at the time scale of 100 to 130 month throughout the record. Moreover on figure 4c, alternation of purple (shaded) and white (unshaded) bands can be seen. The purple band represents rainfall of above normal while the white band represents rainfall of below normal. The dominant periodicity mode of SPI of above and below normal is seen to be dominant at time scale of 3, 5 and 10 years which can be associated with QBO, ENSO and QDO respectively.

For the case of Ruvuma region (Figure 3d) wavelet analysis reveals the largest power to be dominant at time scale of 10 to 30 month in the 1985s to 1990s and in the 2000s to 2005s. Alternating purple (shaded) and white (unshaded) bands can also be observed in figure 4d with dominant periodicity mode of above and below normal at time scale of 3, 7 and 12 years. This mode can be the result of the QBO, ENSO and QDO respectively. Even though the magnitude of the departure from normal do differs for each region, the general result reflects the decrease in amount of rainfall recorded in between 1985 to 2010 compared to the period 1970 to 1984. The rainfall over these regions show the dominance periodicity mode in the time scale of 2-3, 5-7 and 10-12 years which can be associated with QBO, ENSO and QDO respectively. Similar results also have been shown by Mapande and Reason (2005a) for the period in between 1970 to 1999 which compromise with this research work.







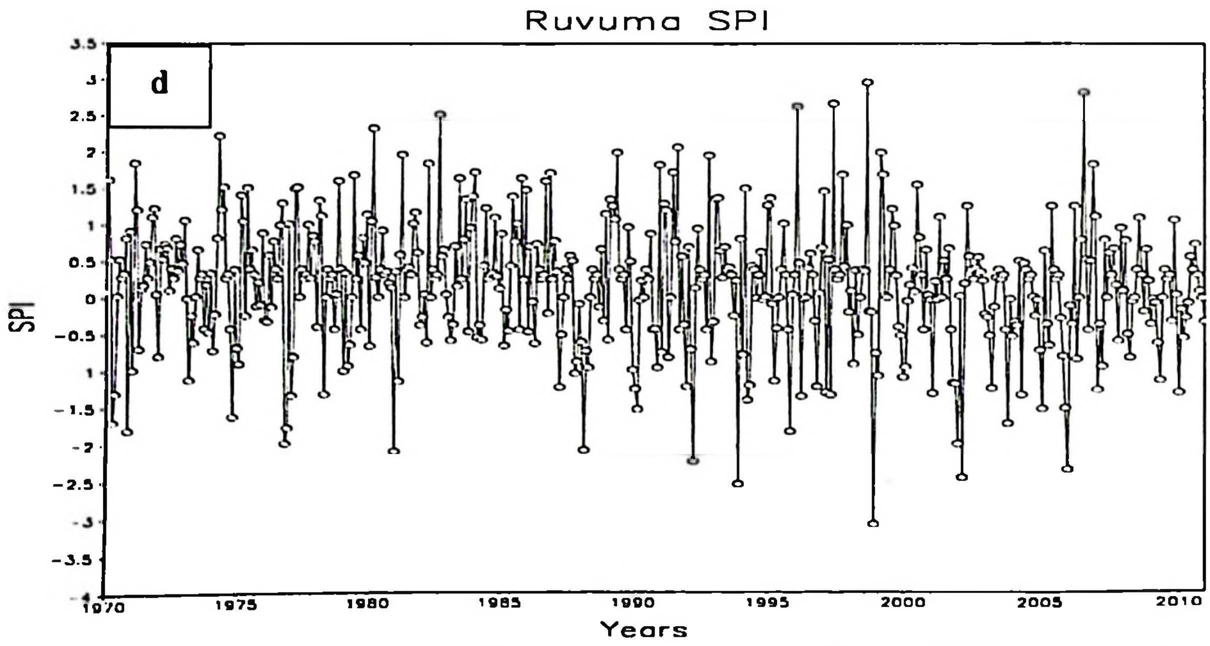
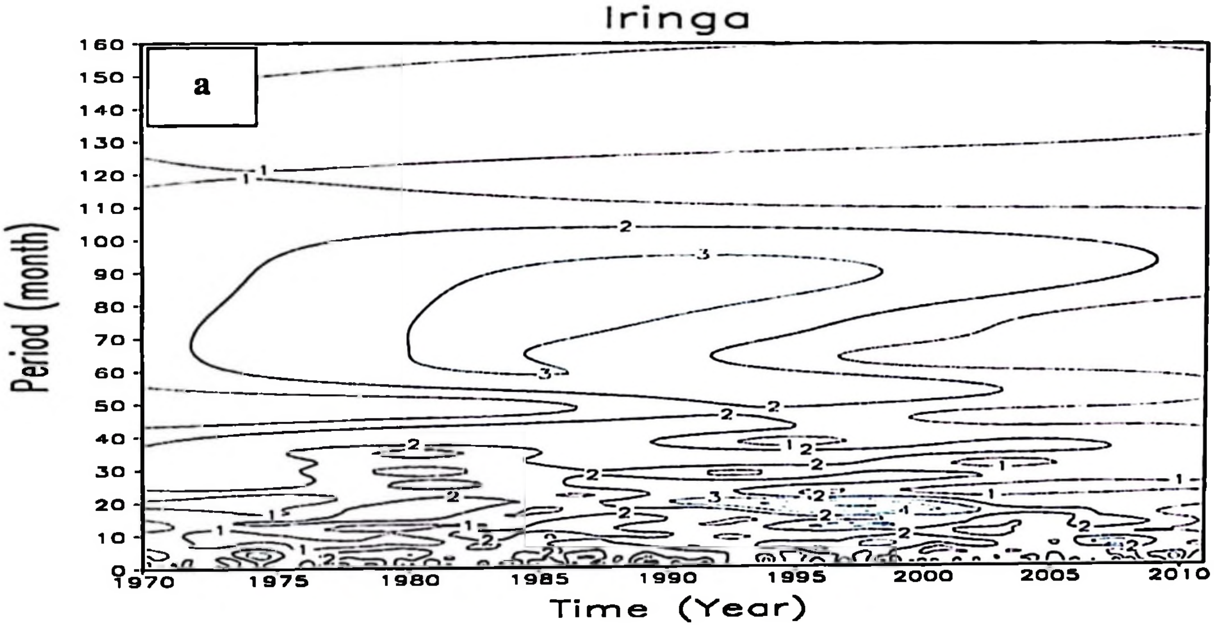
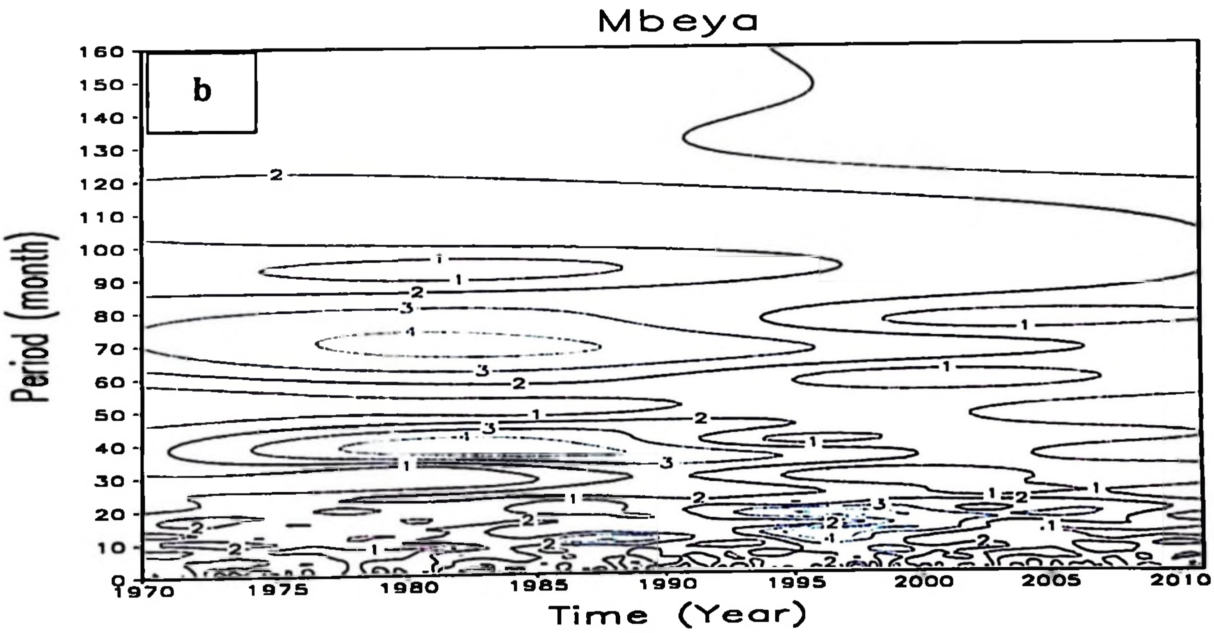
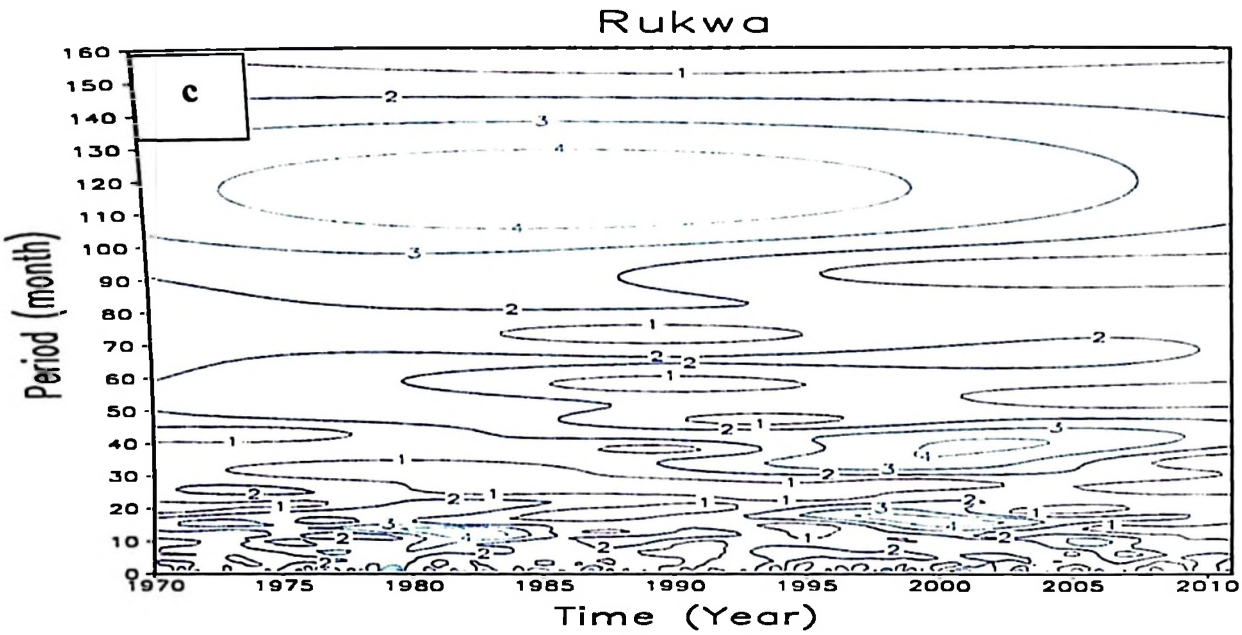


Figure 2: Schematic representation of Standardized Precipitation Index (SPI) for one month period from January 1970 to December 2010. The x-axis represents Years and y-axis represents amplitude of SPI value. The positive (negative) SPI value shows the rainfall of above (below) normal and the number is the magnitude of the departure from normal. (a) Iringa (b) Mbeya (c) Rukwa (d) Ruvuma region


