THE INFLUENCE OF THE INDIAN AND ATLANTIC OCEANS ON WET AND DRY SPELLS OVER SOUTHERN TANZANIA

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Abstract

Rainfall over Tanzania is highly variable. In recent decades the country has been devastated by floods and droughts. The Tanzanian population relies heavily on seasonal rainfall. Over the northern part of the country, the rainy season occurs in two phases, the short rains (October-December) and the long rains (March - May). Over the southern and the western areas, the rainy season occurs during November – May. This study aims at identifying factors that may play a role in the rainfall variability over the southern region of Tanzania.

This study indicates that over the Indian Ocean, the sea surface temperatures (SSTs) over the northeast of Madagascar have a strong relationship with the rainfall in southern Tanzania during the OND rainfall, while the SSTs over the southeast Atlantic have a strong relationship during the JFM rainfall. It has also been revealed that the El Niño/ Southern Oscillation (ENSO) have influence on rainfall variability over the region. The warm/cold ENSO events would impact both a wet or dry year. Such contradiction has imposed a challenge to the forecasters of seasonal rainfall over southern Tanzania.

During the JFM rainfall the moisture fluxes originated from the northwest Indian Ocean and southeast Indian Ocean converge along the zonal arm of the ITCZ influencing rainfall over southern Tanzania. The trade easterly air flow through northern Madagascar becomes a dominant flow over southern Tanzania. During the JFM period, the ITCZ is well located further south, its effectiveness results in a rainfall increase over southern Tanzania. At this time the tropical easterly jet dominates the circulation in the upper levels over low latitudes of southern Africa, while the subtropical westerly jet apparently lies at latitude 25^0S.

The JFM rainfall intensifies over southern Tanzania when the low level cyclonic circulation over Angola strengthens and anticyclonic flow over the southern

Indian Ocean shifts further south, with relatively strong easterly the air flow from the central Indian Ocean to flow over southern Tanzania. The intensification of the cyclonic flow over southern Angola results in the tropical easterly jet becoming dominant at the upper level, with vertical uplift over Tanzania and a likely develop Walker circulation over the north Indian Ocean.

The interannual and longer term variability of the SST in this region is often associated with the ENSO. It has been observed that the ENSO events may be associated with the rainfall variability over southern Tanzania, although the relationship is not well defined or linear. It has been shown that during the El Niño events (warm ENSO), floods may occur as well as droughts. Similar effects have been observed with the La Niña events (cold ENSO).

The other mode which could associate with rainfall variability is the Indian Ocean zone dipole mode (IOD). The IOD has been observed to have influence with the rainfall over southern Tanzania. It has been observed that some years of the IOD events have correlated with rainfall over southern Tanzania, and some other years do not correlate.

Apart for the ENSO years, some neutral years (non ENSO year) have shown considerable amounts of rainfall over southern Tanzania. It has been observed that synoptic weather systems like tropical cyclone may play significant role in rainfall distribution over southern Tanzania. For example during March 1978, Mtwara station recorded a rainfall total of about 453.5 mm on two days. This rainfall was associated with the tropical depression situated over the central Indian Ocean, which did not develop into a tropical cyclone.

The variability of the cyclonic flows over the ocean is very important. The intensification of the cyclonic flow over the southeast Atlantic Ocean together with the ascending limb of the Walker circulation over Angola may weaken the southeasterly flow from southwest Indian Ocean and northwesterly from northern

Atlantic Ocean. In this case relative convergence may be stronger over Angola with dry conditions over Tanzania. Similarly, the occurrence of the cyclonic flow over the central Indian Ocean may be accompanied by the deflection of the moist southeasterly air flow. The resulting offshore winds along the southern coast lead to dry conditions over southern Tanzania.

Chapter 1

1.1 Introduction

Tanzania is located in East Africa between latitudes 1° and 12° S, and longitudes 29° and 41° E. It borders with Kenya and Uganda to the north, Rwanda, Burundi and the Democratic Republic of Congo (DRC) to the west, Zambia to the southwest; Malawi and Mozambique to the south and the Indian Ocean to the east (see fig.1.1). It has an area of approximately 945,000 km^2, and contains numerous lakes, river basins and mountains. The highest mountain (5900 m) in Africa, Mount Kilimanjaro, is in Tanzania. Lake Tanganyika, the second deepest lake in the world, with the floor lying 358 m below sea level, is located in the west of the country. The largest tropical lake in the world, Lake Victoria, with an area of 60,000 km^2 lies in the northwest of the country. Most of the country is 200 m above mean sea level, except the 100 km wide coastal strip, which is about 200 m above mean sea level. Farming and animal husbandry are the main activities in Tanzania. Eighty percent of the 36 million population of Tanzania are farmers, predominantly small- scale and dependent on rainfall.

The large size of the country and its different geographical features yield a variety of rainfall patterns. Over the past few decades, frequently occurring droughts and floods have caused considerable damage to the Tanzanian economy. The country's economy depends heavily on the agricultural sector, which is believed to form half of the Gross Domestic Product (GDP). Thus, it is evident that the country's economy is extremely vulnerable to a highly variable local climate, characterised by an intermittent rainy season (Mpeta and Jury, 2001).

The recent droughts in 1974, 1996 and 1998 - 2000, which were linked to La Niña events, resulted in the local government spending scarce funds on purchasing more food for the people's survival (Nicholson and Selato, 2000). The most recent drought, in 2005 - 2006, was also found to be related to La Niña conditions and low sea surface temperatures (SSTs). These negative SST anomalies occurred over the western Indian Ocean (Kijazi and Reason, 2005).

In contrast, during the 1997/98 El Niño event, wide spread flooding occurred resulting in 80% of the region being covered (Mpeta and Jury, 2001; Mhita et al. 2003). This lead to considerable damage to local infrastructure, loss of life, as well as economic hardship, which was estimated at billions of Tanzania shillings in damages (Mpeta and Jury, 2001; Jury *et al.* 1995; Nicholson and Selato, 2000). Many of the abnormalities were foreseen, but mitigating actions by government agencies were insufficient to prevent the loss of infrastructure and life.

Lack of forecasting capacity and limited data availability in most developing countries, including Tanzania, affects the accuracy of seasonal climate prediction. Particularly, prediction of the onset and cessation dates of the rainy season and also the occurrence of wet and dry spells within the season. The information is crucial for agricultural planning, and water resource management, especially in the case of the fishing industry. The inadequate forecasts have also been found to have a negative affect on the health and tourism sectors. The required meteorological information would play a vital role in the agricultural sector if the information can be received in advance. The agricultural communities may then be able to plan for the next season. Poor planning leads to serious impacts on agricultural output for the majority of small hold farmers, who form the bulk of the rural poor in Tanzania (CLIVAR, 1999). For them, crop depreciation is not a matter of profit but of survival, as agriculture is their only source of food and income.

In this study, we focus on southern Tanzania (Fig.1.1 below) roughly defined as the region between latitudes 7.5^0 S and 11.1^0 S and longitudes 33.0^0 E and 40.5^0 E. This area has several mountains, low lands and river basins, which offer potential for agricultural activities. The seasonal rivers in this area flow into the

Mtera dam (not shown), which supplies water for electricity production for the national hydropower grid.

Attempts have been made by other researchers to identify precursors that may be associated with wet and dry spells over the south western highlands. Little or no attempt has been made for the southern region of southern Tanzania, apart from Kijazi and Reason (2005). These two authors found that the ENSO impacts are coherent along the southern coast and that this region appears to be a transition zone between the opposite signed impacts for the equatorial East and southern Africa.

Therefore, in this study one would like to bridge the gap, by trying to investigate circulation of SST anomalies over both Indian and Atlantic Oceans, and other precursors that might influence rainfall variability over southern Tanzania. Thus, it will contribute towards understanding rainfall variability over southern Tanzania and possibly to improve seasonal forecasting over the region.

Previous research has identified that the rainfall over Tanzania is mainly influenced by the Inter Tropical Convergence Zone (ITCZ) and monsoon circulations. El Niño/ Southern Oscillation (ENSO), and the Indian Ocean zone Dipole Mode (IOD) have influence over north eastern highlands and northern coast (Kijazi and Reason,2005; Mpeta and Jury, 2001).

This thesis wants to examine:

1. The effect of the variability of the SSTs in the Indian and Atlantic Oceans to the rainfall over southern Tanzania.
2. The influence of the ENSO events to the rainfall over southern Tanzania.

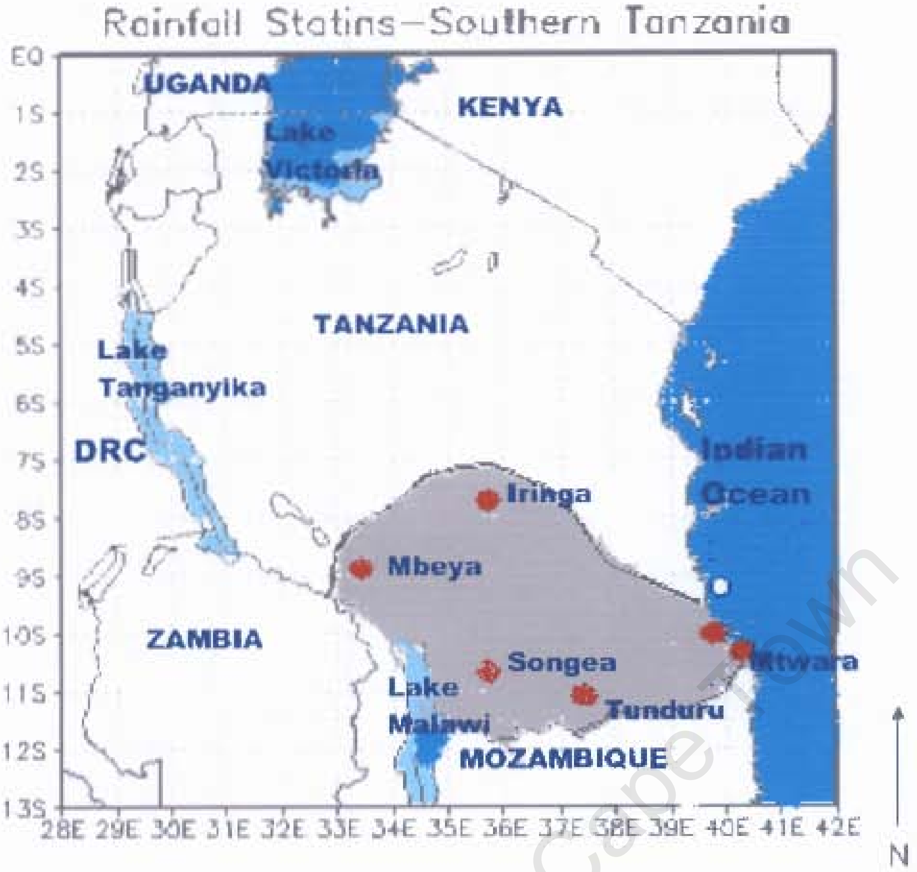


Fig.1.1: Map of East Africa showing the study area over southern Tanzania and the 5 rainfall stations. Lakes (Lake Victoria, Lake Tanganyika, and Lake Malawi) and the Indian Ocean are in blue areas and the grey area represents the study area.

Chapter 2

Climate of Tanzania

2.1 Introduction

The climate of Tanzania depends on the movement of the Inter Tropical Convergence Zone (ITCZ) and the monsoon flows, which interact with the topographical features, oceans and lakes to produce rain. In the tropical regions (including Tanzania) the heat energy received is intense. This provides a unique setting for diurnal mesoscale circulations forced by variation in topography, water bodies and other land surface properties (Asnani, 1993). The regional land and sea breezes, lake breezes, valley and mountain winds, dominate when the large scale flow is weak. For the large scale circulation, easterly trade wind flows are dominant throughout the year and bring moist air for formation of rain over the region. The southerly component of the trade winds dominates during the boreal summer and the northerly component during the northern winter. The interaction between the large scale and various mesoscale circulations produce a variety of rainfall patterns, which would give diurnal precipitation variations over the region (Asnani, 1993).

2.2 Synoptic features

2.2.1 Inter Tropical Convergence Zone

In the tropics, vertical motion can be produced by forced air ascent over high ground, low level convergence, and uneven heating between the land and water masses. The diurnal variations are due to isolated heating patterns, while the seasonal variation is due to the movement of the ITCZ. The ITCZ is an area of low level convergence where the trade winds of the two hemispheres meet and converge, resulting in ascending air, which produces rain (Asnani, 1993). During the rainy season, low level equatorial trade winds accompanied by moist air from the Indian and Atlantic Oceans, converge along the ITCZ for the formation of rain (Palmer, 1999). The southeasterly trade winds from southern Indian Ocean together with northeasterly trade winds from northern Indian Ocean converge with the westerly trade winds originating from northern tropical Atlantic Ocean to enhance rainfall over western Tanzania.

In East Africa, the ITCZ has a large annual oscillation and migrates longitudinally through the region twice a year. The ITCZ remains north of the equator during the Northern Hemisphere summer and south of the equator during the Northern Hemisphere winter. When the ITCZ is positioned north of the equator, dry air from the Sahara desert is present north of the ITCZ, while a deep layer of moist air favourable for the formation of convective clouds is present to the south of the ITCZ, and this is when the monsoon rains are experienced (Asnani, 1993). The ITCZ runs roughly in a north-south direction when located over most parts of the East Africa region, except when it is positioned over northern Mozambique and Madagascar, where it is then oriented in a more east - west direction. The monsoonal rainfall occurs not far from the surface position of ITCZ (Asnani, 1993).

In Tanzania, the ITCZ has two distinctive parts, which are the meridional and zonal arms. Southern Tanzania is more under the influence of the zonal arm of the ITCZ. Southern Tanzania on the east is bordered by the Indian Ocean, where the sea surface temperature (SST) may influence rainfall variability over the region. To the west, the SSTs over the Atlantic Ocean may also be responsible for the rainfall variation over the south western highlands and the western areas (Mapande and Reason, 2005). The warm (cold), moist (dry) air from the ocean may interact with the local large-scale topography to give summer (winter) monsoon circulations (Mapande and Reason, 2005).

During the September - November and March - May periods, the southwest trade wind component dominates as the ITCZ is crossing the equator. When the ITCZ oscillates over the region it influences both the bimodal and the unimodal areas (Mapande and Reason, 2005). The movement of the ITCZ depends strongly on the strength of the subtropical highs/pressure centre. When the southern subtropical anticyclone intensifies, strong southeasterly trade winds converge into the ITCZ along with the northeasterly monsoonal flow.

During the December – March period, the land surface temperatures over the low pressure central areas between latitude 10°-15°south become more significant. The high pressure centre over the northern parts of Africa and the Arabian ridge intensify allowing a dry northeasterly monsoon to flow over northern Tanzania, bringing little rain to the north and northeastern highlands (Kabanda and Jury, 1999). Over southern Tanzania, the weak easterly and southeasterly flow from the southwest Indian Ocean becomes dominant, which may lead a moist southeasterly, triggering the onset of the rainy season over the region.

2.2.2 Monsoon winds

The monsoon winds are due to the uneven heating of the Earth's surface by the sun, and large meridional overturning cells develop. The low level trade winds form part of the lower limb of these circulation cells resulting in the air rising in the tropics being replaced by air from the higher latitudes. This rising air in the tropics is driven by the energy received from the sun, which is overhead at the equator all year round. As the Earth rotates it results in the winds being deflected due to the Coriolis force. In the Northern Hemisphere, this causes the air to spin clockwise around a high pressure cell and anti-clockwise around a low pressure cell. The wind circulates in the opposite direction in the Southern Hemisphere. The Coriolis effect is also responsible for deflecting any wind (or pressure system) in the Northern Hemisphere to the right of its direction of travel. This produces the northeast and southeasterly trade winds, which blow towards the equator from each hemisphere (Asnani, 1993; Hunt, 1979).

Monsoonal winds are also part of the trade winds, which result from the imbalance in heating that occurs between continental landmasses and equally large bodies of water or oceans. The word monsoon is derived from the Arabic word *mausim* and means *season*. It refers to seasonal changes of the prevailing winds, which bring the moisture for rainfall production (Barry and Carleton, 2001). The basic formation of the monsoon is provided by the annual cycle of solar radiation interacting with different heat capacities of the tropical oceans and land areas and their respective geographic arrangements. In Tanzania, the existence of the complex topography and large lakes modifies the monsoonal circulation, which results in spatial and temporal variation in rainfall patterns over the region (Asnani, 1993; Mpeta and Jury, 2001; Mapande and Reason, 2005).

The Indian Ocean is closed off in the north by the Asian continent and in the west by Eastern Africa. The monsoon circulation over this basin is largely determined by the Asian landmass. The seasonal cycle is dominated by the Asian monsoon, with dramatic reversals of wind from the northeast/southwest, unlike in other tropical and subtropical oceans, where the trade winds are constant (Slingo *et al.* 2005). The northeasterly monsoon occurs mainly in the December, January, and February period, while the southwesterly monsoon occurs in the months of June, July, and August. In the June – August period, the East African highlands have an influence on the cross equatorial flow, forming the Somali or Findlater Jet in the atmosphere (Findlater, 1969). When the monsoon is established, rapid cooling occurs due to the strong winds and the up welling of cold water caused by the Somali Jet (Findlater, 1969; Slingo *et al.* 2005). During the transition seasons of March - May and September – November, the winds over the northern Indian Ocean become much lighter, allowing the ocean to warm (Slingo *et al.* 2005). In winter, the NE monsoon is dominant and cold air will flow from the Asian continent to the coast of East Africa. The cool air over the Bay of Bengal and the Arabian Sea is countered by the increasing solar input due to the clear skies, which reverses the wind direction (northeast/ southwest). Despite a large reversal in wind, the variations in (surface heat flux) SSTs are found to be steady away from the East African coast. Consequently the highest SST, up to 30^0 C may be found in the northern Indian Ocean just before the onset of the monsoon in May (Slingo *et al.* 2005).

The analysis of moisture budgets over the equatorial region of the Southern Hemisphere (Veiga *et al.* 2005), showed that the monsoon circulation is mainly characterized by a region of high and low precipitation. The regions of high (low) precipitation are strongly associated with vertically integrated moisture flux convergence (divergence). Furthermore the adiabatic heating (cooling) is balanced by the adiabatic cooling (heating) over the regions with the convective (non-convective) regimes. Loss of the radiation to space over non-consecutive areas is balanced by the adiabatic heating due to a sinking motion (Veiga *et al.* 2005). The heating over the continents is presumed to be associated with the ascending branch of the Walker Circulation, and the cooling over the intermediate oceans is related to loss of radiation in the descending branch of the Walker Circulation. That implies the easterly trade winds and low level monsoon winds are part of the low-level component of the Walker circulation.

2.2.3 The Walker Circulation and El Niño/Southern Oscillation (ENSO)

Several decades ago, scientists were speculating that there were persistent planetary scale standing waves in the tropical regions with pronounced upward and downward motions in association with waves along a latitudinal circle (Asnani, 1993). The vertical upward motion covered half of the wavelength and the vertical downward motion covered the other half. These motions tended to be zonal motions moving in opposite directions in the lower and upper troposphere to form a closed circulation. This type of air circulation is now known as the Walker circulation, named after Sir Gilbert Walker, who first suggested its existence (Asnani, 1993; TOGA, 1996). In 1924, Sir Gilbert Walker wanted to examine circulation patterns that were associated with the monsoon variations, flood and drought events, which were a frequent occurrence. He correlated meteorological variables such as the sea level pressure, rainfall, air temperature, as well as the sunspot activity. He managed to establish the existence of the Southern Oscillation (SO) as a new global spatial pattern of the interannual climate variation in the tropics (TOGA, 1996). The SO is related to a zonal circulation cells along the equatorial Pacific, comprising descending air (high pressure) over the colder eastern equatorial Pacific and surface easterly winds, rising air (low pressure) over the western equatorial Pacific, with high-level westerly winds. Thus, the Walker circulation is associated with the areas of warm moist ascending air and cool dry descending air, these areas corresponded with the active and deficit rainfall regions, respectively.

This phenomenon helps to explain the occurrence of the El Niño and La Niña events over the Pacific Ocean. The major work in understanding the mechanisms of Walker's Southern Oscillation (SO) was undertaken in 1960 by Jacob Bjerknes, who examined meteorological conditions associated with El Niño. This warm SST anomaly feature has had a major economic impact on the fishing industry in this region. In 1966, Bjerknes was able to associate El Niño with the trade wind anomalies in both the western and southern Pacific Ocean. Bjerknes (1969) noted that the trade wind fluctuations correlated with the SO. This author found that the SO tended to correlate positively with pressure anomalies centered near northern Australia in the warm pools in the western Pacific and the eastern Indian Ocean. The anomalies of this negative correlation were centered east of Tahiti in the eastern and central Pacific. The association of the SO and SST warming is now called ENSO (El Niño and Southern Oscillation; Philander, 1990). The ENSO is the terminology used to describe the full range of Southern Oscillation events for El Niño and La Niña as well as differences in the sea level pressure between Darwin and Tahiti (Southern Oscillation Index), and is accompanied by changes in the SST. In a normal situation, wind stress over the western tropical Pacific become weak or reverse lead to a complex, dynamic response in the ocean (Preston-Whyte and Tyson, 1988). An El Niño feature is associated with a depression of the thermocline in the eastern Pacific Ocean. These changes have an impact on the atmospheric convective and circulation processes. During an El Niño event, the sea level pressure over the Indonesian region becomes anomalously high, the thermocline will rise over the eastern

Pacific and the upwelling is weakened off the South American coast. The El Niño is highly irregular and leads to atmospheric interactions/teleconnections between the geographically separated regions.

During the neutral years (non ENSO years), the ascending motion occurs over the western equatorial Pacific over the warm pool, and the descending motion occurs over the eastern equatorial Pacific (TOGA, 1996). During El Niño, the warm phase of the ENSO, changes of large circulation occur in the atmosphere across the Pacific Ocean. The changes develop as in the Walker circulation, which is associated with the eastern Pacific Ocean SSTs becoming warmer than normal and the western Pacific becoming colder than normal, hence resulting in the ascending limb of the Walker circulation over the eastern Pacific and a descending limb of the Walker circulation over Indonesia (TOGA, 1996). When the Pacific Walker circulation weakens or reverses, surface easterly winds decrease and sometimes their direction even reverses. When at the surface, easterly circulation intensifies; the upper level flow becomes westerly to complete the cell. Similar sets of cells appear over the Indian Ocean and the Atlantic Ocean areas, with the descending limbs over eastern Africa and South America (TOGA, 1996). During a La Niña event, conditions reverse and act to strengthen the Walker circulation (TOGA, 1996).

During the warm ENSO, the changes in the atmospheric circulation occurs, resulting in the SST anomalies, which increases the rainfall in the eastern Pacific and decreases the rainfall in the western Pacific, Australia and Indonesia (TOGA, 1996). Over the equatorial east Pacific, above average rainfall tends to occur during the October – December period during an El Niño year, while below average rainfall tends occur during the La Niña year (TOGA, 1996). Over eastern and southern Africa, the ENSO signals over the Indian Ocean are the most dominant mode of interannual climate variability (Ropelewski and Halpert, 1987; Tourre and White, 1997; Usman and Reason, 2004). The El Niño events are believed to produce the rainfall anomalies over East Africa (Nicholson and

Entekhabi, 1986; Kiladis and Diaz, 1989). It has been observed that the ENSO events play a major role in rainfall variability over East Africa (Ogallo, 1988; Hastenrath *et al.* 1993; Kijazi and Reason, 2005). The occurrence of droughts in India and floods in southeastern Brazil during the major warm events of ENSO are explained by the teleconnections. Although the ENSO episode originated in the Pacific Ocean, it has a worldwide influence. During El Niño, not only do the SST anomalies occur in the Pacific Ocean, but also in the Indian Ocean, where SSTs become warmer than usual, often resulting in floods over East Africa and a drought over southern Africa. Ropelewski and Halpert, (1987), Tourre and White, (1997), and Reason *et al.* (2000), provided evidence that the strong ENSO signals over the Indian Ocean are the most dominant mode of interannual climate variability in eastern and southern Africa. It has also been observed that some of the ENSO years are accompanied by the Indian Ocean Zone Dipole Mode (IOD) events, which tend to enhance the rainfall over East Africa (Saji *et al.*1999; Webster *et al.* 1999). Saji *et al.* (1999) and Webster *et al.* (1999), suggested that the IOD is another uniquely coupled ocean-atmosphere mode over the Indian Ocean that influences the rainfall variability over East Africa.