Iringa
a
Period (month)
Time (Year)
1970
1975
1980
1985
1990
1995
2000
2005
2010


Mbeya
b
Period (month)
Time (Year)
1970
1975
1980
1985
1990
1995
2000
2005
2010



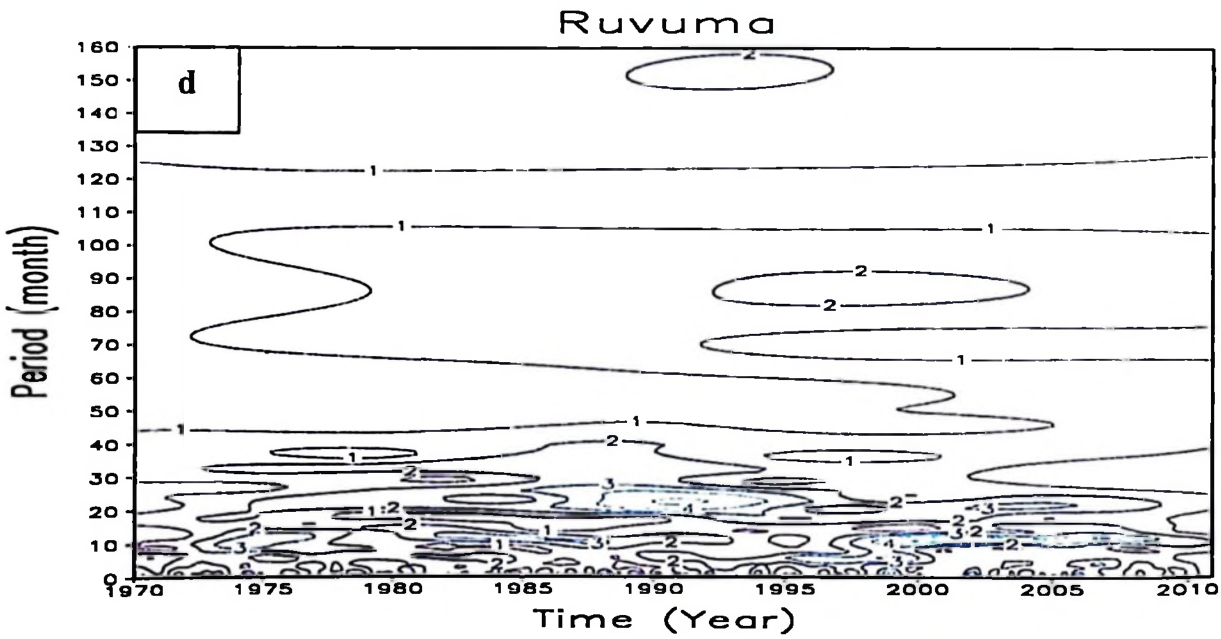
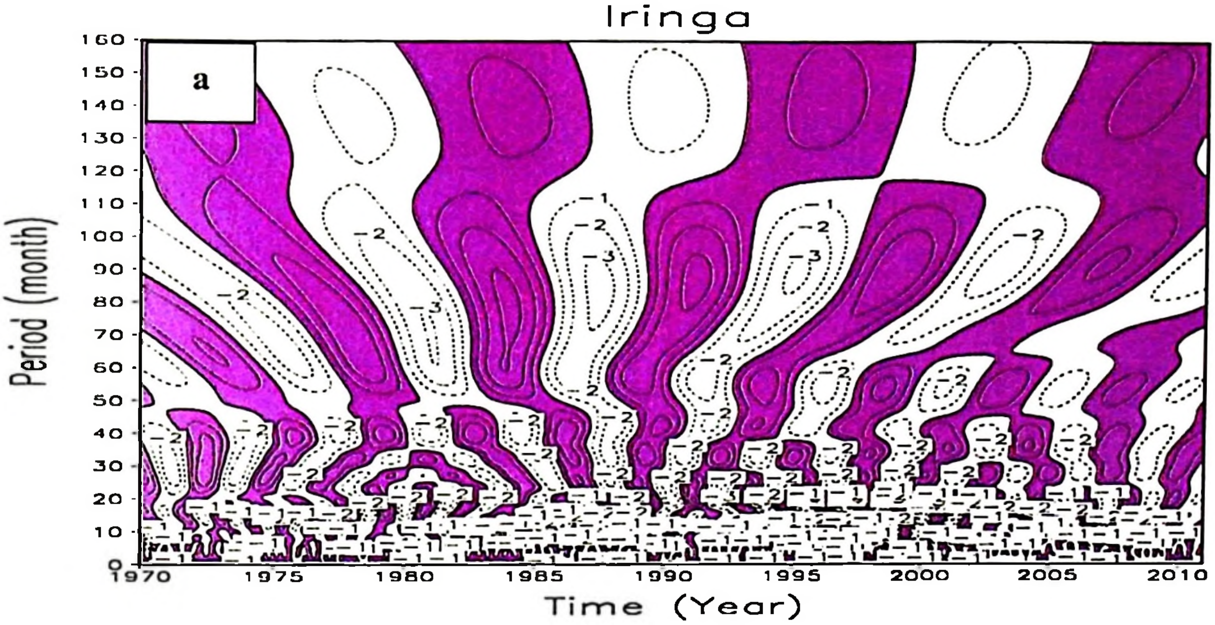
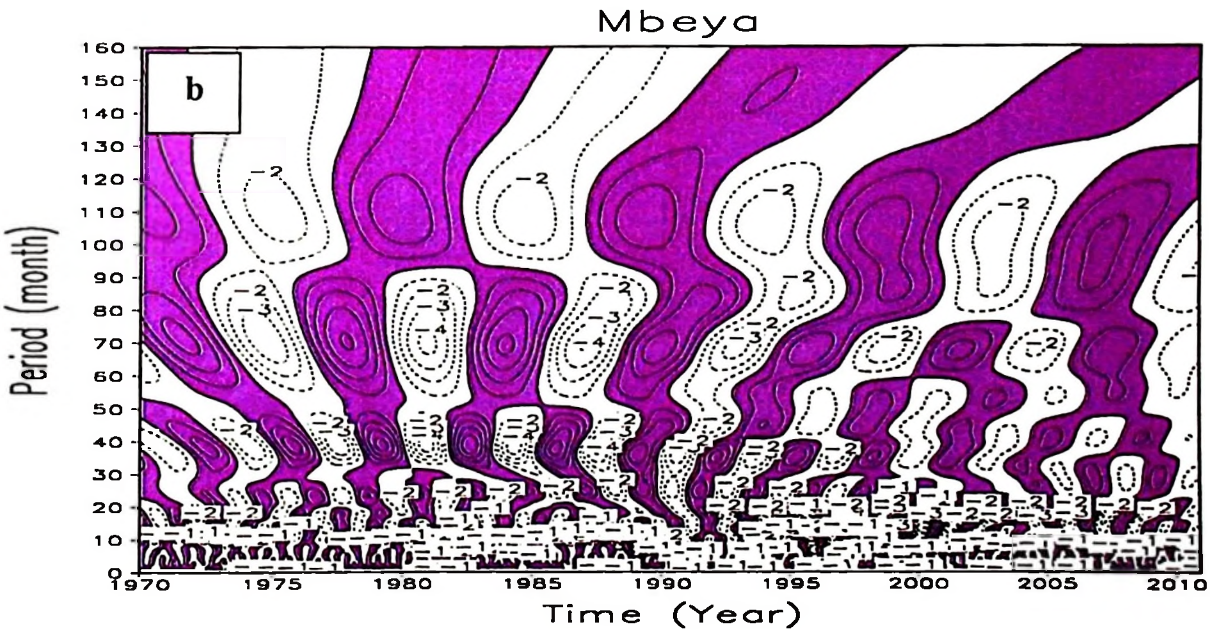
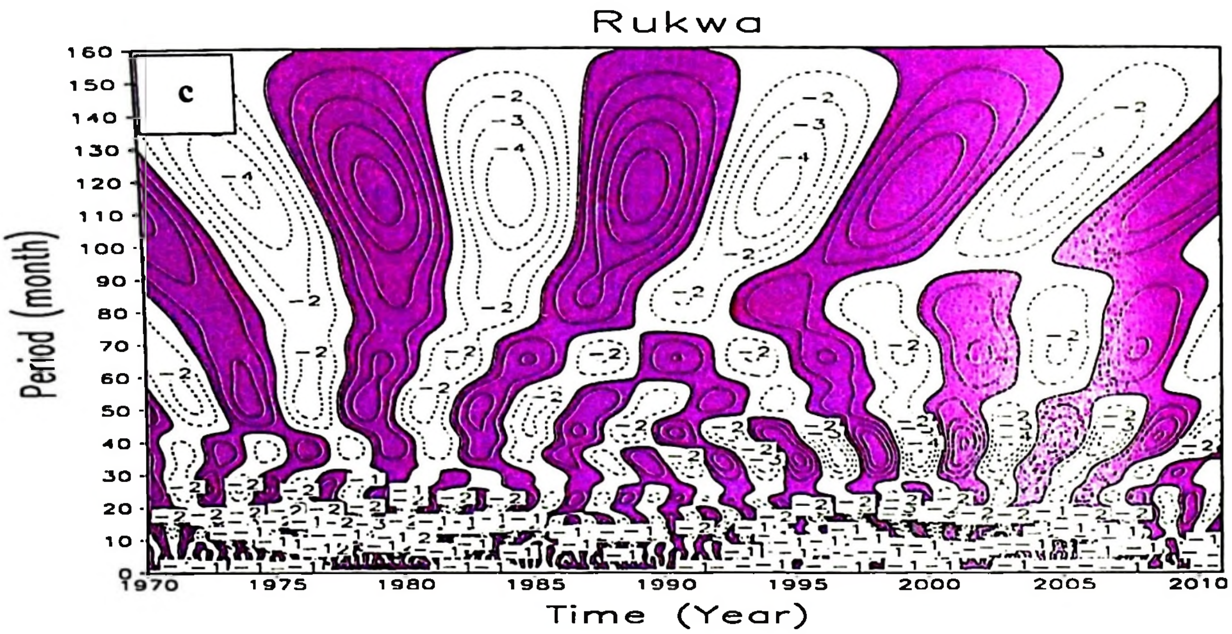


Figure 3: Wavelet power spectrum of Standardized Precipitation Index (SPI) for one month period from January 1970 to December 2010 showing largest powers found in each region during the study period. The x-axis represents Year and y-axis represents the period in Months where the largest powers fall. (a) Iringa (b) Mbeya (c) Rukwa (d) Ruvuma region


Iringa
a
Period (month)
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
Time (Year)


Mbeya
b
Period (month)
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
Time (Year)



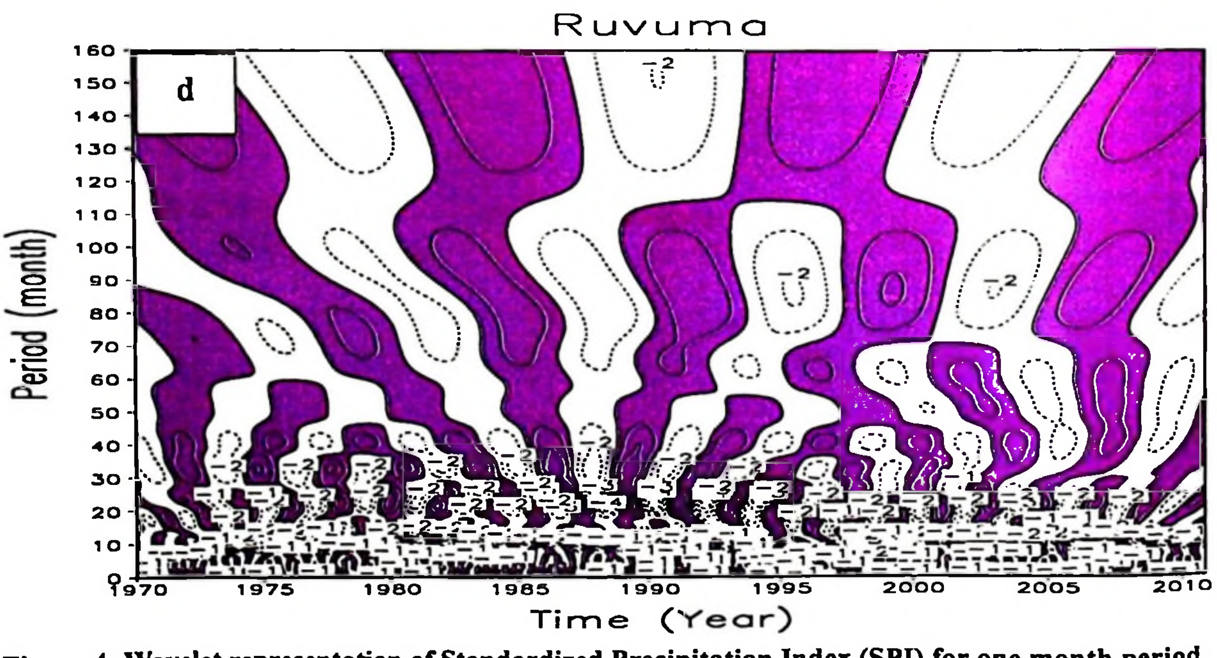


Figure 4: Wavelet representation of Standardized Precipitation Index (SPI) for one month period from January 1970 to December 2010 showing dominant periodicity modes found in each region during the study period. The x-axis represents Year and y-axis represents period in Months where dominant periodicity modes fall. (a) Iringa (b) Mbeya (c) Rukwa (d) Ruvuma region

§ 4.2 Regional Standardized Precipitation Index

In order to relate rainfall demand with practical applications, 6-month time steps of SPI for November to April rain season have been applied in this study. During these months is when the agricultural activities are taking place such as plowing and seed planting so the soil moisture demand is at maximum level, therefore relation of this period is done to mean rainfall amount. Most of the annual rainfall experienced in southern highland Tanzania occurs during this period, and as such, water availability for vegetation is determined primarily by the amount of seasonal rainfall alone. So this seasonal rainfall is the most important single factor for water availability in agricultural activities. The 6-month scale is not only suitable in this research work, but it is also the most common used time scale for regional agricultural drought. Other research works which used this time scale are like those of Ntale and Gan, 2004; Manatsa et al, 2010 among others. Moreover, other months which fall outside the growing period (May to October) will not be analyzed because the region during this period is normally virtual dry. In any case, the rainfall that falls within this period mostly goes to waste since crop growing is not undertaken during this period. Thus, 6-month SPI analyzed during this dry period may be misleading in the sense that large negative or positive SPI values may be associated with rainfall not very different from the mean. This is because during the dry periods, the mean total will be small, and hence, relatively small deviations on either side of the mean could have large negative or positive SPI values. Figure 5 below represent the regional SPI (Iringa, Mbeya, Rukwa and Ruvuma) for the duration of 6 month. The plot shows the departures in November to April from 1970/71 to 2009/10 seasons for the region where the year axis refers to the April month (i.e. For 1970/71 season, it represent November of 1970 to April of 1971) of a given season. Although there are some variations in magnitude of the anomalies for each year, the region is experiencing the normal rainfall as the SPI values are at the range of -0.523 to 0.523

values as indicated in Table 4 below.

In order to shed more light on the regional SPI, the wavelet power spectrum is used to reveal the rainfall characteristics of the region. Wavelet representation for the regional SPI presented in figure 6 below shows the largest power at the time scale of 4 to 8 years particularly in the 1970s to 1990s, and time scale of 2 to 4 years in the 1990s to 2005s. Figure 7 shows the series of purple (shaded) and white (unshaded) bands with numbers representing powers. The purple band represents rainfall of above normal while the white band represents rainfall of below normal. The dominant periodicity mode is seen at the time scale of 2 and 7 years which may be associated with the quasi biennial oscillation (QBO) and El Nino Southern Oscillation (ENSO). Similar results to this quasi periodic oscillation over the region have been presented by Nicholson and Entekhabi (1986); Indeje and Semazzi (2000) and Mpeta (2002) among others. Furthermore, figure 7 show above and below normal rainfall to be dominant between the year 1978s to 1991s and the year 1999s to 2010s respectively; consistence with results presented in Table 3. From this point of view, it can be forecasted that, for the next 2 to 7 years, the area will experience rainfall which is normal to below normal if the dominants modes which are causing this phenomenon will remain uninterrupted with other systems.

Inspection from the regional SPI value obtained, reveals that, the wettest season in record was that of 1978/1979 which can be classified as "Severely wet" (SPI value of 1.62) and the driest season was that of 1999/2000 which can be classified as "Moderate drought" (SPI value of -1.26) according to Manatsa et al (2010) classification presented in Table 4. Table 3 shows five (5) wettest and driest years in record for the region during the study period. Similar results have been shown by Mapande and Reason (2005a) and Ogallo (1993) for the period in between 1970 to 1999 and 1970 to 1993 respectively, for the period which compromise with this research work.