2.2.4 Indian Ocean Zone Dipole Mode (IOD)

The climatic variability over the tropical Pacific and Atlantic oceans has been well documented, unlike the tropical Indian Ocean, to which little attention has been given (Black, 2005). Only in recent years have Saji *et al.* (1999) and Webster *et al.* (1999) reported the existence of similar modes over the Indian Ocean, where ocean-atmosphere interaction would cause interannual climate variability. The excessive rains that occurred in 1961 in East Africa, which raised the water levels of Lake Victoria, followed by excess discharge into the White Nile, have been linked to the IOD. The strong El Nino of 1997/98 was also linked to the IOD (Reason *et al.* 2000; Saji *et al.* 1999; Jury, 1992; Black, 2005). The anomalous cooling of the surface waters, lower sea levels in the eastern ocean and increases of through flow from the Pacific (Potewa, Lukas and Mitchum, 1997), allow transportation of heat flux into the western Indian Ocean. Hence, an increase in the atmospheric convection due to the higher SST values resulted in excessive rainfall in the region.

Normally a positive phase IOD starts to develop between the June – August period, when cooling of SST starts over the Sumatran coast and warming starts to develop over the north west of the Indian Ocean. By October, the IOD usually reaches its peak, coinciding with the onset of the short rains over most parts of East Africa. The increase/decrease of the SSTs is also accompanied by changes in strength of the surface winds. The region of the negative SST anomalies is typically dominated by positive wind anomalies, while the regions of the positive SST anomalies are dominated by negative wind anomalies. The opposite of these circulations and SST anomalies tend to occur during a negative phase of the IOD event.

2.2.5 Quasi-Biennial Oscillation (QBO)

The Quasi-Biennial Oscillation (QBO) is an oscillation of the equatorial zonal winds (easterly and westerly winds) in the tropical stratosphere and has a mean period of 28 months. It moves eastwards or westwards with a maximum speed of $20ms^{-1}$ in the lower stratosphere, which is approximately 23.5 km above mean sea level pressure (MSLP). The alternating wind regimes develop at the top of the lower stratosphere and propagate downwards at about 1 km per month until they are dissipated at the tropical tropopause.

The presence of the QBO and warm ENSO events are believed to enhance convection over the region (Kabanda and Jury, 1999). The strong La Niña events tend to occur when the QBO is in its westerly phase over the equatorial Pacific. The previous research has revealed that the QBO and the SO have a strong influence on rainfall variation over East Africa (Ogallo *et al.* 1994; Indeje *et al.* 1999; Kabanda and Jury, 1999).

The latest research carried out at DMC–Harare by Unganai *et al.* (1996), observed that the teleconnection between southern African and Ethiopian rainfall may be influenced by the QBO. It has been found that some regions of rainfall respond significantly to the QBO phase shift. The areas that were pointed out were northern Zambia, northern Malawi, and Tanzania (Drought Network News, June 1996).

The effects of the QBO include a mixing of the stratospheric ozone layer, modifying the monsoon precipitation, and influencing the ocean in a sudden warming by the stratospheric circulation in the Northern Hemisphere winter. The height and amount of the deep tropical convection may also be associated with the stratospheric QBO (Martin *et al.* 2003). The QBO modulates the tropopause height which may then allow convection to penetrate deeper. A deep convective region is likely to provide more favourable conditions for the formation of the tropical cyclones (Martin *et al.* 2003).

2.3 Weather systems

2.3.1 Tropical cyclones

The Tropical Cyclones (TCs) are also known as hurricanes or typhoons, and are the deadliest and costliest natural disasters resulting in high death tolls and damages. For example Hurricane Andrew in 1992, resulted in approximately $26.5 billion (U.S.) worth of damage in the southeastern United States (Holland, 1993, Hebert *et al.* 1997). A recent TC, named Katrina, caused catastrophic damage along the coastlines of the USA on August 29th 2005. This particular TC is estimated to be responsible for $75 billion in damages, making it the costliest hurricane in U.S. history. The storm killed at least 1,836 people, making it the deadliest U.S. hurricane since the 1928 Okeechobee Hurricane, (WMO/TD-No1129).

A tropical cyclone derives its energy from the oceans through evaporation and condensation in convective clouds concentrated near their centre (Holland 1993).

The TCs are characterized by a "warm core" (relatively warmer than the environment at the same pressure level) in the troposphere. The greatest temperature anomaly generally occurs in the upper troposphere near the 250 hPa level. It is this unique warm-core structure within a tropical cyclone that produces the very strong winds near the surface and caused damage to the coastal regions and the islands through the extreme winds, a storm surge, and strong waves (Hall *et al.* 2001).

Apart from its destructive nature, a TC has the important role of transporting heat from the tropics to the higher latitudes. It has a role in preventing the tropics from continuously heating and the poles from continuously cooling from the net radiation surplus and deficit in the respective regions. Along with the oceanic currents, there is the Hadley circulation system comprising latent heat releases in atmospheric storms. This, coupled with the baroclinic eddies plays an important role in the transport of the heat.

The vast majority of the TCs in the Indian Ocean are found in the vicinity of the ITCZ (Hall *et al.* 2001). McBride and Keenan (1982) estimated that 85% of the cyclones in the Australian region have their genesis regions near the ITCZ. The TCs over the South West Indian Ocean have an influence on the moist south easterly flow over the southern Tanzanian rainfall, which may result in positive/negative rainfall anomalies in the region.

2.3.2 Heat Low

A heat low over Angola may influence the rainfall over southern Tanzania. The intensification of the heat low may cause a reduction in the moist westerly flow over the Congo basin. The heat low would cause reduction of the moist westerly flow, resulting in a weak moist westerly converging with the weak easterly trade winds from western Indian Ocean along the meridional arm of the ITCZ bringing little rain to western Tanzania. The westerly monsoon flow and the easterly trade winds play a significant role in the distribution of rainfall over the south western highlands and western Tanzania. The cyclonic flow associated with the Angolan heat low over the southeast Atlantic Ocean and a cyclonic flow over southeast Indian Ocean may weaken the westerly and easterly moisture transportation from the Atlantic and southwest Indian Oceans respectively. This may result in the reduction of precipitation in Tanzania (Mpeta and Jury, 2001; Mapande and Reason, 2005).

2.3.3 Subtropical anticyclones

The intraseasonal and interannual variations of the low level tropospheric moisture flux over southern Africa and adjacent oceans are driven by the subtropical anticyclones (Asnani, 1993; Kijazi and Reason, 2005). The transport of the water vapour to southern Tanzania in early summer has been found to originate from the southern Atlantic and southwest Indian oceans (Asnani, 1993; Kijazi and Reason, 2005). The subtropical anticyclone is a prominent feature in transporting the water vapour to the tropical trough (ITCZ), which may result in favourable conditions for rainfall production there. The Mascarene and St. Helena anticyclones from the Southern Hemisphere, and the Arabian ridge, Azores anticyclone, and Siberian anticyclone from the Northern Hemisphere are major transporters of moisture towards the ITCZ.

2.3.4 Intraseasonal Oscillations (ISO)

In the tropics, unlike in the mid-latitudes, different atmospheric features modulate the weather patterns. In the mid-latitudes, the weather is largely governed by the upper-tropospheric Rossby waves, which are generated through baroclinic instability which help to determine the surface weather. In the tropics, barotropic instability is important together with convective processes, which are difficult to forecast. Thus weather prediction for more than a ten day period ahead is less reliable (Geerts and Wheeler, 1998).

The ISO's were not well known until in 1971 when Madden and Julian (1971, 1972) tried to analyze zonal wind anomalies of the tropical Pacific, using ten years of pressure records of the Canton (2.8^0 S in the Pacific) and the upper level winds of Singapore. In their work they found that the surface, and the upper level winds were oscillating every 40-50 days in a coherent manner. This phenomenon is now more commonly known as the Madden Julian oscillation (MJO). The MJO is associated with the low frequency variations in the tropics, which are both intraseasonal (less than a year) and interannual (more than a year) variations. The MJO affects the entire tropical troposphere, but is more evident in the Indian and western Pacific Oceans. This feature involves anomalies in the wind patterns, sea surface temperature (SST), outgoing long wave radiation (OLR) and rainfall. Since the tropical rainfall is convective in origin and associated with the cold cloud tops, it may be evident in variations of the outgoing long wave radiation (Geerts and Wheeler, 1998).

Attempts were made to explain the physical mechanism of the excitation, maintenance and propagation of the low frequency intraseasonal oscillation waves, but at the time were not sufficient to understand their evolution. In 1977 Chang suggested that the intraseasonal oscillation is driven by the trapped equatorial Kelvin waves, which result from an interaction between the equatorial dynamics and the tropical convection. The large wavelengths and long period Rossby and Kelvin waves, are considered to be important in the dynamics of the oscillation (Matsuno, 1966). The tropical and the subtropical heat sources are able to force the equatorial Kelvin, Rossby and Yanai waves to propagate from one place to another (Gill, 1980; Kalnay *et al.* 1981; Kalnay *et al.* 1986).

The MJO or ISO, which fluctuates on a timescale longer than a week, but shorter than a season, plays a significant role in the onset of the rainy season over southern Africa (Makarau, 1994). The intermittent wet and dry spells over the south western highlands and north eastern highlands of Tanzania appear to be associated with the ISO (Mapande and Reason 2005; Mpeta and Jury, 2001, Madden and Julian, 1994). Mpeta (2001) reported that the intraseasonal convective systems which span across the continent of Africa contain small amplitude and propagate eastward into the Indian Ocean with increasing amplitude. The active MJO favours rainy conditions over East Africa and the adjacent western Indian Ocean, as well as creating drier conditions in most of subtropical Africa (Makarau, 1994; Mpeta and Jury, 2001).

The ISO coincides with the upper westerly winds over the Atlantic and becomes more significant during the El Niño years when there are positive SST anomalies over the Indian Ocean. The strong equatorial convection actively favours the rainy conditions over East Africa and the adjacent western Indian Ocean, and also the dry conditions over subtropical Africa (Mpeta and Jury, 2001).

2.4 East Africa rainfall variability

The climate variability directly affects the livelihoods of many people living next to the Indian Ocean. It has large impacts on all aspects of economic activity, such as farming, electrical power, industry and domestic consumption. The progress in understanding the role of the oceans in the global climate, as well as a moderate skill in predicting seasonal rainfall is important for society and economic development. Increasing skill in seasonal rainfall prediction will benefit all sectors of society, even if the increase is marginal, the impact of natural disasters on life and infrastructure would have been minimized (Jury *et al.* 2000, WMO/TD-No.1129; Mpeta and Jury, 2001).

The moisture content over the equatorial region of the Southern Hemisphere is dominated by high monsoon precipitation. In East Africa, rainfall variability is influenced by the Asian monsoon with dramatic reversals of the northeasterly monsoon flow. The northeasterly and the southeasterly winds are mainly dominant in the December - February, and June – September periods respectively. During the transition seasons of the March - May and October – November periods, the winds over the northern Indian Ocean are much lighter, which allows the ocean to warm up (Kijazi and Reason, 2005; Mapande and Reason, 2005; Kabanda and Jury, 2000; Mpeta and Jury, 2001). The climate variability in Africa, Asia, and Australia is partly controlled by the basin scale modes of variability in the Indian Ocean, for example the IOD and ENSO, which occur on seasonal to interannual time scales (Saji et al. 1999; Reason et al. 2000). Many of the events which affect climate variability over the region are associated with the Indian and the Atlantic oceans. The excessive rainfall of 1961, 1964, 1967, 1994, 1972, 1997/98 over East Africa, the floods of 2000 over Mozambique, and the intense droughts of 2000 - 2004 over Zambia, Malawi, and Zimbabwe are linked to large scale climate features (Reason *et al.* 2004; Saji *et al.* 1999; Behera *et al.* 2005). During the wet summers, when El Niño is present, the SST anomalies extend from east to west over the Indian Ocean. These SSTs are higher over the western Indian Ocean and lower over the eastern Indian Ocean near the Sumatran coast. The ENSO is believed to have a diverse affect over the region, where during an El Niño (warm phase of ENSO), most of the East African regions receive above average rainfall, while during a La Niña (cold phase of ENSO) most of the East African states experience below normal rainfall (Kijazi and Reason, 2005; Mhita et al. 2003).

The concept is reversed over the southern African states, during El Niño; most of the southern African countries tend to experience droughts, while floods are known to occur during the La Niña events. However, during the 1997/98 El Niño event, the southern African states received relatively normal to above normal rainfall over most parts of the region. In addition, the SST variability over the South Indian Ocean has a strong influence on the summer rainfall over southern Africa (Reason and Mulenga, 1999; Reason et al. 2001; Behera and Yamagata, 2001).

2.4.1 Tanzanian rainfall variability.

The rainfall in East Africa mostly occurs during the boreal spring (long rains, March-May) and autumn (short rains, September -December), as the ITCZ migrates across the equator during the seasons. Sometimes the ITCZ fails to provide an even distribution of rain over the region due to other weather elements which need to be taken into consideration. The southeasterly trade winds and the northeasterly monsoons which flow from the Indian Ocean become dominant during the periods of March - May and October – December. These winds are the primary sources of moisture, which converge into the ITCZ to produce rain over the northeastern highlands, the northern coast and the Lake Victoria basin (bimodal area). The westerly flow from the central Atlantic Ocean and the northwesterly winds from the North Atlantic Ocean would flow through the Congo basin to pick up more moisture, which will then converge into the meridional arm of the ITCZ to enhance rainfall over the western areas and the south western highlands (unimodal area). The southeasterly flow and the easterly winds from the central Indian Ocean will converge along the zonal arm of the ITCZ enhancing the rainfall over the southern areas and south western highlands (Mapande and Reason, 2005; Mpeta and Jury, 2001).

Over southern and western Tanzania, a single rainy season occurs in austral summer. The ITCZ becomes more active when the sun is overhead. The maximum elevation of the sun lags behind for four to six weeks before the ITCZ becomes effective. The sun is nearly overhead on the 21^{st} of March and again on the 23^{rd} of September, and the ITCZ becomes most effective about a month later around April/May and October/November respectively (EAMD, 1963). The movement of the ITCZ leads to the short rains in bimodal areas during the October - December (OND) period, and the longer rains during the March - May (MAM) period. Both movements are associated mainly with the zonal arm of ITCZ (Griffiths, 1959; Nyenzi, 1992; and Ogallo, 1989). The unimodal areas receive a single peak of rainfall distribution linked with both the meridional and zonal arm of the ITCZ. The meridional arm lies mainly over western Tanzania while the zonal arm of the ITCZ covers the north eastern highlands extending to the northern coast; southern coast, southern areas and the south western highlands. Southern Tanzania is mainly a unimodal area where the rainy season starts in mid November and ends in early May.

The previous studies show that the rainfall variability over most parts of Tanzania is linked with the global SST anomalies (Hastenrath *et al.* 1993). The SSTs and the ENSO shows the association with interannual climate variability in the world climate. It is well known that El Niño is associated with droughts over the western tropical Pacific, torrential floods around the eastern tropics and that it modulates the weather patterns over various parts of the world (Philander, 1990). The extreme events that result in the droughts or floods in East Africa have been linked to the large scale features of general circulation, including the SSTs (Nicholson, 1996; Camberlin, 1995; Mutai, *et al.* 1998; Glantz, *et al.* 1991; Hume, *et al.* 1996; IPCC, WGII 1998; Jury and Pathack, *et al.* 1996). Janowiak (1988) showed that the rainfall anomalies during the austral summer over eastern and southern Africa are associated with the ENSO events. Indeje *et al.* (2000) noted that there are distinctive seasonal evolution patterns in East African rainfall during the ENSO cycles. Ogallo (1988) reported that 50% of the variance in East African rainfall was associated with the ENSO. It has been observed that the probability of receiving below average rainfall in East Africa during the El Niño events is low for most parts of the East Africa. Most of the above average rainfall over the northern coast appeared to be associated with the El Niño events, while the below average rainfall was associated with the La Niña events (Kijazi and Reason, 2005; Indeje, M., and Semazzi, F. H. M., 2000; Cadet, 1985; Ogallo, 1987; Ogallo *et al.* 1988; Mhita *et al.* 2003). During the El Niño of 1997/98, 80% of the country was severely affected by excessive rainfall, which left many regions flooded. The country also had a shortage of rainfall during the La Niña event of 1973/74, which induced extensive famine throughout the country (Mhita *et al.* 2003). The SSTs over the Pacific region are used as indicators for the ENSO events.

Chapter 3
Data and methodology

3.1 Data and sources

The data used in this study includes the daily rainfall data from the Tanzania Meteorological Agency (TMA), which is used to create rainfall pentads and monthly data. The pentad rainfall totals were used to investigate the onset and cessation dates, while the monthly rainfall totals were used to define distribution of rainfall composite over southern Tanzania. The Optimum Interpolation Reynolds (Reynolds *et al.* 2002) V2 SSTs produced by the National Oceanic and Atmospheric Administration (NOAA) from 1982- 2003 were used to study the Sea Surface Temperature (SST) patterns. The National Centers for Environmental Prediction (NCEP) wind data were used to study the wind patterns during the study period. The wind data (Fig 4.2 (a - n)) and derived pentad rainfall totals (Fig.4.1.2 and Fig.4.1.2 (a-e)) were from TMA for the period of 1970 – 2003. The climatology of the SSTs over the Indian and Atlantic Oceans were computed to derive the anomalies. Other variables such as the Climate Research Unit (CRU) precipitation data sets (Doherty *et al.* 1999) were employed in the correlation analysis to identify the possibility of a correlation between SSTs and the rainfall over southern Tanzania.

3.1.1 Rainfall data

The daily rainfall data was used to derive pentad totals and also used to define the rainfall distribution over southern Tanzania (see Fig.3.1 below). The Pentads values are believed to be more consistent in smoothing the patterns than the daily rainfall data, and the pentads were defined according to the calendar year. The Pentad 1 corresponds to the days 1st – 5th of January and ends on pentad 72, which includes days 27th – 31st of December (details are in Appendix 1). The distribution shows this region has a unimodal (a single peak) type of the rainfall regime, where the rains starts in pentad 61 (2nd -6th of November) and ends around pentad 30 (27th May – 1st June) of the following year. The rainfall data used were for five stations, four were synoptic meteorological stations and one was a voluntary rainfall station. The synoptic stations are Mbeya, Iringa, Songea and Mtwara, while the Tunduru station is the voluntary rainfall station. Mbeya and Iringa are in the south western highlands, while Songea and Tunduru are in the southern region. Mtwara station is situated along the southern coast of Tanzania. All rainfall data used were from the 1970 – 2003 period, except for Tunduru which has data from the 1970- 2000 period. The data underwent quality control by the TMA and there was little data missing. The missing values were replaced with the long term mean. In Tanzania, most of the rainfall stations have long rainfall records (since 1921), which were observed using the standard rain gauge.

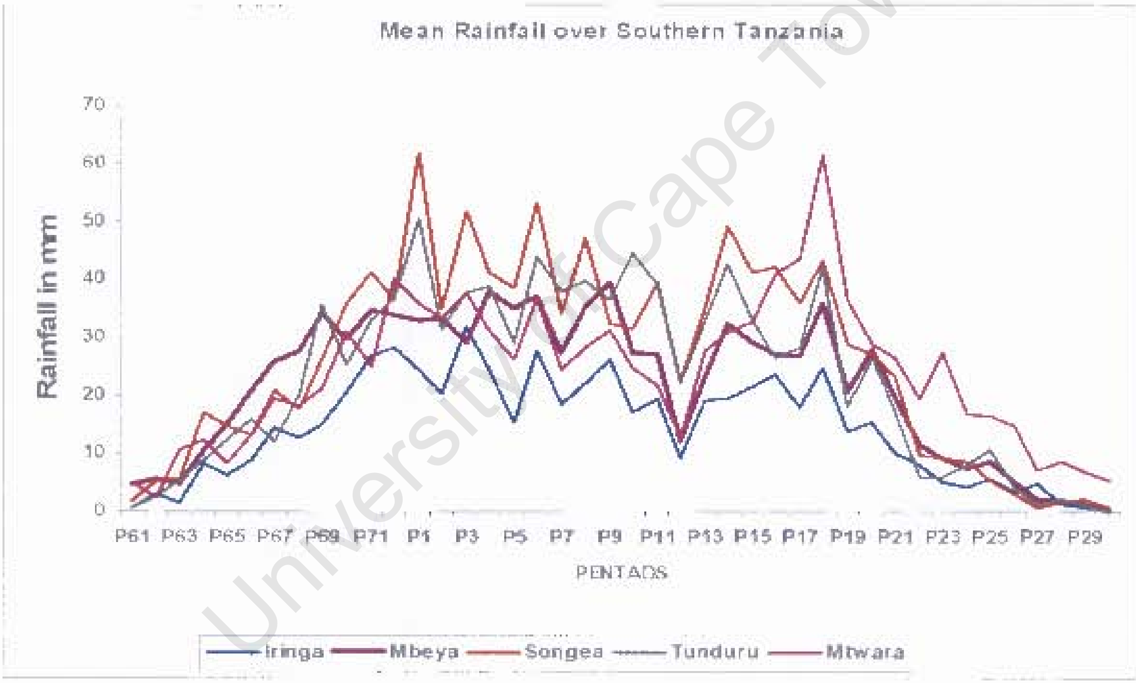


Fig.3.1: The seasonal mean rainfall distribution over southern Tanzania for the period of 1970 – 2003, where the rainfall is in mm per pentad. The distribution analysis was done from pentad 61 (2nd – 6th November) up to pentad 30 (27th May – 1st June) of the following year.

3.1.2 Sea Surface Temperature and Wind data

The sea surface temperature (SST) data used were from the Optimum Interpolation (OI) Reynolds SSTs data set, produced by the NOAA. The monthly OI Reynolds SST data sets for the period of 1982 - 2002 were computed from the October - May periods for the study of the evolution of the SSTs over the Indian and Atlantic Oceans (Fig.4.3 and Fig 4.3(a-h)). The KNMI climate Explorer website was used to extract the OI Reynolds SST for the OND and JFM seasons over the Indian and Atlantic Oceans. The data were used to correlate them with the southern Tanzanian rainfall (Fig. 5.2(a – f)).

3.2 Methodology

This section highlights different methods used in this study. Different analysis techniques have been employed to study the evolution of interannual and intraseasonal variability. This will be discussed in more details in chapter 4.

3.2.1 Spectral analysis

A spectral analysis was performed for the period November - March to determine the signals that influence the rainfall variability over southern Tanzania. The SSTs global signals in the NINO 3.4 region and the SSTs over the Indian and Atlantic Oceans were used to correlate with the rainfall over southern Tanzania.
The NINO 3.4 region is in the Pacific Ocean (5^0S - 5^0N; 170^0 W -120^0 W) is the region used to monitor SSTs anomalies which may influence the climate variability in the world. NINO3.4 region generally preferred because the SST variability in this region has the strongest effect on shifting rainfall in the western Pacific. And in turn shifting the location of the rainfall from the western to central Pacific modifies greatly the location of the heating that drives the majority of the global atmospheric circulation. Therefore the ENSO index of the NINO3.4 region and the Indian Ocean zonal dipole mode index from the NOAA website were extracted and used to study the relationship of rainfall over southern Tanzania.