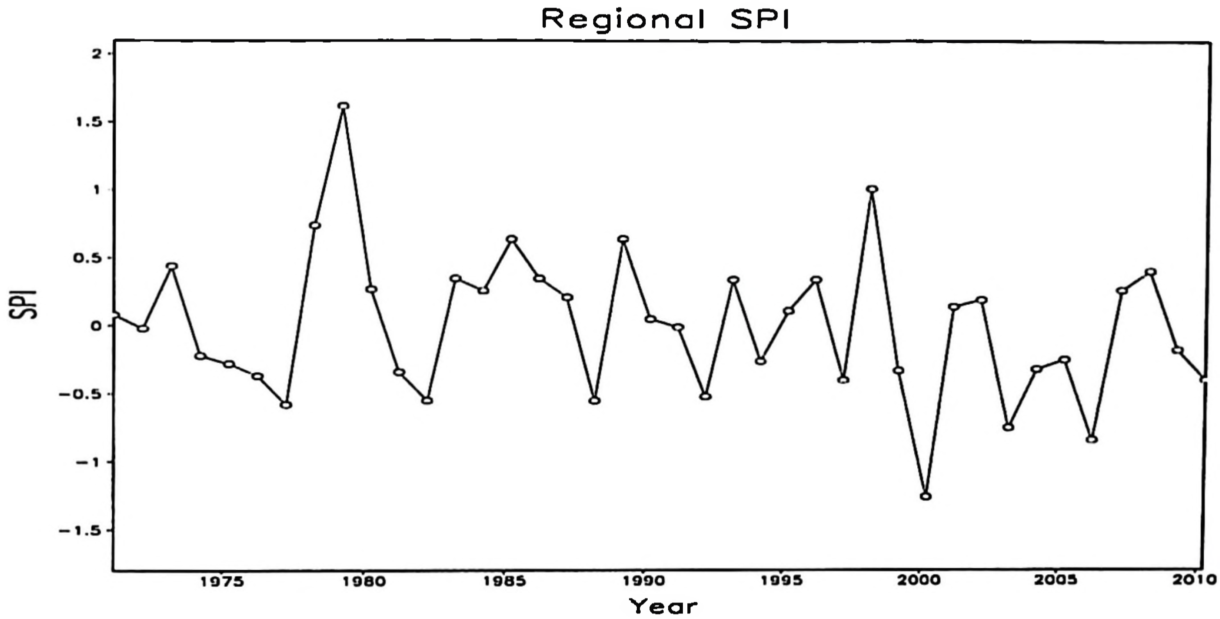


Figure 5: Schematic representation of Regional (Iringa, Mbeya, Rukwa and Ruvuma) Standardized Precipitation Index (SPI) for six month, November to April from 1970 to 2010. The period which fall outside this six month, May to October are not shown as they are normally dry. The x-axis is Year and y-axis is the amplitude deviation of SPI from normal. The positive (negative) SPI value shows the rainfall of above (below) normal and the number is the magnitude of the departure from normal.

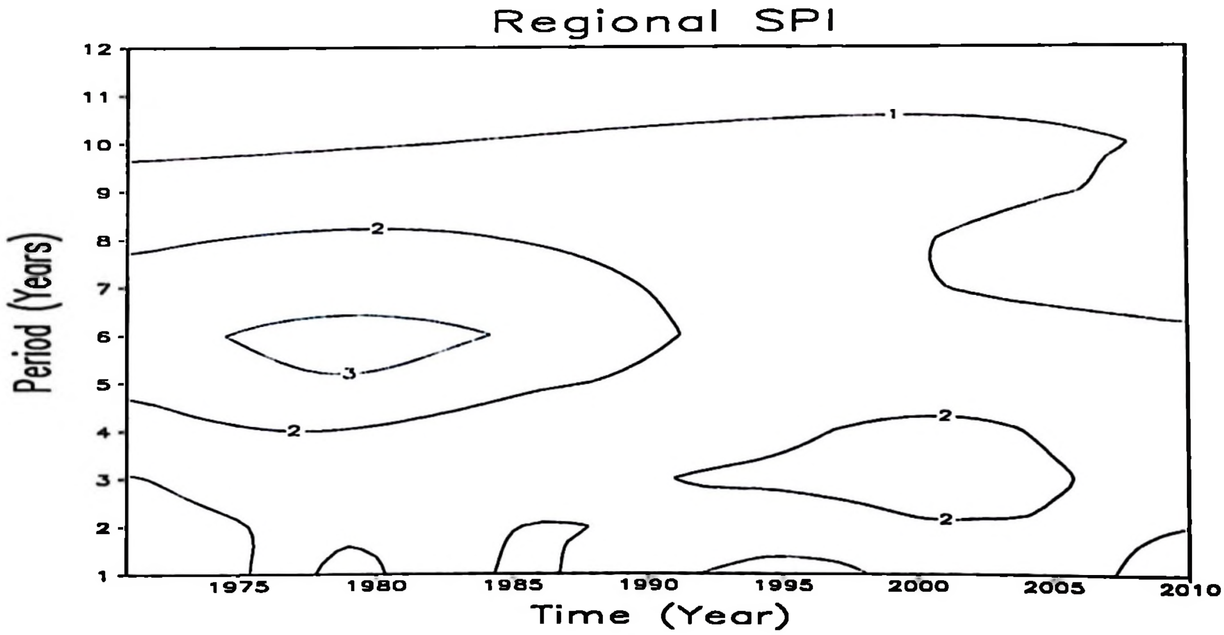


Figure 6: Wavelet power spectrum of Standardized Precipitation Index (SPI) for six month, November to April period from January 1970 to December 2010 showing largest powers found within the region (Iringa, Mbeya, Ruvuma and Rukwa) during the study period. The x-axis

represents Year and y-axis represents the period in Years where the largest powers fall.

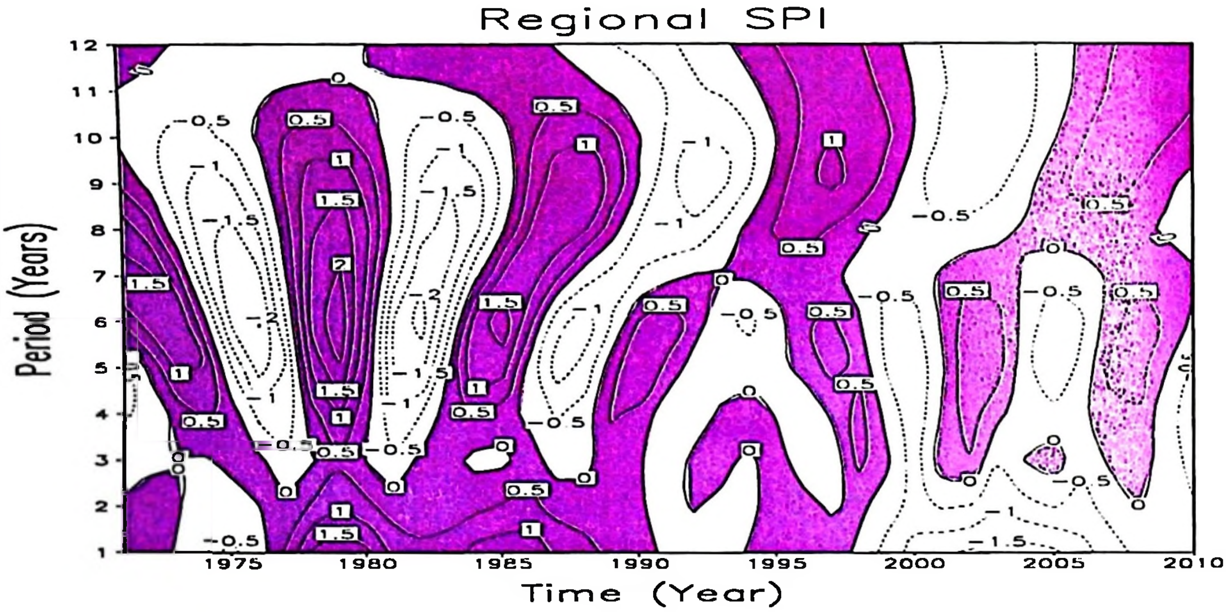


Figure 7: Wavelet representation of Standardized Precipitation Index (SPI) for six month, November to April period from January 1970 to December 2010 showing dominant periodicity modes found within the region (Iringa, Mbeya, Ruvuma and Rukwa) during the study period. The x-axis represents Year and y-axis represents period in Years where dominant periodicity modes fall.

Table 3: Table showing wettest and driest years in records for southern highland Tanzania during the study period of 41 year, from 1970 to 2010

No.	Wettest years	Driest years
1	1977/78	1976/77
2	1978/79	1987/88
3	1984/85	1999/00
4	1988/89	2002/03
5	1997/98	2005/06

Table 4: Table showing classification of SPI value and their corresponding event probability which are commonly used in southern African region adopted from Manatsa et al (2010).

SPI value occurrence	% Occurrence	Nominal SPI class
>1.645	≤5	Extremely wet
1.644 to 1.282	6-10	Severely wet
0.842 to 1.281	11-20	Moderate wet
0.524 to 0.841	21-33	Slightly wet
-0.523 to 0.523	34-50	Normal
-0.841 to -0.524	21-33	Slightly drought
-1.281 to -0.842	11-20	Moderate drought
-1.644 to -1.282	6-10	Severely drought
<-1.645	≤5	Extremely drought

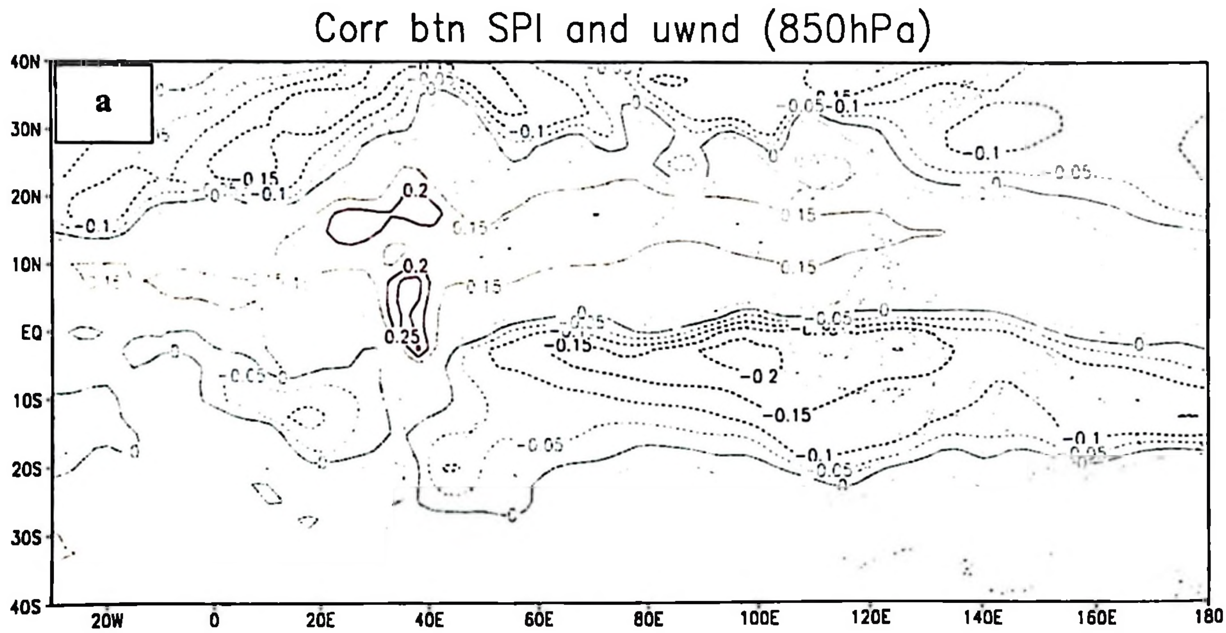
Table 5: Years of positive and negative IOD, and El Nino and La Nina adopted from Yamagata et al, (2002). Pure events are shown in bold i.e. no El Nino during positive IOD and no La Nina during negative IOD.

Years of positive IOD	Years of negative IOD	Years of El Nino	Years of La Nina
1972	1970	1972	1970
1977	**1989**	**1976**	1971
1982	**1992**	1982	**1973**
1994	**1996**	**1986**	**1975**
1997		**1991**	**1988**
		1997	**1999**

§ 4.3 Influence of general circulation and SST on rainfall patterns

4.3.1 Correlation analysis between SPI and Zonal wind

The influence of general circulation on the observed rainfall pattern over Tanzania was studied using regression analysis to verify if there is any association between SPI and global wind patterns. The regression analysis was done with wind patterns of different levels, the lower level wind, 850hPa and upper level wind 200hPa. At lower level 850hPa, the result shows that there is significant correlation between the northeasterly monsoon winds and the SPI at 99% level of significance (see Figure 8). Several other studies (Hastenrath et al, 1993; Mapande and Reason, 2005b) on the rainfall pattern over the region show the significance of these monsoon winds. Also parts of Arabian high, Benguela region, Mascarene high and St. Helena high shows significant correlation with SPI value at 95% level of significant. The westerlies winds over the western and central Indian Ocean have the negative correlation with the rainfall observed over the region at 99% level of significance. The upper level wind, 200hPa shows significant correlation at 95% level of significance only at Lake Victoria basin and negative correlation with the westerlies wind of the eastern Indian Ocean. Therefore, the development over western Indian Ocean followed by eastern Atlantic Ocean and the strength of northeasterly wind are main determinant of the amount and distribution of rainfall over the region.