3.2.2 Composite analyses

A seasonal composite analysis was performed using the rainfall pentad values. The composite product consists of a parameter value at the same level at each grid point in the domain and was divided by the same size to get a mean value. This technique has been used by many researchers, such as Cadet (1985), Mukarami (1988), Matarira and Jury (1992), Park and Schubert (1993), Levey (1993), Nassor (1994), Kabanda and Jury (1999); Kijazi and Reason (2005); Mapande and Reason (2005) and others. The advantage of composite analysis is that it can isolate outliers, and the patterns are more identifiable than those found in individual cases. Furthermore this method can considerably reduce the total number of maps and figures needed. Therefore, in this study we used seasonal composite analysis to investigate patterns associated with the wet (dry) evolutions. And also the wind composites at 850 and 200 hPa for the November - March seasons, which were used to investigate systems in the atmosphere that are responsible for the wet and dry spells.

The rainfall variability for the rainy season of the November - May periods will be discussed in chapter 4. The rains were defined in pentads starting from pentad 55 in the October to pentad 72 at the end of the December, proceeding to pentad 1 in January to pentad 30 in May of the following year (Fig.4.3 (a-h)) below. The pentads were defined according to the calendar year (appendix1). These pentads were used to define onset and cessation dates for the seasons of 1970 - 2003.

Chapter 4

4.1 Climatology of selected meteorological parameters

The Indian Ocean plays a vital role in supplying moisture to the monsoon circulations of India and East Africa (Schott and Julian, 2001). Over the past few decades, the ENSO, the monsoons and Indian Ocean SST variability appear to be associated with other components of the regional climate of Tanzania. However, analysis of variations in the Indian Ocean SST on the decadal and longer time scales is hampered by limited observations (Schott and Julian, 2001). The climate variability in the western Indian Ocean, which is adjacent to the eastern African coast, is reflected in the seasonal changes of the SSTs, currents, and atmospheric convergence zones.

The previous studies show that the rainfall over Tanzania is mainly associated with the ITCZ in strength and position, which oscillates through the region twice a year. It has been observed that the northeasterly monsoon and southeasterly trade winds converge into the ITCZ to produce rain during the October - December (OND) and March - May (MAM) periods. The warming or cooling in the Atlantic and Indian Oceans also appear to have an influence on rainfall distribution over southern Tanzania, but to what extent remains unknown. The main focus of this chapter is on the onset and cessation dates of the southern Tanzanian rainfall, as well as the changes that take place in the monthly mean fields of the SSTs and atmospheric circulation.

4.1.2 Climatology of southern Tanzanian Rainfall

The rainfall composite shows that the rainfall distribution in southern Tanzania is characterized by a unimodal (or single peak) distribution, where the rains appear to start around the first pentad of December (pentad 67) and end during the last pentad of April (pentad 24) the following year (Fig 4.1.2). The rainfall distribution of the independent stations has been shown to differ slightly from place to place.

Therefore one may find worth studying the characteristics of the rainfall stations, separately.

When the individual stations are investigated, we find that the Mtwara rainfall data (Fig 4.1.2a) shows the onset is likely during the first pentad of December (pentad 67), while cessation is during the second pentad of May (pentad 26). The Tunduru rainfall (Fig 4.1.2b), starts during the last pentad of November (pentad 66) and ends during the third pentad of April (pentad 21). For Songea the rainfall figures (Fig 4.1.2c) shows that the onset of the rainy season is during the fourth pentad of November (pentad 64), and the cessation is during the fourth pentad of April (pentad 22). For Mbeya the rainfall figures (Fig4.1.2d) show that the onset is during the fifth pentad of November (pentad 65), and ends is in the fourth pentad of April (pentad 22). The Iringa rainfall (Fig 4.1.2e) shows that the onset is during the first pentad of December (pentad 67), and ends in the third pentad of April (pentad 21).

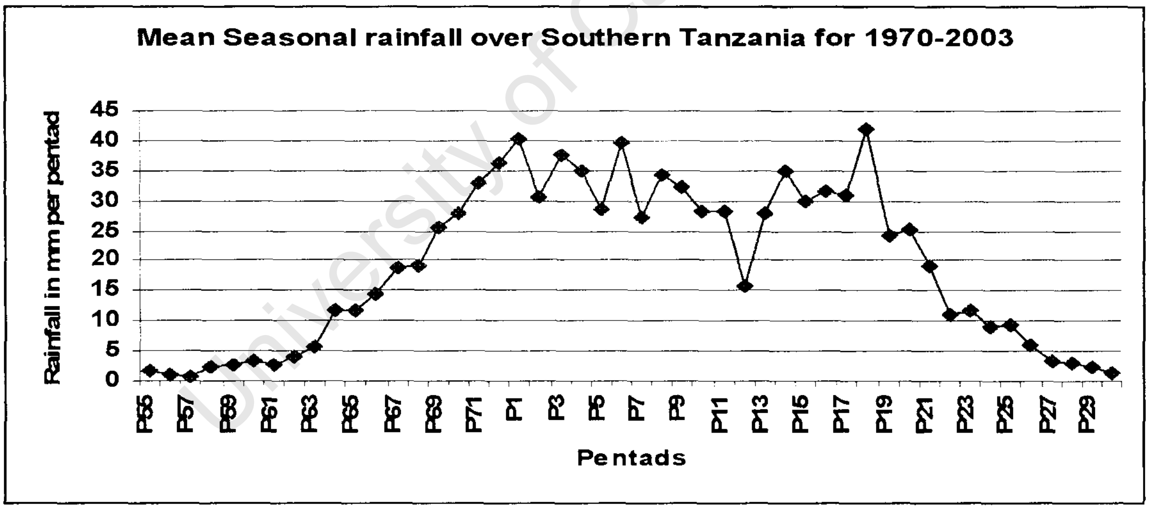
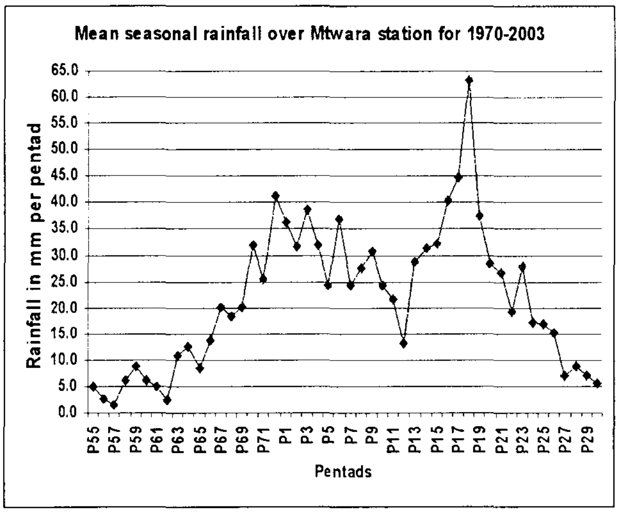
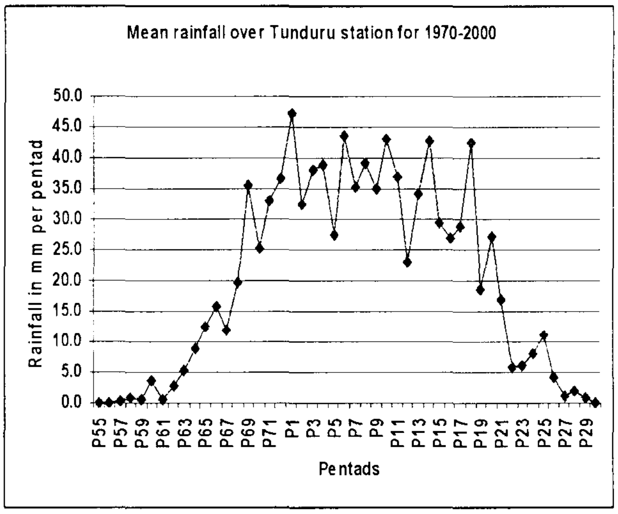


Fig.4.1.2: The southern Tanzanian rainfall composite (from 1970-2003) in pentads, where rainfall is measured in mm. The data starts from pentad 55, which corresponds to the days 2^{nd} – 6^{th} of the October through to pentad 30 of 27^{th} May – 1^{st} June of the following year.

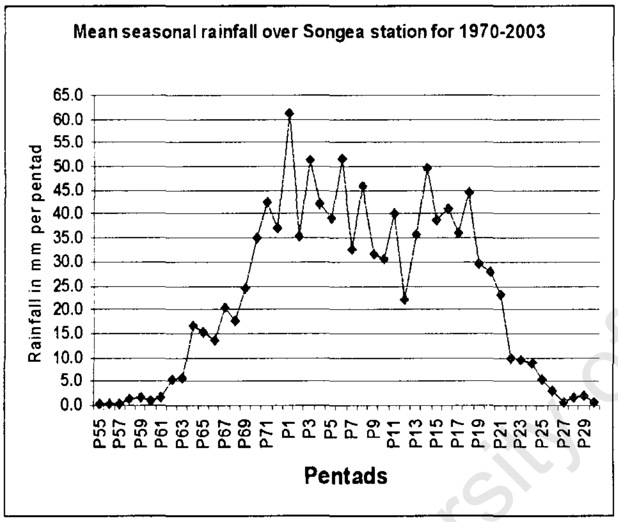
a) Mtwara rainfall station



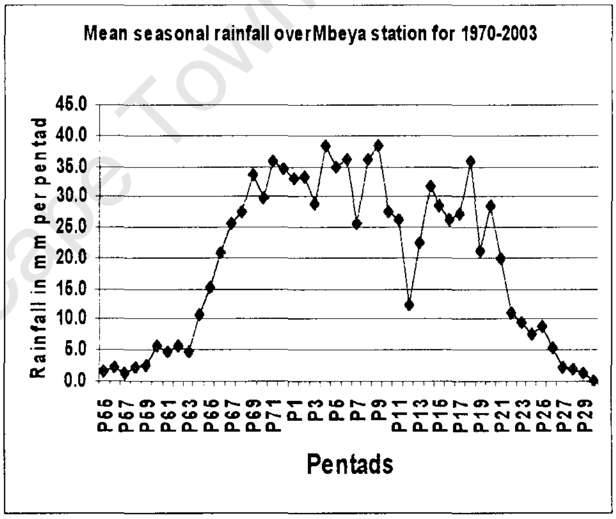
b) Tunduru fall station



c) Songea rainfall station



d) Mbeya rainfall station



e) Iringa rainfall station:

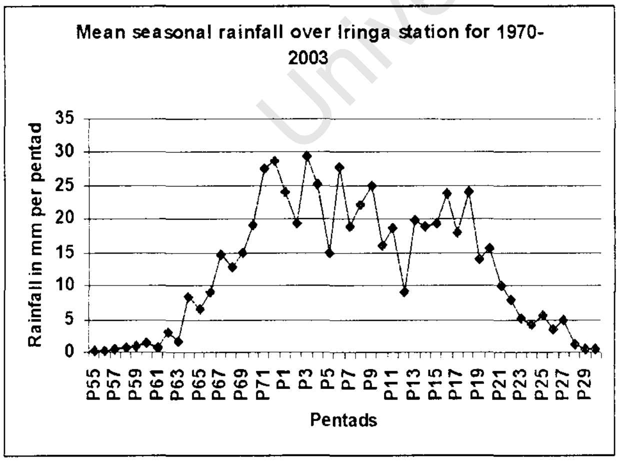


Fig. 4.1.2(a- e): Rainfall pattern for the five southern Tanzania stations for the 1970 - 2003 periods.

These pentad results show that the rainfall composite of southern Tanzania has the onset of the rainy season during pentad 67, which agrees with the onset of Mtwara and Iringa rainfall. At the Songea station the rain starts earlier, (onset is during pentad 64), followed by Mbeya station (pentad 65) and then Tunduru station (pentad 66). During the cessation, Iringa and Tunduru are the first stations to experience the cessation of the rainy season (pentad 21), followed by Songea and Mbeya (pentad 22). Mtwara is the last, where its cessation is during pentad 26, and thus it has the longest rain season in the region. Iringa station has the shortest rainy season in the region.

Table 4.1.2: Onset and cessation dates in pentads.

Station name	Onset date (in pentad)	Cessation date (in pentad)	Seasonal length (In pentads)
Southern TZ	67	24	32
Mtwara	67	26	32
Tunduru	66	21	28
Songea	64	22	31
Mbeya	65	22	30
Iringa	67	21	27

We now look at what factors may play a role in the timing of the rainfall over these regions. Particular focus is placed on the atmospheric circulation, which is linked with the ITCZ, and the SST variability in the Indian and Atlantic Oceans. The following sections, which illustrate and discuss the monthly composites of the atmospheric circulation and the SSTs, will provide a good indication of what seasonal changes take place that influence the rainfall in southern Tanzania.

4.2 Mean Monthly Atmospheric Circulation

The lower tropospheric winds are significantly influenced by the coastal topography, which varies greatly as we move inland from the Indian Ocean. As previously mentioned, most of the country is at least 200m above mean sea level, except the 100 km wide coastal strip. About a 100 km from the coast, the ground rises rapidly westwards, to about 1.5km or more, above the mean sea level (Asnani, 1993). The lower tropospheric winds during the January - March period off the southern coast were observed to have an easterly component. The winds rise over the slopes of the high grounds, which lie roughly parallel to the coastal strip. When the rising airs has sufficient moisture, clouds then begin to develop. Most of the rainfall observed over eastern Tanzania results from interaction between the moist easterly trade winds and orographic lifting (Kijazi and Reason, 2005).

Figures 4.2 (a-n) below are the monthly plots of climatological winds at 850 and 200 hPa for the November – May period. The seasonal rains over southern Tanzania typically start in mid November and end towards the end of the April. The ITCZ, which is associated with rainfall distribution, has a great influence on the onset and cessation dates of the rainy season. The 850 and 200 hPa levels have been used to infer areas of likely convergence and divergence and hence potential convection.

During November (Fig 4.2a) the ITCZ has begun to move southwards as it follows the movement of the sun. Its mean position is well defined over the equatorial Indian Ocean, which is indicated by the weak southeast monsoon and northeast monsoon at about 5^0S near the Tanzanian coast. The strong low level easterly flow from the central Indian Ocean, together with the weak moist south easterly will flow into southern Tanzania and may trigger the onset of the rainy season over the region.

The position of the ascending limb of the Walker circulation can now be identified by the presence of a low level weak cyclonic feature near the 25^0S, 40^0E and an anticyclonic feature located near the 10^0S, 45^0E at 200hPa level (Fig. 4.2b). The strong upper level westerly flow is observed south of 15^0S.

During December (Fig 4.2c) the weak low level easterly was backing to westerly in the central equatorial Indian Ocean, highlighting a shift of the ITCZ to about 8^0S. This is where the northeast monsoon circulations converge with the southeasterly trade winds, marking the position of the ITCZ over the central Indian Ocean. East of Madagascar, the easterly winds are dominant, which signifies the relaxation or shifting further south of the subtropical high pressure over the southwest Indian Ocean. Similarly the weak westerlies were observed over the Congo basin. Over western Tanzania, the low level north easterlies from the western Indian Ocean and weak westerlies from the Congo basin converge, marking the position of the meridional arm of the ITCZ. These low level winds which converge over western Tanzania reflect an increase in rainfall over the western and south western highlands (Mapande and Reason, 2005). The 200 hPa level plots (Fig 4.2d) show a weak anticyclonic flow over Angola during the same period.

The Walker circulation is still not well defined, although one may suggest the rising limb of the Walker circulation is located over southern Africa. At the 850 hPa level, a convergent wind pattern was observed along the coast of Tanzania, with an easterly flow over the equatorial western Indian Ocean.

During January the ITCZ is located south of Tanzania with its southernmost position being over the Mozambique Channel at about 20^0S, where easterly trade winds converge with north easterlies (Fig 4.2e). This is evident with the rainfall increase which occurs over the region (Fig 3.1above). Over western Tanzania, the north easterlies from the northwest Indian Ocean together with westerlies from the tropical southeast Atlantic Ocean will converge along the Lakes, Victoria and Tanganyika. These trade winds converge at about 10^0S indicating the position of meridional arm of the ITCZ. Over the Tanzanian coast, the westerly flow over the western Indian Ocean feeds the maritime convection.

The ascending branch of the Walker circulation is located around 10^0S, 40^0E (Fig 4.2e and Fig 4.2f). The cyclonic flow observed over the Mozambique Channel is enhancing convective activities over the southern coast of Tanzania. Over the southern Indian Ocean, the subtropical anticyclone systems are beneath the descending branch of the Hadley circulation shift lies further south. At the upper levels, the strong westerly flow has shifted southwards to 25^0 S (Fig 4.2e).

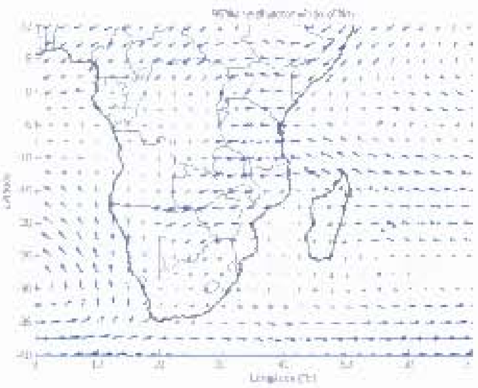
In February (Fig 4.2g) the ITCZ is now at its southern most position. The ITCZ mean position over the Indian Ocean is indicated by a weak westerly flow at low levels (850 hPa) at about 15^0S. The Angola low has also deepened, which signifies the reduction of the moisture over western Tanzania, and this, together with the southward migration of the ITCZ, leads to the decrease of rainfall over southern Tanzania. This is reflected in the rainfall data, which shows the minimum rainfall values were obtained during the 12^{th} pentad (26^{th} of February – 1^{st} of March) for all stations (Fig 3.1 above). At the upper levels, the wind pattern has similar characteristics to those found in January.

During March (Fig 4.2i) the ITCZ begins to retreat northward as it follows the seasonal movement of the sun. Weak westerlies were observed along the Tanzanian coast, while the southeasterly winds had intensified inland. This is reflected in the cessation of the northeast monsoon and onset of the southeast monsoon over the Indian Ocean. This is referred to as a transition period, which is associated with the retreat of the ITCZ from the Southern Hemisphere to Northern Hemisphere. Over the northern Atlantic Ocean, the ITCZ also starts to move northward as indicated by the weak north easterlies and south easterlies observed along the equator. The Angola low has filled up, which results in offshore winds along the coast of Angola. Over the Western Indian Ocean the low level cyclonic flow observed over the Mozambique Channel becomes much weaker and the ITCZ has shifted northward, evidenced by the weak wind field along the southern coast of Tanzania, implying enhancement of the convective activities over there. This result in an increase in rainfall over the region, which is reflected in the maximum rainfall measured during the last pentad of March over southern coasts. For example, Mtwara station (Fig 3.1) received the highest amount of rainfall compared to the other stations in the region of interest. Fig. 4.2j shows the wind plot at 200hPa level, indicating the increase of a westerly flow south of 25^0S.

In April (Fig 4.2k) the ITCZ is located at about 2^0S, while over the southern Indian Ocean, the anticyclonic cell has intensified and shifted northwest. The low level southeasterly winds are now dominant over the entire eastern African region, with the weak westerlies over the central equatorial Indian Ocean. The southeasterly flow has strengthened over southern Tanzania, implying linear divergence and signifying the end of the rainy season over the region. The westerly flow at the 850 hPa and the weak easterly flow at 200 hPa over the equatorial western Indian Ocean (near 8^0N) mark the position of the ITCZ. Over the Atlantic Ocean near the coast of Guinea, the discontinuities of winds reflect the position of the ITCZ there. So the ITCZ has shifted further north and the ascending limb of Walker circulation is well defined at about 7^0S, 60^0E (Fig 4.2k). The winds at the 200 hPa level (Fig. 4.2l) are similar to those found in the month of March at the same level.

During the month of May (Fig 4.2m) the ITCZ is now positioned north of the equator and the southern Indian Ocean anticyclone has shifted further northwest. The strong low level easterly backing to southeasterly was a dominant feature over the entire eastern African region. The easterly flow veers to the south westerly over the Somalian coast, forming the Somali jet that feeds into the Indian monsoon. The wind patterns reflect low level divergence over southern Tanzania. Figure 4.2n shows similar circulation features at the 200 hPa level as it was during the month of April. The low level easterlies winds (westerlies) over the southern (Equatorial) Indian Ocean feed into the convection zone. Little rain is expected over northern Tanzania and the development of stratus clouds takes place along the eastern slopes of the northern coastal region.

a) 850 hPa November



b) 200 hPa November

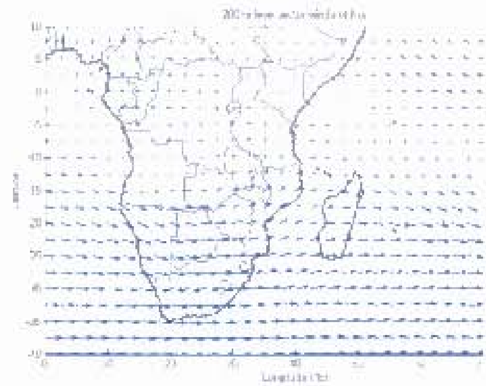
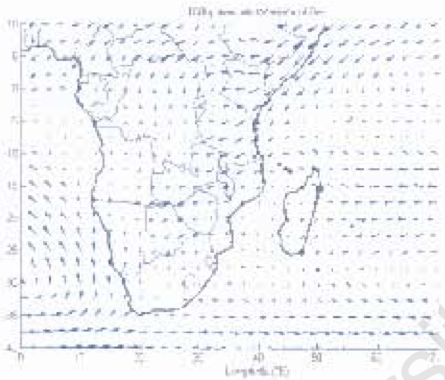
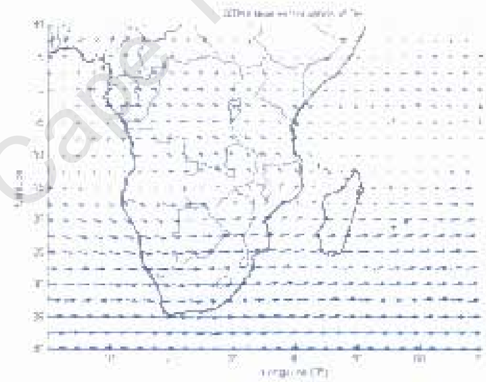


Fig. 4.2(a-n). Monthly mean Wind vectors for the period of 1970- 2003 at 850 hPa level (right) and 200 hPa level (left)