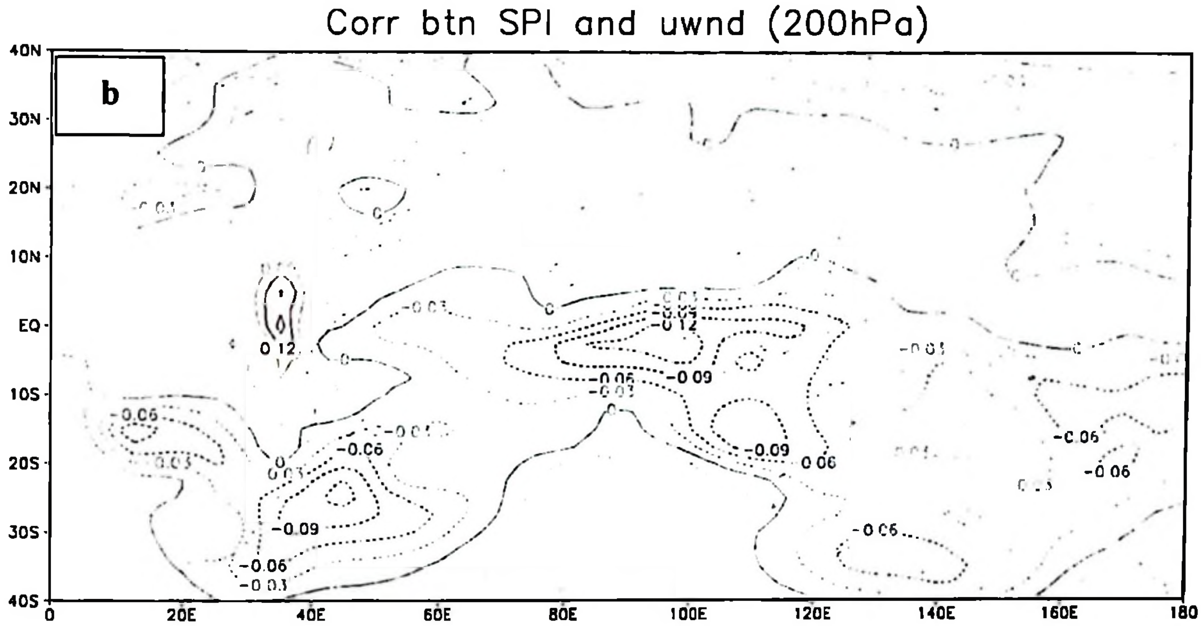


Figure 8: Schematic representation of correlation between the Regional Standardized Precipitation Index (SPI) value for one month and Zonal wind. The continuous (dashed) line shows the positive (negative) correlation coefficient at different levels. (a) Correlation between SPI and zonal wind at 850hPa level (b) Correlation between SPI and zonal wind at 200hPa level

4.3.2 Correlation analysis between SPI and SST

4.3.2.1 Correlation analysis between SPI and global SST

To reveal the association which exists between the rainfall recorded over the study area and SST over the key areas of Indian and Atlantic Ocean, correlation analysis is performed between the global SST and SPI. The 6-month regional SPI is used versus global six month average SST. Six different time lag (i.e. 0, 1, 2, 3, 4 and 5) comprising six month average SST was used versus regional 6-month SPI. Results from this correlation analysis show more likely the same key areas have significant correlation with the SPI. The key areas over the Indian and Atlantic Ocean which have significant correlation coefficient (r) at 90% level of confidence have been shaded and showed in figure 9 below. The key areas which have been identified and look to have significant influence on the rainfall over Tanzania lays roughly in between 5°S-18°S and 58°E

-70°E for the Indian Ocean and between 2°N-17°S and 5°W-10°E for the Atlantic Ocean. Summarized results for key areas with significant correlation at different time lag have been tabulated in Table 6 below. Closer monitoring of the local SST conditions of this part of the ocean can help in proper forecasting the rainfall condition over the study area.

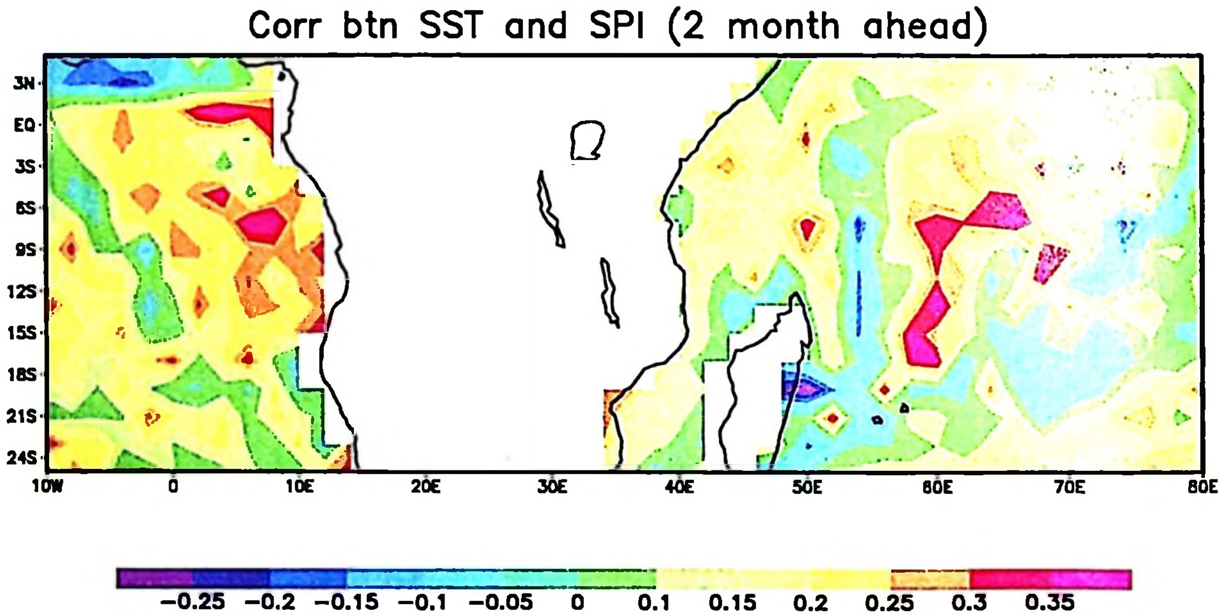


Figure 9: Correlation between 6-month regional SPI and global six month average SST. The SPI value is ahead by two month. Orange colour shows the areas with significant correlation at 90% confidence level.

Table 6: Identified key areas which have shown significant correlation at 90% level of significance between the global six month average SST (Indian and Atlantic Ocean) and regional 6-month SPI.

Key areas	Indian Ocean (Lat, Lon)	Atlantic Ocean (Lat, Lon)
Zero month time lag	(5°S-17°S), (58°E -65°E)	(3°N-10°S), (2°E-10°E)
One month time lag	(5°S-18°S), (58°E -70°E)	(3°N-10°S), (0°E-10°E)
Two month time lag	(5°S-18°S), (58°E -70°E)	(2°N-8°S), (1°E-10°E)
Three month time lag	(5°S-10°S), (60°E -70°E)	(2°N-10°S), (5°W-10°E)
Four month time lag	(5°S-15°S), (60°E -70°E)	(2°N-10°S), (1°E-10°E)
Five month time lag	(5°N-15°S), (60°E -75°E)	(2°N-17°S), (5°W-10°E)

4.3.2.2 Correlation analysis between SPI and IOD

To shed more light on the correlation between rainfall recorded over the region and SST over the Indian Ocean, SST data set as used in Saji et al (1999) who considered the IODZM as the anomaly difference between the SST anomalies of the western (50°E-70°E, 10°S-10°N) and eastern (90°E-110°E, 10°S-Equator) tropical Indian Ocean was adopted and used. The western Indian Ocean considered here is the same area which has been identified to have correlation with SPI in subsection above. The SSTs anomaly for the IODZM dataset (November 1969 to December 2003) was downloaded from http://www.jamstec.go.jp/frcgc/research/d1/iod/kaplan_sst_dmi.txt. The regional one month SPI for the same period, one and two month ahead was also prepared to match with this downloaded data. The correlation coefficient (r) between one month regional SPI and IODZM was found to be +0.178 for the same time and +0.158 for one month ahead, significant at 99% confidence level. For two month ahead, the correlation was +0.109, significant at 95% confidence level. This result suggests that, the rainfall amount and distribution over southern highland Tanzania is directly linked to local condition which are happening over Indian Ocean. Closely follow-up on the local variation of SST over this key area can help in forecasting the year to year rainfall variability.

4.3.3 Wind flow pattern and SST anomaly

4.3.3.1 850 hPa level and SST anomaly

The results presented to this point indicate that Atmospheric circulations over the Indian Ocean act as an important factor in influencing rainfall over East Africa. Study by Goddard and Graham (1999) reveal 850 hPa level to be most representative of the behaviour of the vertically integrated moisture flux over East Africa. This level was proposed for the purpose of reducing the effects of high grounds in some areas. Indeed, low level winds are of significant importance as the convergence of these winds may result in the development of clouds and precipitation when enough moisture content is present (Mpeta, 2002). Thus, the data from 850 hPa were used as most representative of the behavior of the low level winds in this region. Wettest (1997/1998) and driest (1999/2000) years were selected from Table 3 to study the dominant moisture patterns and SST anomaly. Monthly plots corresponding to the approximate beginning, peak and end periods of the rainy season over southern highland Tanzania in November, February and April are shown. The other months which tend to show anomalies that are a transition between those for November and February, and between February and April respectively, are not shown for brevity.

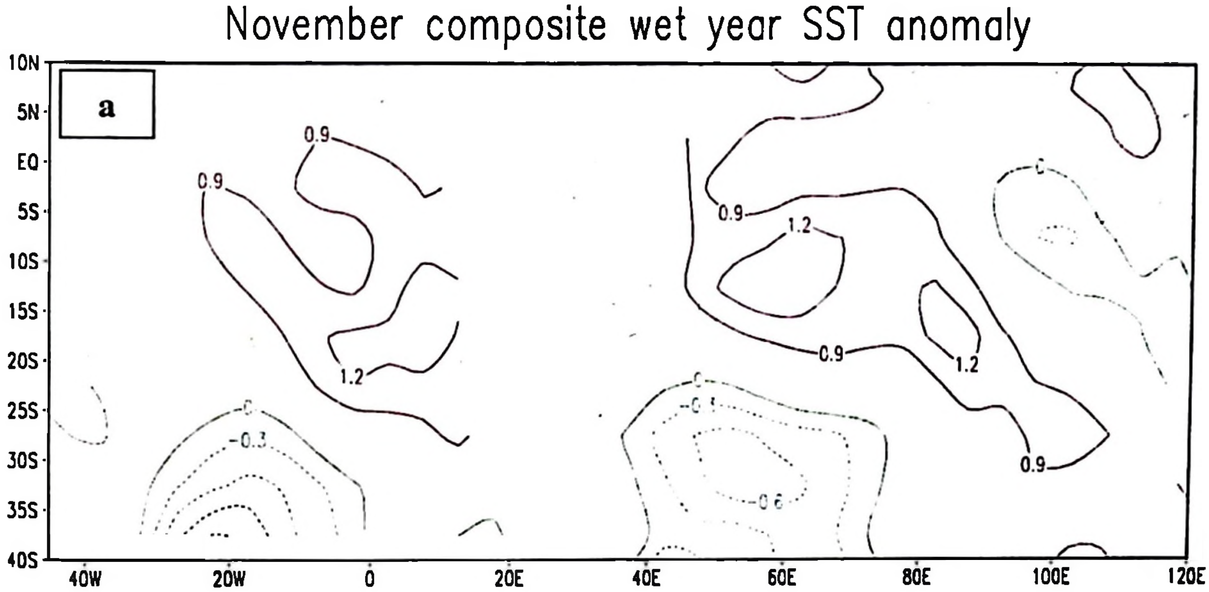
In November, the beginning of the rain season of the wet year (Figure 10a) indicates anomalously positive SST anomalies over the western Indian Ocean, particularly at the northeastern part of Madagascar. Study by Webster et al (1999) reveals the same trend and suggest that, the development of this anomalous warm SST anomaly in western Indian Ocean started in June 1997 and reached its maximum in February 1998 (Figure 10b). At about the same time, the eastern Indian Ocean developed a strong negative SST anomaly starting in July 1997 and reached a maximum in November 1997 (Figure 10a). This SST anomaly pattern is evocative of the subtropical South Indian Ocean SST dipole pattern suggested by Saji et al (1999); Behera and Yamagata (2001) and tends to influence southern African summer rainfall. Over the Atlantic Ocean, positive SST anomalies are observed in the Gulf of Guinea, Namibia and Angola coast. Several studies (Florenchie et al, 2003; Mapande and Reason, 2005b) suggest that these positive SST anomalies are evocative of Benguela Nino in the tropical and southeast Atlantic Ocean. The Benguela Nino is often associated with floods in Angola and Namibia and abundant rainfall in the usually arid Namib Desert (Florenchie et al, 2003; Rouault et al, 2007).

Simulated moisture patterns in November, the beginning of rain season of the wet year indicate that there is enhanced northeasterly and easterly moisture flux convergence (Figure 11a) hence increasing moisture penetration in Tanzania. This observational is consistent with previous studies (Goddard and Graham, 1999; Mpeta and Jury, 2001) which observed the same trend during the wet years. Also there is presence of enhanced cyclonic flow over northern Namibia which induces an increased flow of moist air. As a result, increased low level moisture convergence is expected over northern Zambia and southern highland Tanzania. Another moisture source for East Africa is the tropical East Atlantic Ocean. Anomalous westerlies from East Atlantic and Congo basin (Figure 11a) oppose the easterly flux that exists at this time of year from the Indian Ocean. As a result, relative convergence of low level moisture occurs over western Tanzania, Uganda and northern Zambia.