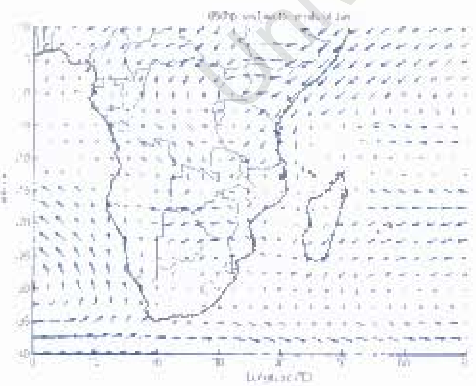
c) 850 hPa December



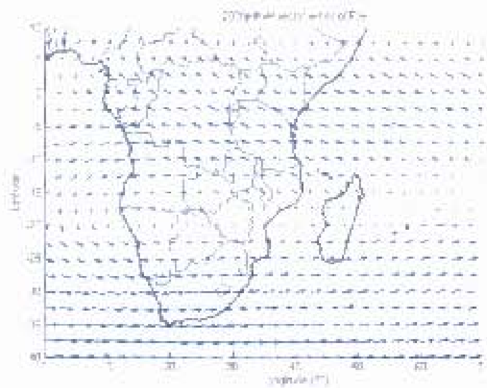
d) 200 hPa December



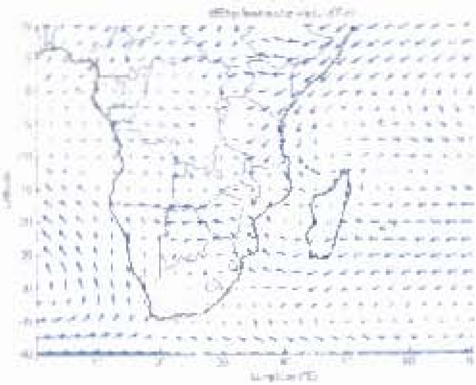
e) 850 hPa January



f) 200 hPa January



g) 850 hPa February



h) 200 hPa February

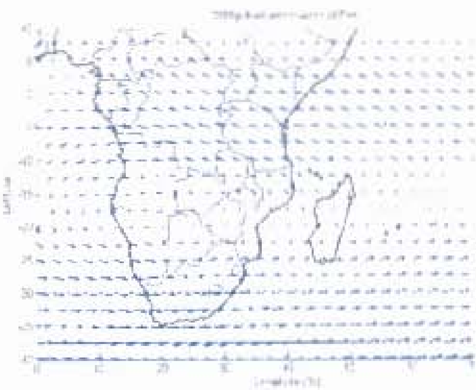
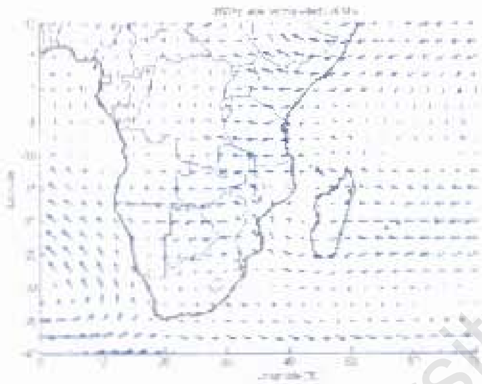
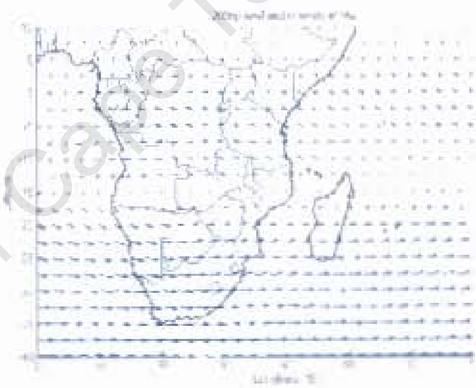


Fig. 4.2(c-h): Cont.

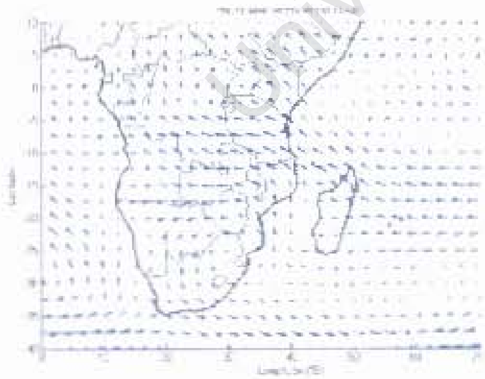
i) 850 hPa March



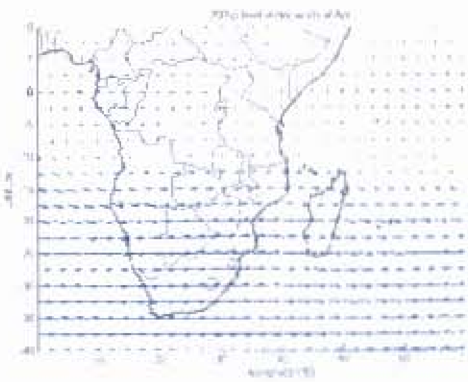
j) 200 hPa March



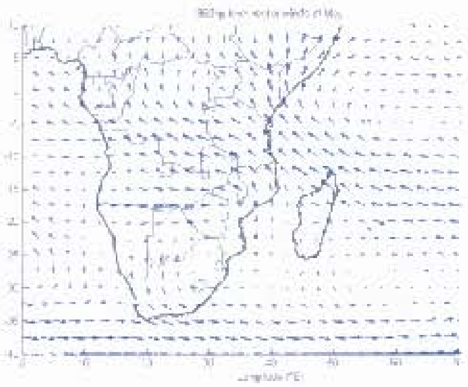
k) 850 hPa April



l) 200 hPa April



m) 850 hPa May



n) 200 hPa May

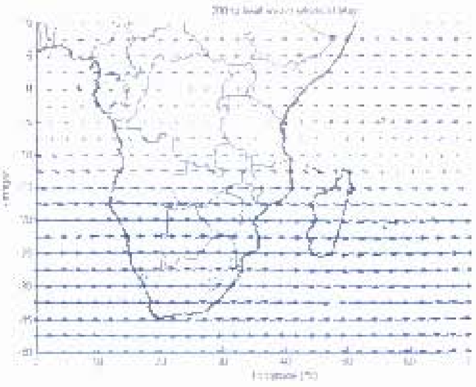


Fig. 4.2(i-n): Cont.

4.3 SST climatology

The moist air that originates over the Indian Ocean flows over the topography in southern Tanzania and may result in the production of rainfall. Thus, it is important to obtain a better understanding of the climatology and variability of SSTs in the Indian and Atlantic Oceans, because they may have an influence on rainfall variability over southern Tanzania.

The monthly OI Reynolds SST data was averaged seasonally (November - March) for the period of 1982-2003. Fig 4.3 represents the mean SST for the November - March period, over both the Indian and Atlantic Oceans. Over the Indian Ocean, a pool of warm SST (above 28^0C) extended from the northwest Indian Ocean to southern Mozambique Channel. Over the Atlantic, the SST above 28^0C is above the equator along the coast of Guinea. The monthly composites of the SST in these two oceans are shown in Fig 4.3 (a-p). It is likely that the variation in the SST is associated with the movement of the sun as manifested by location of the ITCZ in the tropical oceans. The development of the ITCZ increases significantly when it is positioned over the areas where the SST values extend above 28^0S. For example, during the austral summer, the position of the ITCZ lies over the Southern Hemisphere around 5^0 - 10^0 S, which coincides with the SST above 28^0C (Fig 4.3). Over the Atlantic Ocean, the ITCZ is located at about 5^0N where the SST is above 28^0C.

In October, the ITCZ is located between 1^0 - 2^0S, where high SST values are observed over the Indian Ocean (Fig 4.3a). Over the Atlantic Ocean, the highest SST values above 28^0C were observed near 5^0N. The weak easterly flow from the central Indian Ocean passes through Madagascar before reaching southern Tanzania. This easterly flow possibly did not contain enough moisture to cause the onset of the rainy season.

The onset of the rainy season in the southern Tanzania is likely in mid November, when the ITCZ has reached nearly latitude 5^0S, and it has reflected by high SST values over the Indian Ocean (Fig 4.3b). The warming of the SST over the Indian Ocean extended further south; this may promote strong low level moist easterlies flow from the central Indian Ocean to trigger the onset of the rainy season over southern Tanzania.

In December, the 28^0C SST contour extends further south into the Mozambique Channel, indicating the southward shift of the ITCZ over the Indian Ocean (Fig 4.3c), while over the Atlantic Ocean the ITCZ is still located at about 2^0N. The easterly flow from central Indian Ocean may transport enough moisture from the southwest Indian Ocean to cause rainfall over southern Tanzania. The rainfall data from the stations, which has been computed into pentads (Table 4.1.2), suggests that the onset of the rainy season coincides with this easterly movement of moisture from the central Indian Ocean.

During January, the ITCZ migrates further south, while the 28^0C SST contour is now located over the Indian Ocean at about 20^0S (Fig. 4.3d). The moist easterly wind from the Indian Ocean flows over the coastal topography causing rainfall production over southern Tanzania. This pattern is reflected in some of rainfall stations which attain their maximum rainfall in January (Tunduru in Fig 3.1).

In February when the ITCZ is at its southernmost position over the Indian Ocean, the 28^0C SST contour lies at about 20^0 S (Fig 4.3e). Over the Atlantic Ocean, a southward shift of the maximum SST was observed; however the ITCZ is still positioned to the north of the equator (near the SST value of about 28^0C). The low level divergence and northeasterly winds over the southern coast has an influence on the transportation of moisture, which results in a rainfall deficit over southern Tanzania. Again, this is reflected in the rainfall station data, which shows the minimum rainfall (Fig. 3.1).

During March, the ITCZ starts its seasonal movement, where it now moves northwards, following the movement of the sun overhead. At the same time the 28^0C SST contour is now located at about 18^0S (Fig 4.3f). Over the Atlantic Ocean the high SST values were near the coast of Ghana. The warm SST over the southern coast of Tanzania has intensified and hence enhances convective activities in the region, which results in an increase of rainfall over southern Tanzania. The month of March is when the maximum rainfall is measured over southern coast (see Fig 3.1).

In April, the northward shift of the ITCZ is reflected in the high values of the SST over the Indian Ocean extending northwards. The SSTs with values exceeding 28^0C were observed north of Madagascar (Fig 4.3g). Over the Atlantic Ocean, the ITCZ is now found in the Northern Hemisphere. The strong cold and dry easterlies winds from the southeast Indian Ocean flow to southern coast, resulting to a reduction of rain. This signifies the withdrawal of the rainfall belt, hence initiating the cessation of the rainy season over the region.

During the month of May, the ITCZ is positioned at about 2^0S, characterized by the high SST values that exceed 29^0C over the Indian Ocean (Fig 4.3h). Over the Atlantic Ocean, the ITCZ lies in the Northern Hemisphere. The strong southeasterly is dominant over the entire country and the rainy belt is situated further north.

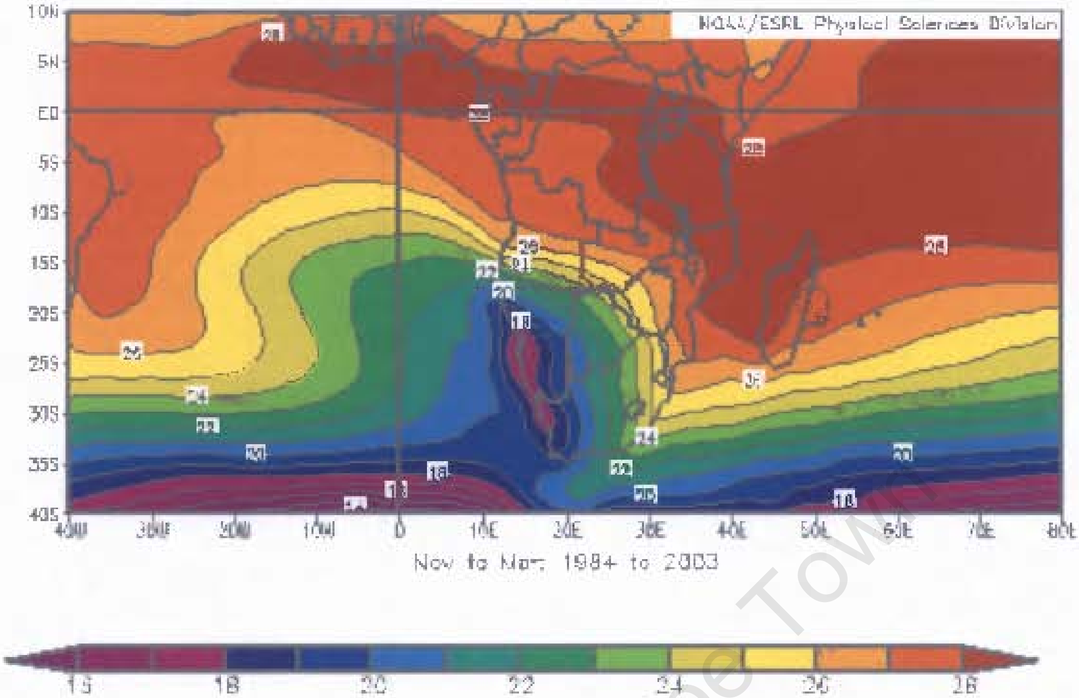
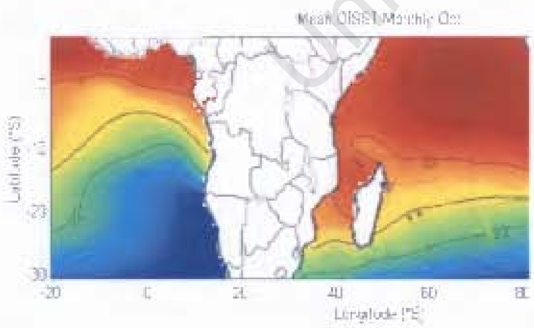
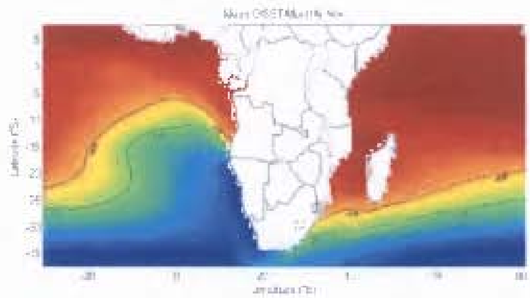


Fig 4.3: A composite of the seasonal mean skin surface temperatures for the November – March period. Where the dark red colour represents the regions of SST above 28^0C, while the dark purple colour represents the region where the SSTs below 18^0C.