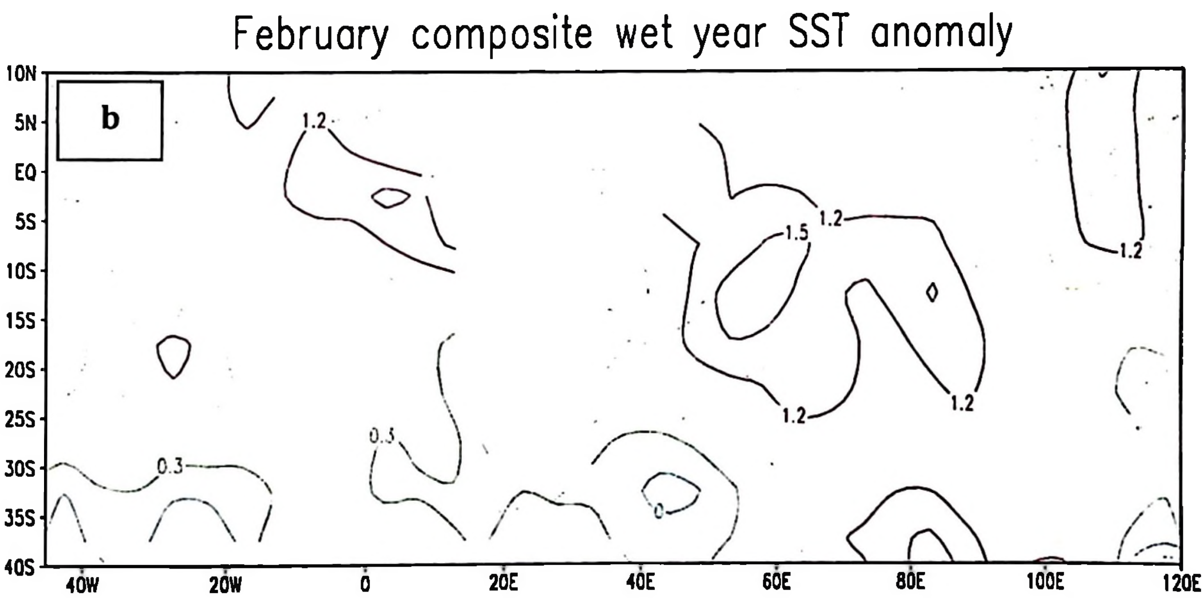
In February, during the peak of the rain season of the wet year (Figure 10b) anomalously positive SST anomalies is enhanced all over the tropical western Indian Ocean. Warmer SSTs near the Tanzanian coast act to increase the local evaporation, and hence the low level moisture over the land. Simulated moisture pattern during this period indicates that the northeasterly wind has enhanced and it penetrates further south (figure 11b). A second source of moisture which is westerly wind from Atlantic ocean and Congo basin have also strengthened therefore transporting more moisture into great lake region and northern Mozambique (Figure 11b). Two cyclonic centers can be seen due to recurving of northeasterlies to southwesterlies, one over northern Namibia and another over the Mozambique Channel. Observations show that, the lower tropospheric anticyclonic anomaly over the tropical south Indian Ocean is stronger than November when the rain season started. Study by Mapande and Reason (2005b) suggest this anticyclonic circulation feature in November and February to be possibly part of the local atmospheric response of cool SST anomaly in the tropical south Indian Ocean.

Moreover, tropical Indian Ocean is seen to be dominated by easterlies during this peak season as the result of warming of the SST in the West and cooling in the East Indian Ocean (Behera and Yamagata, 2003). Taken together with this, the extreme continental southward location of ITCZ between Tanzania and central Mozambique during December and February (Ogallo, 1993; Goddard and Graham, 1999; Indeje et al, 2000; Behera and Yamagata, 2001), suggests a substantial rainfall over southern Tanzania to be recorded during this period.

Towards the end of the rainy season in April, cyclonic moisture flux anomalies (Figure 11c) emerge over the tropical equatorial western Indian Ocean consistent with the small warm SST anomalies (figure 10c) in those regions. The anomalous positive SST anomaly in Indian Ocean is seen to shift toward the eastern side of the Ocean. The presence of strong southeasterly moisture flux which is fed by south western Indian Ocean region suggesting that strong moisture is fetch toward East Africa and Congo basin. Such conditions are favorable for ongoing wet conditions over southern highland Tanzania during this month.



November composite wet year SST anomaly
a
10N
5N
EQ
5S
10S
15S
20S
25S
30S
35S
40S
40W
20W
0
20E
40E
60E
80E
100E
120E
0.9
1.2
-0.3
-0.6



February composite wet year SST anomaly
b
10N
5N
EQ
5S
10S
15S
20S
25S
30S
35S
40S
40W
20W
0
20E
40E
60E
80E
100E
120E
1.2
1.5
0.3

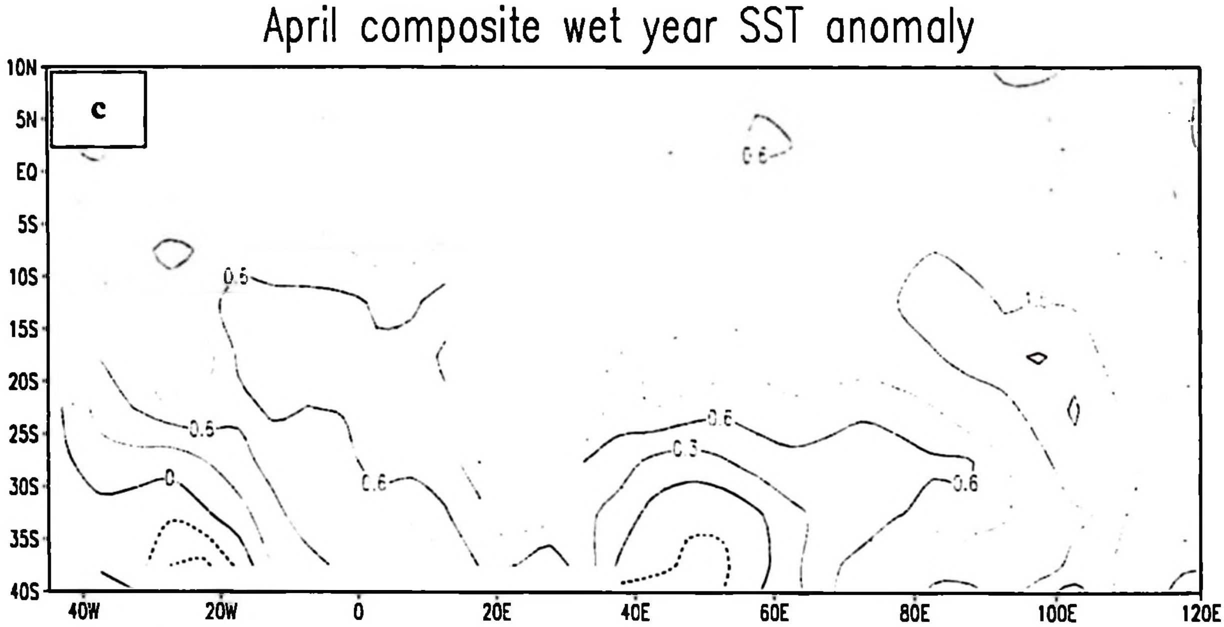
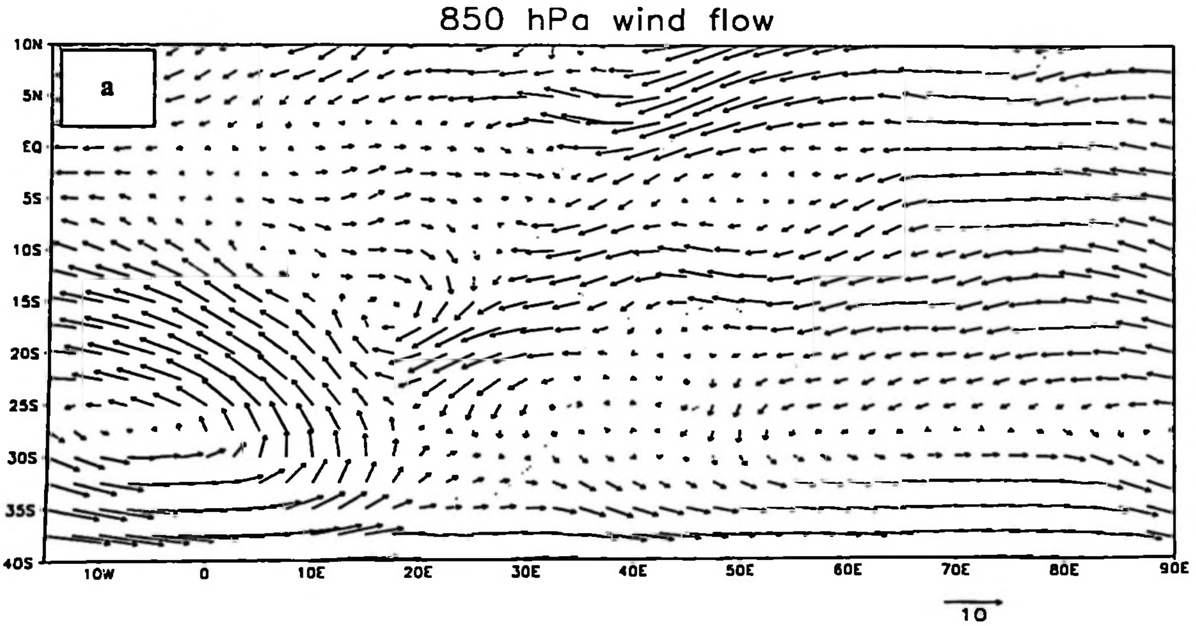
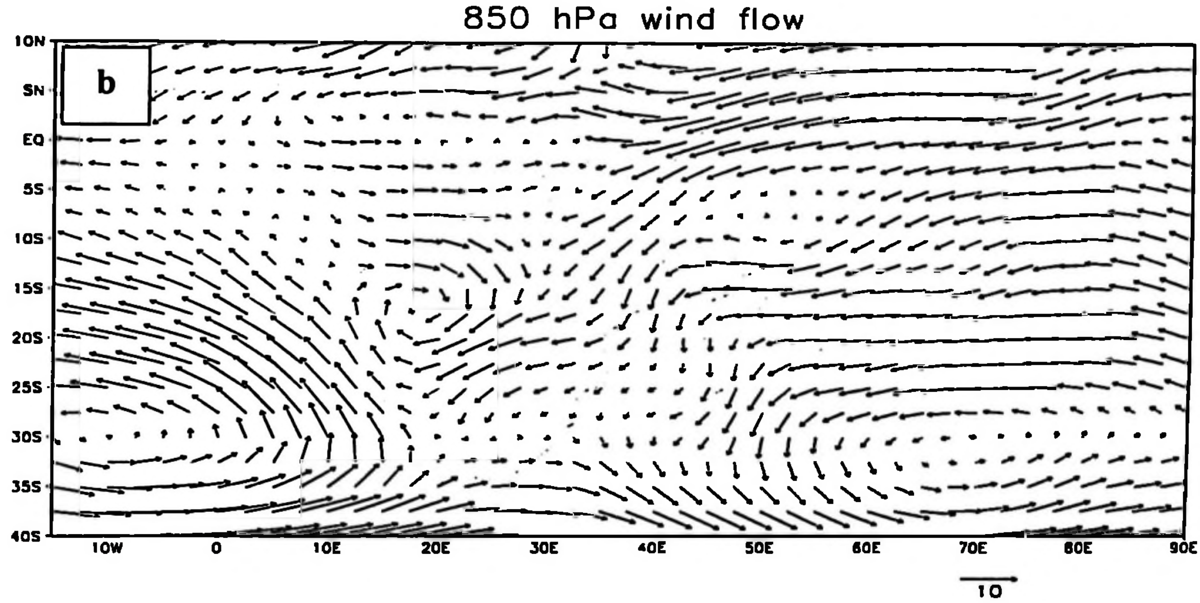


Figure 10: Composite SST anomaly during rainy season of wet year of the 1997/98 in the Atlantic and Indian Ocean in different time. (a) November, 1997 during the beginning of rain season (b) February, 1998 during the peak of the rain season (c) April, 1998 near the end of rain season





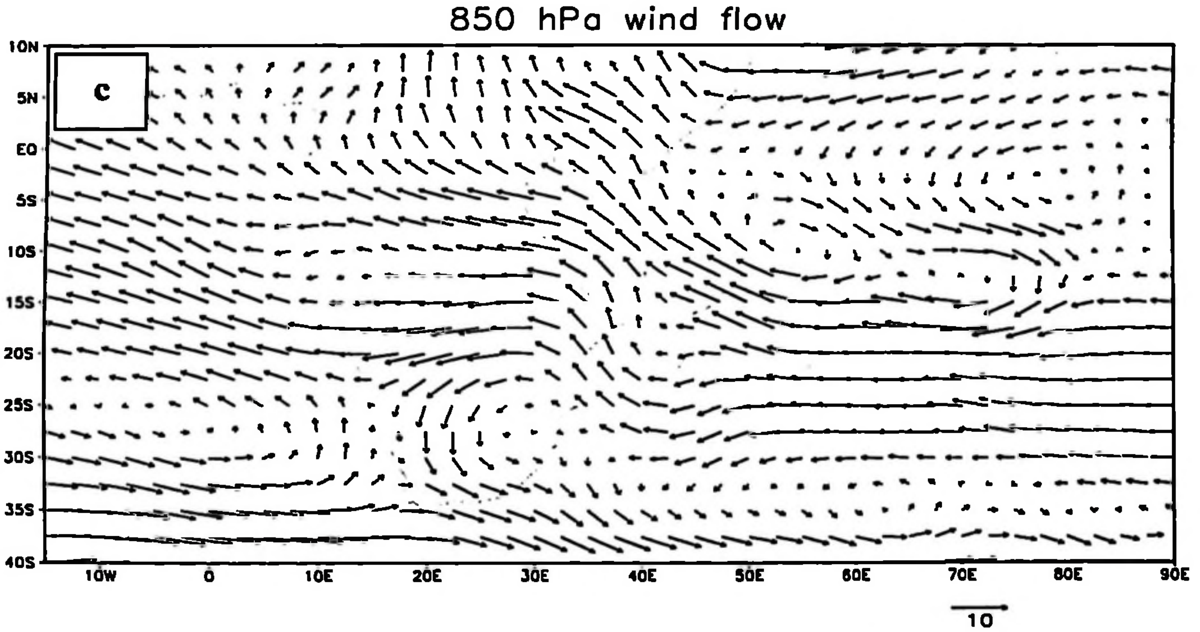
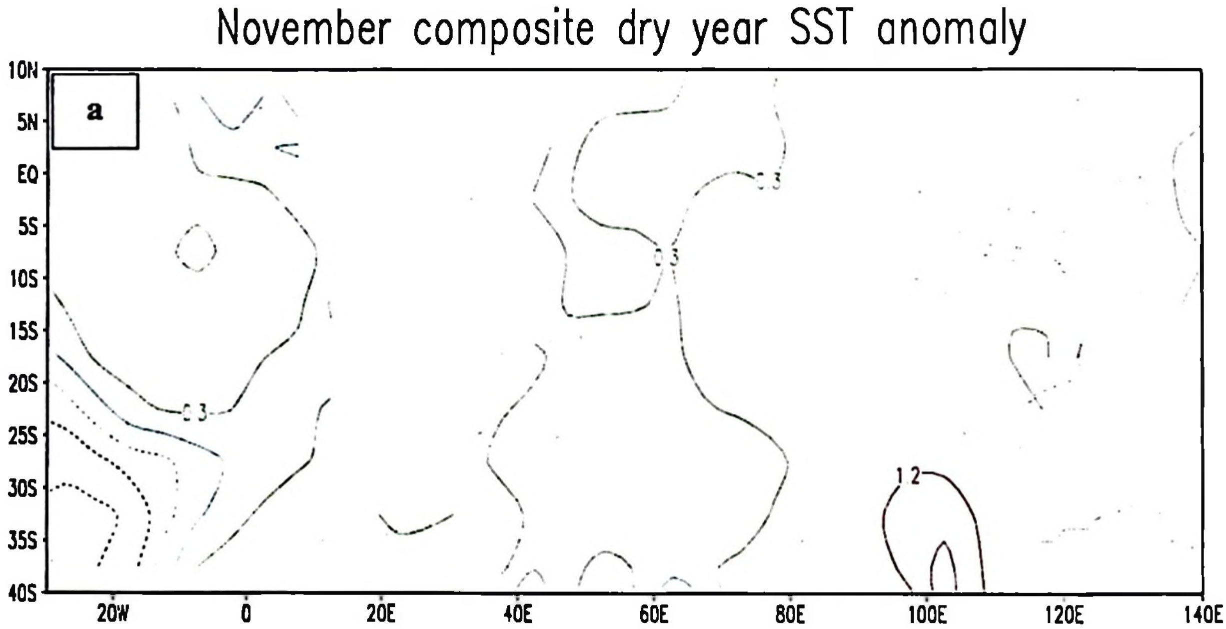


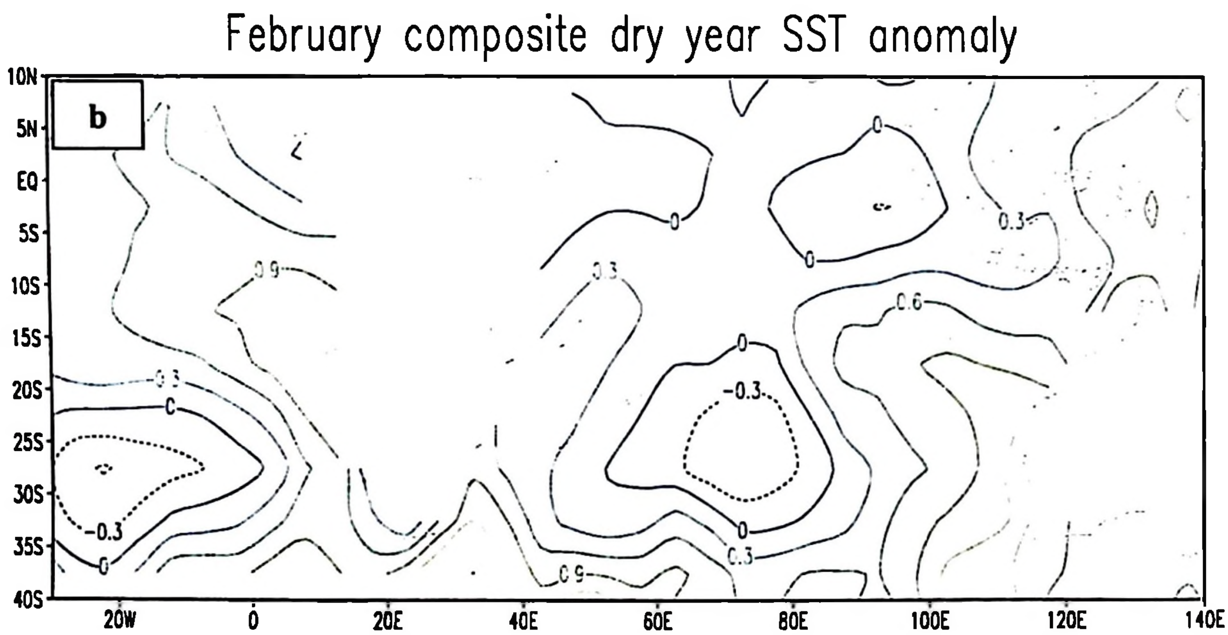
Figure 11: Simulated moisture pattern during rainy season of the wet year of 1997/98 at 850 hPa level (ms^{-1}). (a) November, 1997 during the beginning of rain season (b) February, 1998 during the peak of the rain season (c) April, 1998 near the end of rain season.

During dry year of 1999/2000, simulation of 850 hPa level wind pattern show the equatorial westerlies and south Indian Ocean trade winds are reversed from those of wet scenario described above for 1997/1998. In November, during the beginning of the rain season of the dry year (Figure 12a) indicates anomalously positive SST anomalies in eastern Indian Ocean, while the western part is dominated by near normal SST. The same scenario can be seen over eastern Atlantic Ocean where near normal SST is observed. The inverse is true for the wet scenario discussed above (Figure 10a). Simulated moisture pattern during the beginning of rainy season of the dry year is dominated by northeasterly and weak easterly wind (Figure 13a). A weak cyclonic flow is seen to develop at the western Indian Ocean due to the SST anomaly at this region of the ocean. Also there is westerly wind observed at the tropical center Indian Ocean which denies moisture transport to Tanzania as the result of turning southeasterly wind. In February, during the peak of the rain season of the dry year (Figure 12b), anomalously negative SST anomalies is developed over south western Indian Ocean. Simulation moisture flux at this period indicates a lower tropospheric anticyclone flow over western Indian Ocean right at Tanzania coast and cyclonic flow near northern Namibia (Figure 13b). The northeasterly moisture flux anomaly over the western Indian Ocean turns more north and south due to the presence of anticyclone thereby denying inland penetration of moisture into the mainland Tanzania. Not only that, but also there is strong westerlies wind which is seen over the western Indian Ocean which have been developed due to this anticyclone. In comparison to the scenario of the wet year (Figure 11b), there is a stronger divergence of moisture from the Indian Ocean during this period. The same observations have been reported by Hastenrath et al (2007). Over the Congo Basin, the easterly moisture flux is also turning northward different from the case seen during wet year (Figure 11b) thus, further export of moisture away from the region. Little moisture found in Tanzania is also exported to Madagascar by northeasterly and westerlies wind. As it was the case for the wet scenario, two cyclonic centers can be observed as the result of recurving of northeasterlies to southwesterlies, one over northern Namibia and the other over the Mozambique Channel.

In April, near the end of the rainy season of the dry year (Figure 12c), positive SST anomaly emanate at southwestern Indian Ocean which led to development of anticyclone flow. Simulation of the moisture flux indicates the easterly over southwestern Indian Ocean (Figure 13c) turns more southerly due to development of this anticyclone. On the other hand the northeasterly turn more north over the East Africa coast due to development of weak cyclone and cross equatorial westerly over the Indian Ocean thereby denying inland penetration of moisture to Tanzania. It can also be seen that, there is weak westerly from Congo basin converge with the easterly from Kenya at Lake Victoria basin.

In general, for wet year the moisture flux pattern and SST anomaly plots suggest enhanced convective precipitation over Tanzania to be associated with low level moisture flux from the northeast and southeast Indian Ocean followed by tropical Atlantic Ocean and Congo basin. For the case of dry years, simulation of moisture flux pattern suggest westerly winds over the western Indian Ocean to be more apparent followed by weak low level moisture flux from Atlantic Ocean and Congo basin due to the dominance of cool SST. Since the pattern of winds during the wet years are opposite to that of the dry years, their reversal provide credence to the suggestion by Goddard and Graham, 1999; Mpeta and Jury, 2001; Mapande and Reason, 2005b that the modulation of the atmospheric circulation over the Indian ocean is important factor in influencing rainfall over Tanzania regardless of how much incoming moisture content turns in Mozambique Channel at the beginning of rain season.


November composite dry year SST anomaly
a
10N
5N
EQ
5S
10S
15S
20S
25S
30S
35S
40S
20W
0
20E
40E
60E
80E
100E
120E
140E
0.3
1.2


February composite dry year SST anomaly
b
10N
5N
EQ
5S
10S
15S
20S
25S
30S
35S
40S
20W
0
20E
40E
60E
80E
100E
120E
140E
0
0.3
0.6
0.9
-0.3

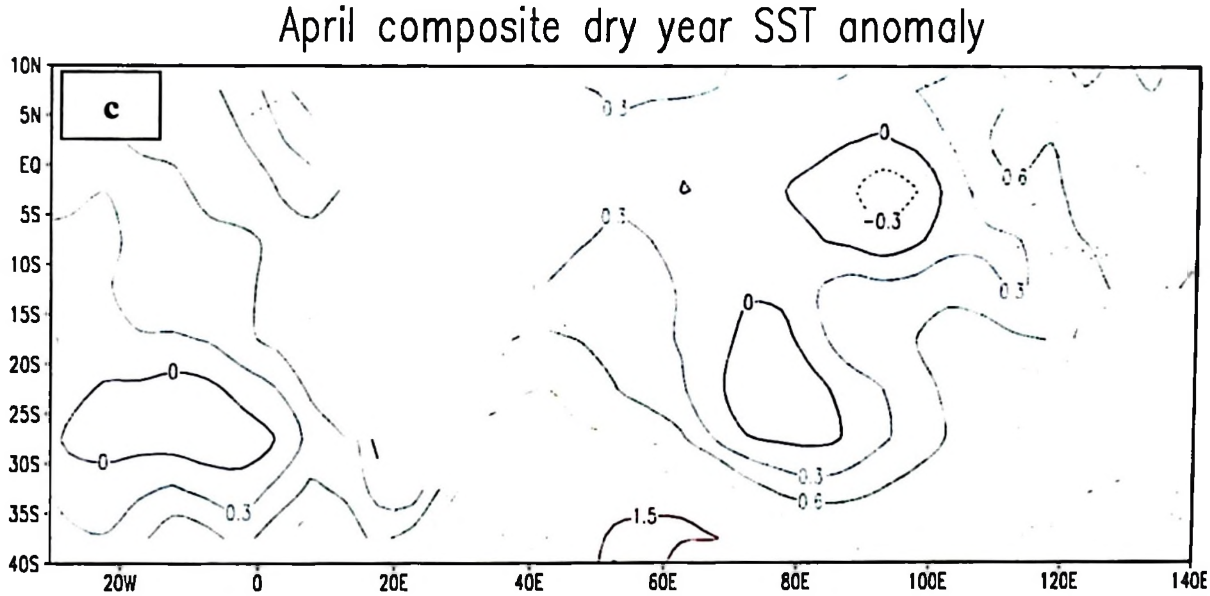
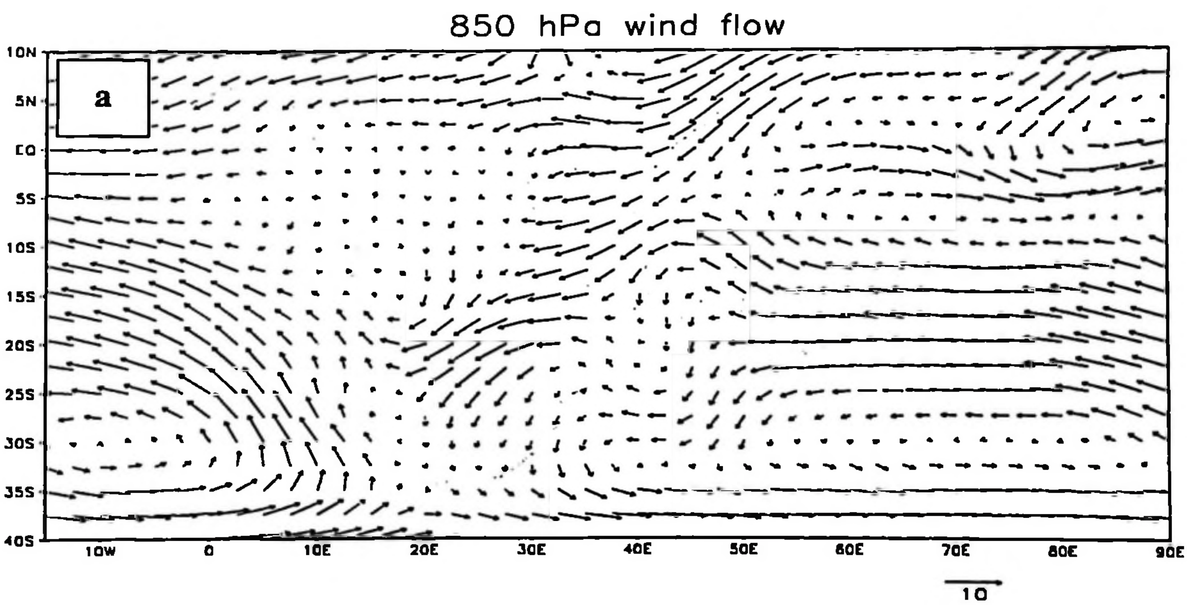
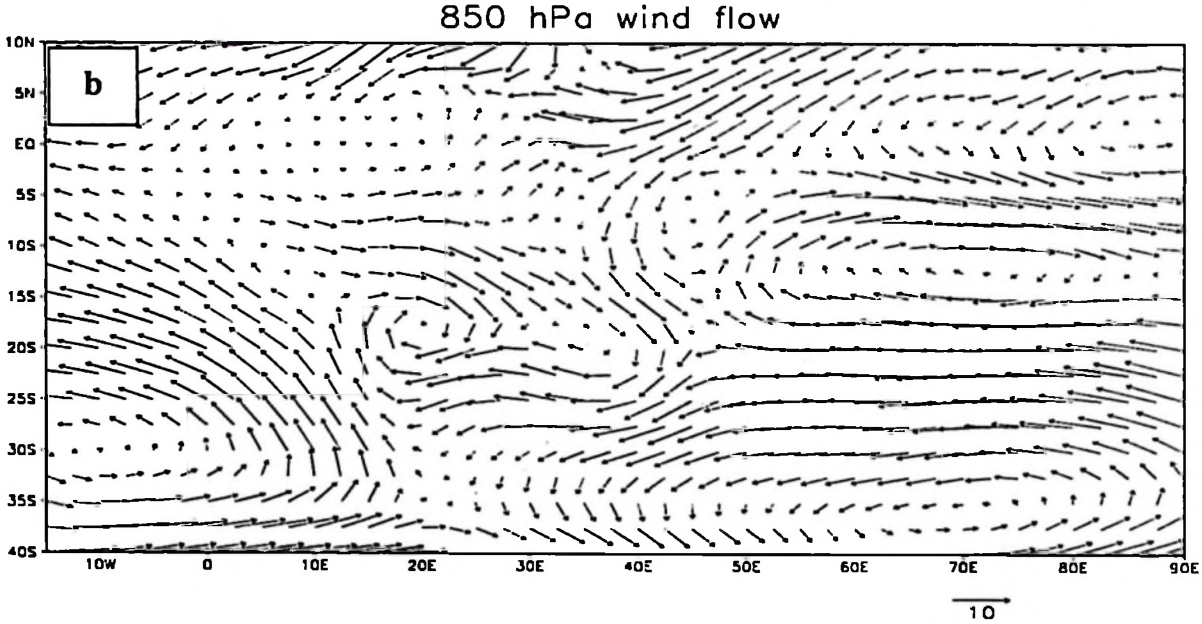


Figure 12: Composite SST anomaly during rainy season of dry year of the 1999/00 in the Atlantic and Indian Ocean at different time. (a) November, 1999 during the beginning of rain season (b) February, 2000 during the peak of the rain season (c) April, 2000 near the end of rain season





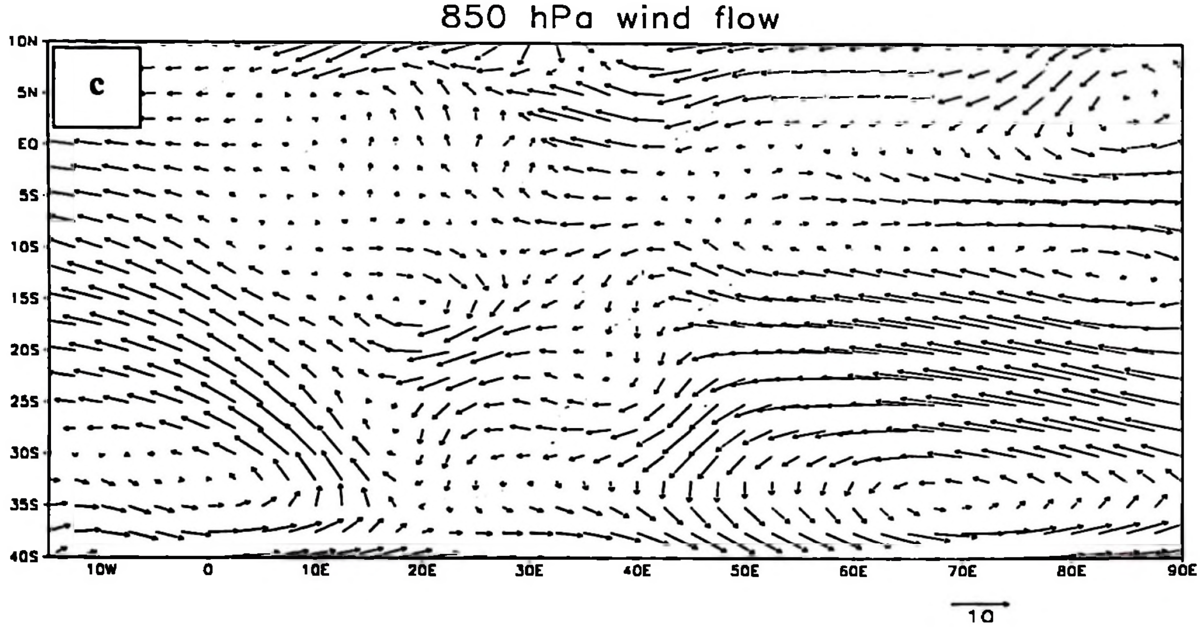
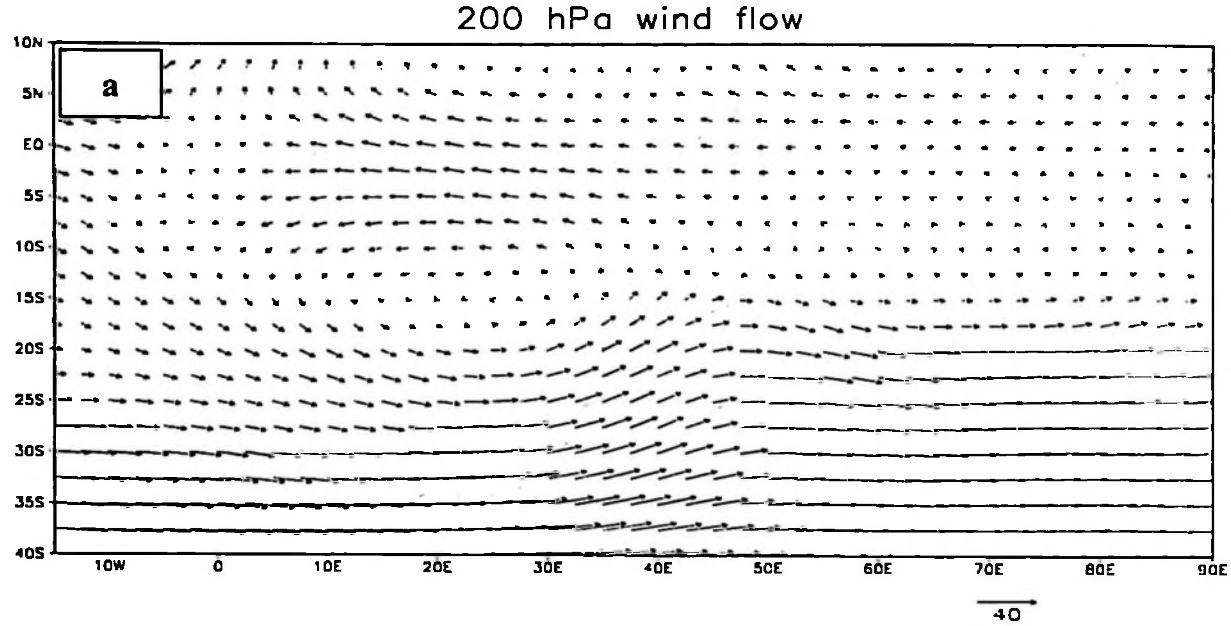


Figure 13: Simulated moisture pattern during rainy season of the dry year of 1999/00 at 850 hPa level (ms^{-1}). (a) November, 1999 during the beginning of rain season (b) February, 2000 during the peak of the rain season (c) April, 2000 near the end of rain season.

4.3.3.2 200 hPa Level

Simulated moisture patterns at upper level of 200 hPa at the beginning of rain season for the wet year reveal the divergence of wind (Figure 14a) over eastern Atlantic and western Indian Ocean. This divergence at high level help to distribute the moisture content arose from the low level. At the peak of the rain season, divergence of wind intensifies (Figure 14b). This intensification of the wind flow can be the results of the presence of the anticyclonic systems at eastern Atlantic Ocean and western Indian Ocean. Near the end of the rainfall season, the divergence of wind is weakened and the westerly winds (Figure 14c) dominate the whole area of southern Africa. At the coast of East Africa there is weak easterly wind seen; this means little moisture is sent to the mainland. Simulated moisture patterns for high level wind at the beginning of rain season of the dry year (figure 15a), is dominated by divergence winds at northern Namibia and convergence at East Africa. The divergence of wind is enhanced by the development of anticyclonic system at the northern part of Namibia. The westerly wind is pushed further south due to the development of cyclonic circulation at East Africa hence decline moisture distribution. Convergence of high level wind at East Africa led to the divergence of low level winds hence little moisture is accumulated. Figure 15b shows simulation of moisture patterns at the peak of rain season of the dry year, where strong easterly wind is developed over the western part of Indian Ocean while the westerly wind is weaken. Near the end of the rain season of the dry year (Figure 15c), the easterly wind is weaken while the westerly wind is pushed further south. The whole part of East Africa is dominated by weak convergence of westerly and easterly winds hence suppress convective activities to the region.


200 hPa wind flow
a
10N
5N
EQ
5S
10S
15S
20S
25S
30S
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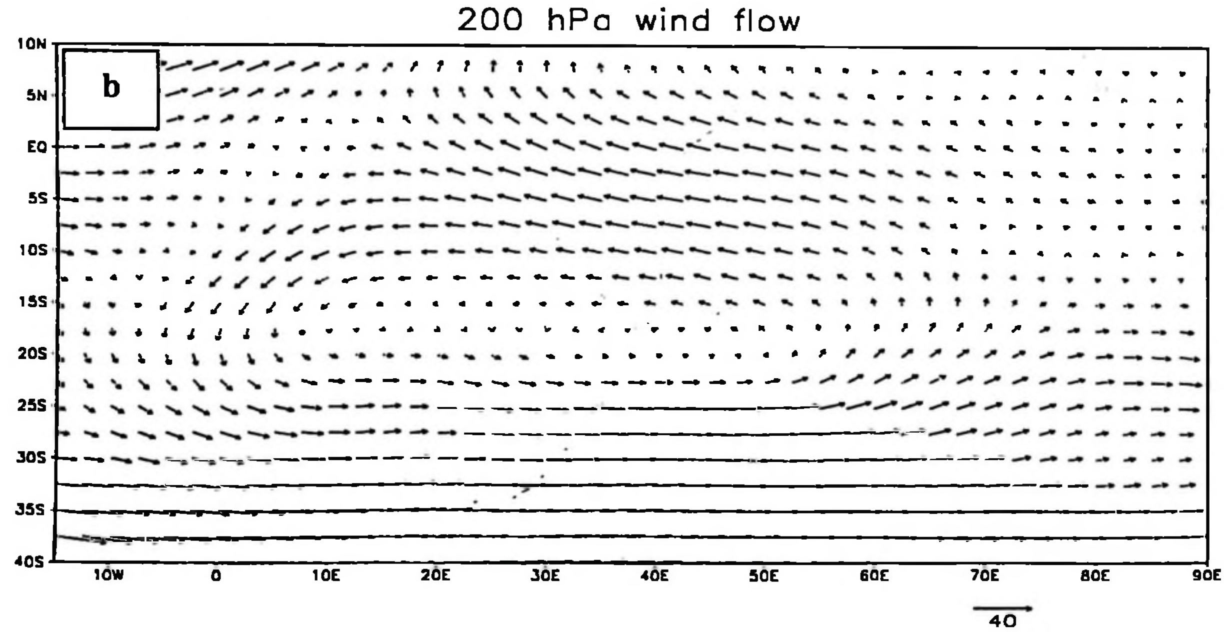
10W
0
10E
20E
30E
40E
50E
60E
70E
80E
90E
40


200 hPa wind flow
b
10N
5N
EQ
5S
10S
15S
20S
25S
30S
35S
40S
10W
0
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20E
30E
40E
50E
60E
70E
80E
90E
40

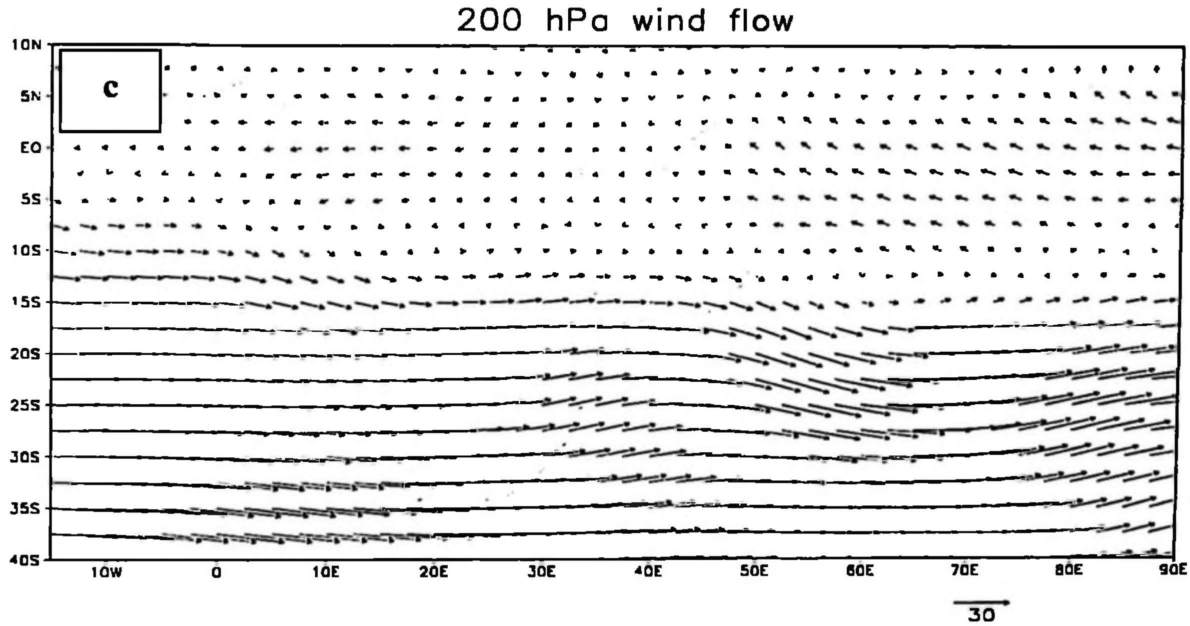
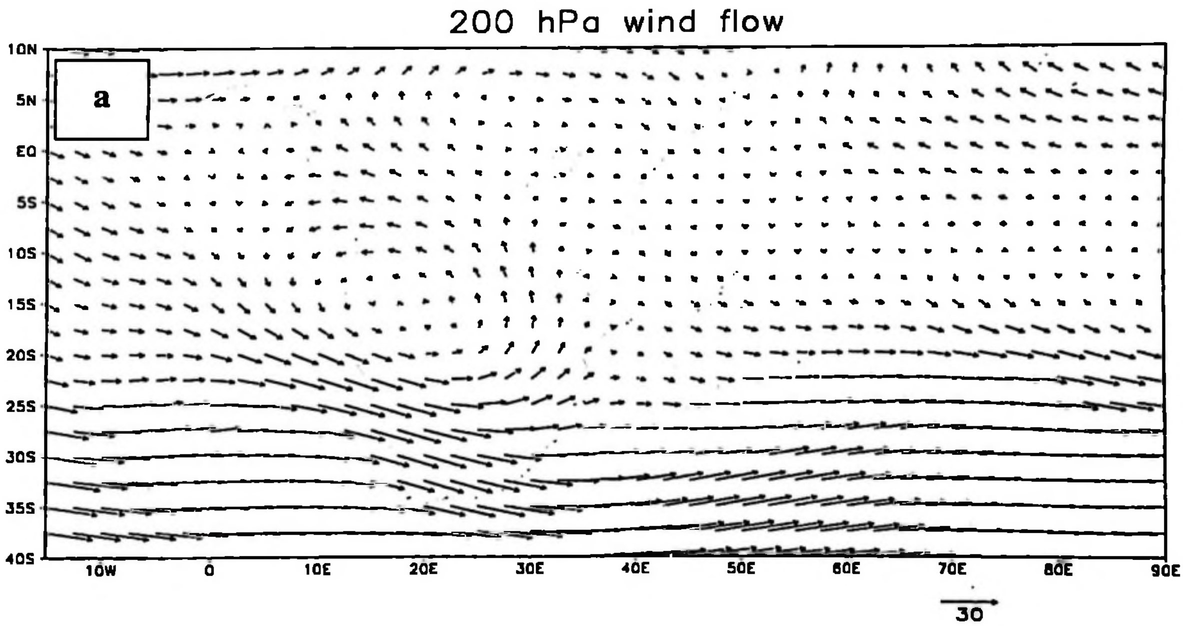
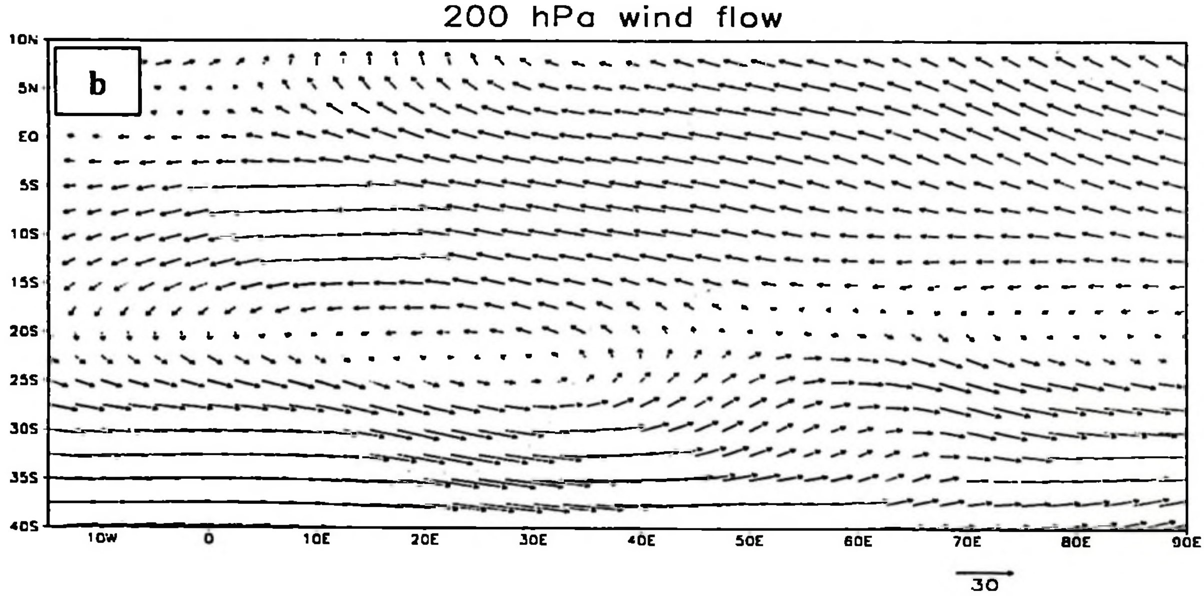


Figure 14: Simulated moisture pattern during rainy season of the wet year of 1997/98 at 200 hPa level (ms^{-1}). (a) November, 1997 during the beginning of rain season (b) February, 1998 during the peak of the rain season (c) April, 1998 near the end of rain season.





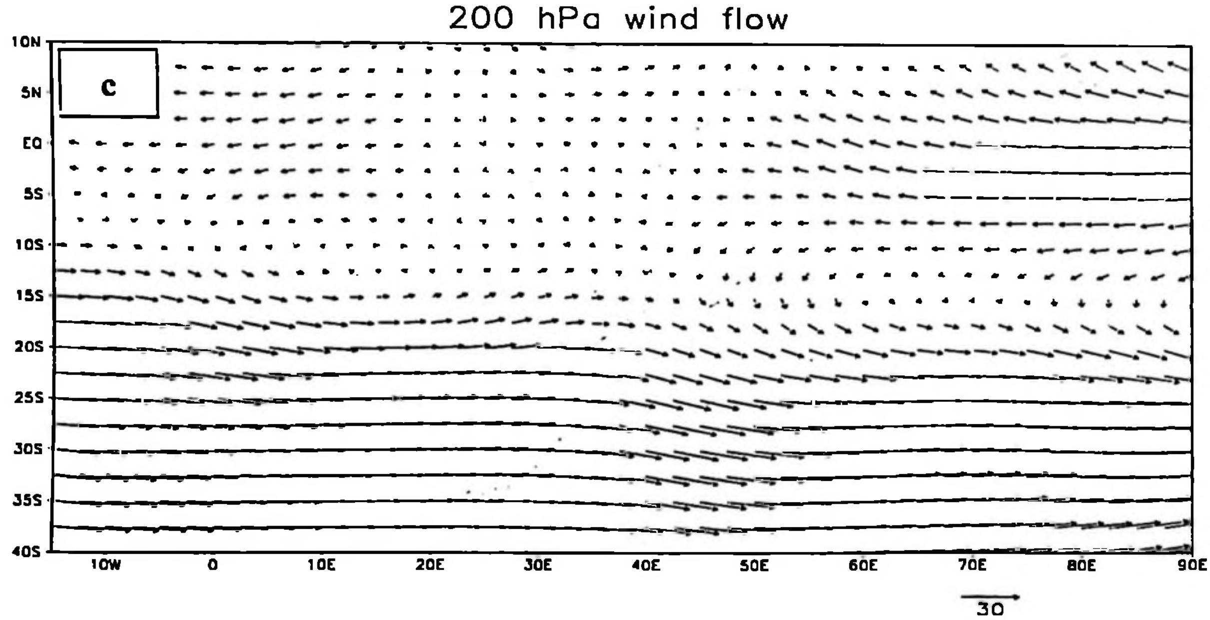


Figure 15: Simulated moisture pattern during rainy season of the dry year of 1999/00 at 200 hPa level (ms^{-1}). (a) November, 1999 during the beginning of rain season (b) February, 2000 during the peak of the rain season (c) April, 2000 near the end of rain season.

§ 4.4 Sea Level Pressure (SLP) and SPI

Winds and rainfall over Africa depend on the relative strength of the subtropical marine high pressure systems while the thermodynamic state of the adjacent Indian and Atlantic Oceans determine the moisture flux (Mpeta, 2002). The most important features on the SLP patterns, during the rainy season (November to April), are the semi permanent subtropical high pressure systems, the Saint Helena and Mascarene in the south and Azores and Arabian high in the north. However, regression analysis which was done between the monthly mean SLP and one month SPI value (Figure 16) shows no significant correlation. Nonetheless, simultaneous warming (cooling) of the equatorial Indian and Atlantic Ocean is associated with the weakening (increasing) of pressures over the tropics and a possible withholding of moisture in the equatorial band. The warming of SSTs over northwest Indian Ocean is associated with a weakening of the Arabian ridge and hence weak northeasterly monsoon. High pressures over the equatorial regions of the Atlantic and Indian Oceans are associated with high rainfall over East Africa. Easterlies over Indian Ocean are associated with wet conditions over large part of southern Africa. Strong easterlies suggest strong Azores and Mascarene anticyclones, hence evaporative cooling of the oceans and moisture is transported to the mainland. Westerlies wind over the equatorial Atlantic Ocean is associated with increased rainfall over east Africa.

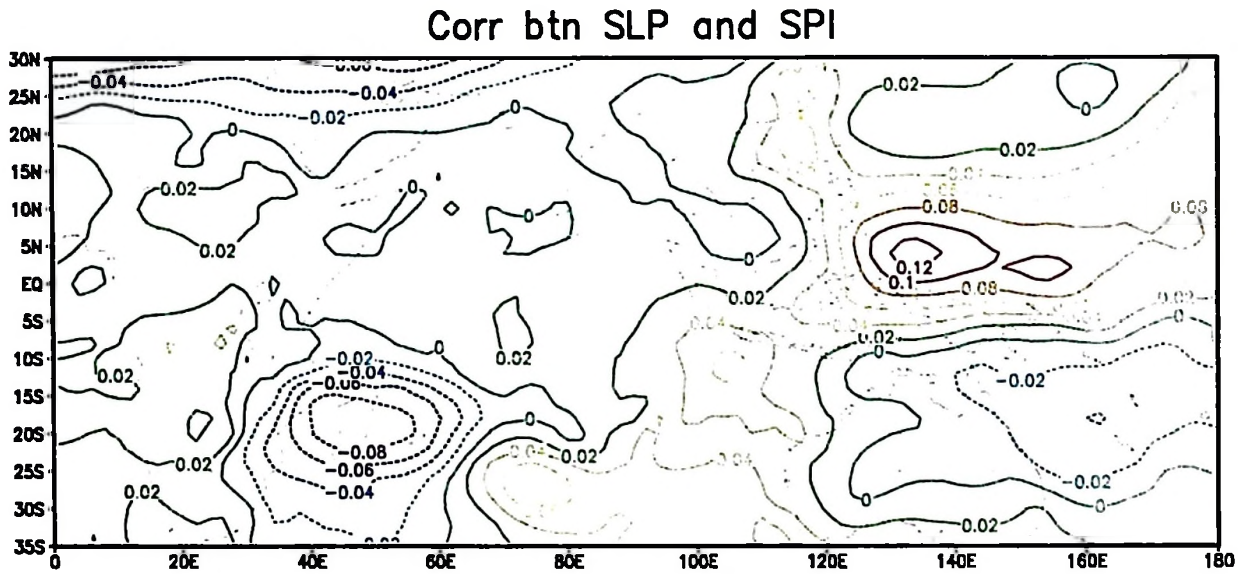


Figure 16: Correlation map which fail to show association between sea level pressure (SLP) and SPI. The analysis period is from 1970 and 2010.

CHAPTER FIVE

§ 5.0 CONCLUSION, INNOVATION AND RECOMMENDATION

§ 5.1 CONCLUSION

The climate characteristic of southern highland Tanzania is studied. Correlation analysis results between the IODZM and the SPI show significant correlation at 99% confidence level. Moreover, SST over key areas identified over the Atlantic and Indian Ocean at different time lag show significance correlation with SPI at 90% confidence level. These key areas which have been identified over the western Indian Ocean fall under the same areas to those which were used by Saji et al (1999) to develop IODZM. From these facts, it is evident that rainfall over the region is linked with the sea surface temperature over the Indian Ocean, where warmer (cooler) western Indian Ocean is accompanied by high (low) amount of rainfall over most part of the Tanzania. During wet (dry) years, weaker (stronger) equatorial westerlies over the western Indian Ocean act to reduce (enhance) the export of equatorial moisture away from East Africa. Not only that, but also moisture influx from the northeast Indian monsoon has significant influence on the rainfall over the region. During the wet years, strong northeasterly Indian monsoon is evident over most of Tanzania while during the dry year the northeasterly is seen to turn north hence denying moisture influx over Tanzania. In addition, increased (decreased) low level moisture influx from gulf of Guinea and Congo basin tend to occur during the wet (dry) seasons, leading to enhanced (reduced) low level moisture convergence over western part of Tanzania.

Although there are some variations in magnitude of the anomalies for each year, the region is experiencing normal rainfall. The results suggest the wettest season in record during the study period to be 1978/1979 which can be classified as "Severely wet" and the driest season to be 1999/2000 which can be classified as "Moderate drought". Furthermore, analysis of rainfall amount received throughout the study period shows that dominance of above normal rainfall condition during 1978s to 1991s and below normal condition during 2000s to 2010s. Different dominant periodicity modes have been observed over the study period, but two of them seem to be more dominant over the whole study period. These modes of rainfall have been identified at time scale of 2 and 7 years which may be associated with the quasi biennial oscillation (QBO) and El Nino Southern Oscillation (ENSO) respectively. Moreover, key areas over the oceans have been identified to be in between 2°N-17°S and 5°W-10°E for the Atlantic Ocean and between 5°S-18°S and 58°E-70°E for the Indian Ocean. Monitoring of SST changes over these key areas can help in forecasting the rainfall in interannual time scale over much Tanzania.

§ 5.2 INNOVATION

As it has been mentioned above, the economic development of Tanzania depends mainly on rain fed agriculture. And since rainfall variation is high in space and time in this part of the world, precise forecasting information is of great value for agricultural productivity. So the desire of this research work was to try to supplement the existing knowledge and understanding on climate characteristics with the new findings which will be obtained.

The innovation part for this dissertation work is based on the development of rainfall index for the study area which will help on forecasting the climatic condition of the near future. Not only the above, but also this research work has reveal relationships which exist between rainfall and other global meteorological parameters which are believed to have significance effect on the climate of the region. Moreover, key regions over the Atlantic and Indian Ocean have identified which can be used in forecasting the climatic condition of the country and for future research works.

§ 5.3 RECOMMENDATION

I recommend responsible institution in the governments to make use of the findings from this study as a benchmark in improving agriculture sector and vigilance for extreme events meaning drought and flood. Also the findings which have been obtained from this study should be transformed into simple and understandable language by the government through responsible institutions for public consumption.

Moreover, effort is needed to investigate the internal modes which are present on the Atlantic and Indian Ocean as it is the case of Pacific Ocean. To achieve this, more observational points are needed over the Ocean basin adjacent to Africa continent to record changes which are taking place and make use of those data.

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