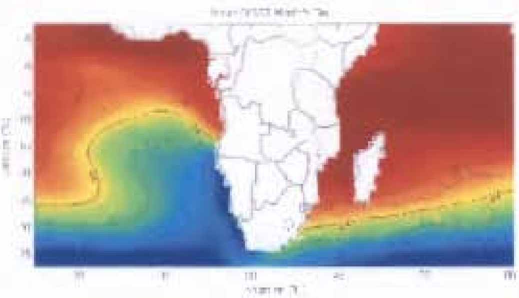
a) October



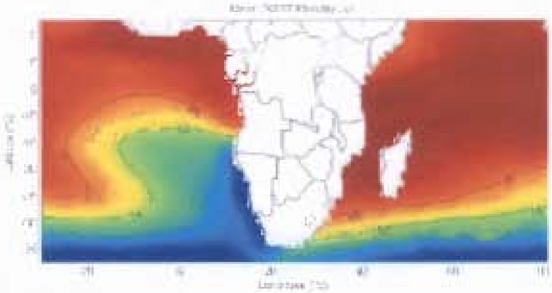
b) November



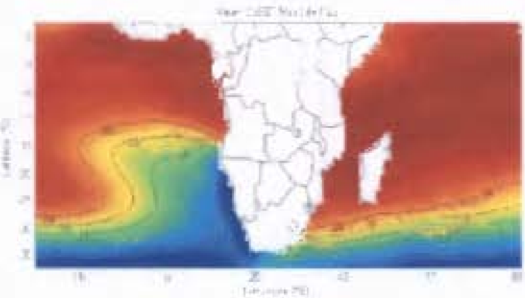
c). December



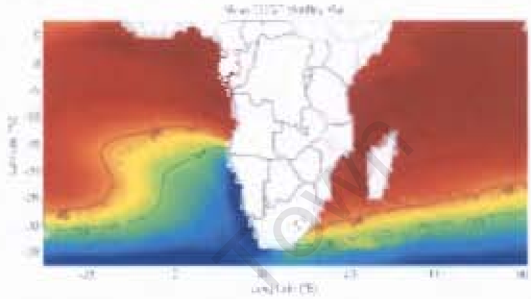
d): January



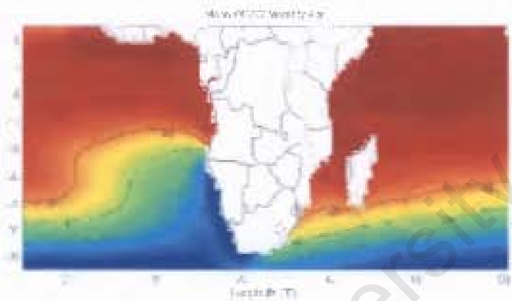
e) February



f) March



g) April



h) May

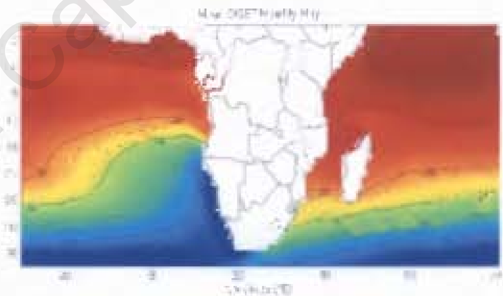


Fig. 4.3(a-h): Monthly mean Sea Surface Temperatures (SSTs) for the October – May period, where dark red colour is the region of the SST greater than 28^{0}C and the dark blue colour is the region of the SST below 16^{0}C.

Chapter 5

Result and Discussion

5.1 Interannual variability

In this chapter the interannual rainfall variability over southern Tanzania is discussed. To do this, seasonal rainfall anomalies are computed by subtracting individual seasonal means from the long term seasonal average. SST anomalies were used to investigate possible link with rainfall variability over southern Tanzania. The data was for the period of November - March. Correlation analysis was then performed using two data sets, the OI Reynolds SST (OISST) data set (Reynolds *et al,* 2002) and the CRU precipitation data set (Doherty *et al.* 1999). These data sets were available in KNMI Climate Explore website, (http://climexp.nl).

The daily rainfall data from the Tanzania Meteorological Agency, for the period of 1970-2003, was also used. The high quality and variability for all stations during this period influence the choice of this data. This data was used to investigate the evolution of wet and dry spells during the period of investigation. Previous studies have shown that the rainfall variability over southern Tanzania was mainly dependent on the movement of the ITCZ (Mapande and Reason, 2005; Mpeta and Jury, 2001). The moist air from the southwest Indian Ocean would flow over the topographic features and Lake Malawi to bring the efficiency of the ITCZ. In this chapter I will try to investigate the SST anomalies over the Atlantic and Indian Oceans as precursors that moderate rainfall variability over southern Tanzania.

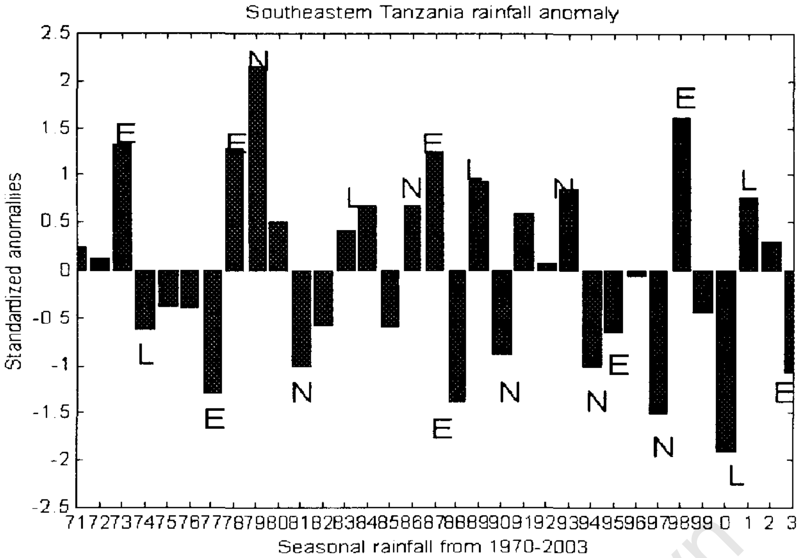
5.2 Rainfall variability

5.2.1 Rainfall Index formulation

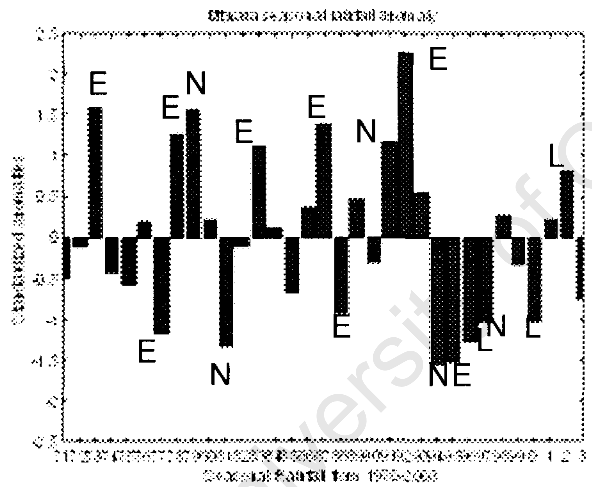
Rainfall data from five stations of southern Tanzania was normalized with respect to the mean and standard deviation using the formula N= (A-Ā)/σ, where N is the normalized departure, A is the total rainfall for the season, Ā is the climatological rainfall, and σ is the climatological standard deviation. The values of N provide significant information of a particular deviation from the mean (Nyenzi, 1988; Kijazi and Reason, 2005). The area rainfall indexes were computed by averaging time series of standardized departures from each pentad and add them to gate the seasonal value. A similar approach was used by Nyenzi (1988), Levey (1993), Makarau (1994), Kijazi (2005), Mapande (2005) and others. The reference limit used was a zero line where the years with values above zero were considered to be the wet season, while the values below zero were considered to be the dry season. The departure values greater than 0.8 or less than -0.8 away from reference line were considered as wet or dry seasons respectively. Similar values were used by Mapande (2004) and have given reasonable results. Furthermore, the seasons that corresponded with the ENSO events were denoted by E for the El Niño, L for the La Niña and N for the neutral years (Fig.5.2).

Figure (Fig 5.2a below) shows the seasonal rainfall composite index of the southern Tanzania, the individual stations are in Fig. 5.2(b – f). Then results shows that the relationship of an ENSO to rainfall variability over southern Tanzania is not well define. El Niño (warm ENSO) events could show good correlation with wet years and also with dry years. Similarly behavior has been observed during the La Niña years. La Niña (cold ENSO) events could correspond with wet years as well as dry years.

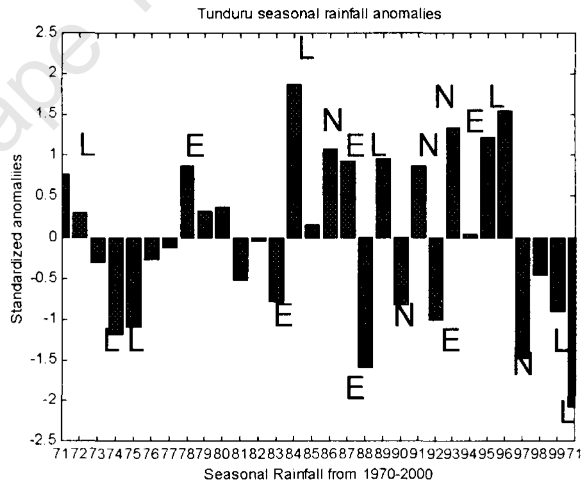
a) Southern Tanzania rainfall index



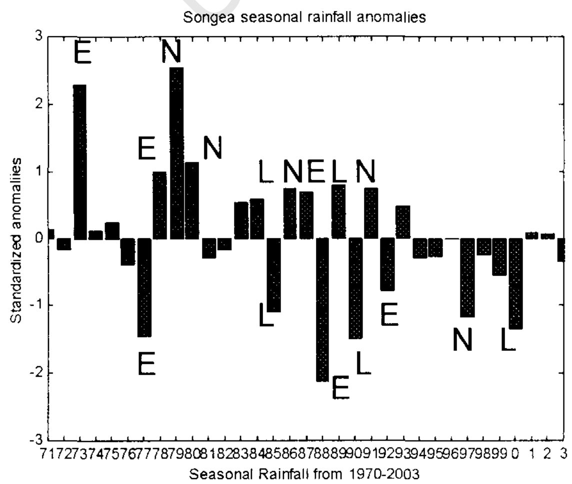
b) Mtwara rainfall index



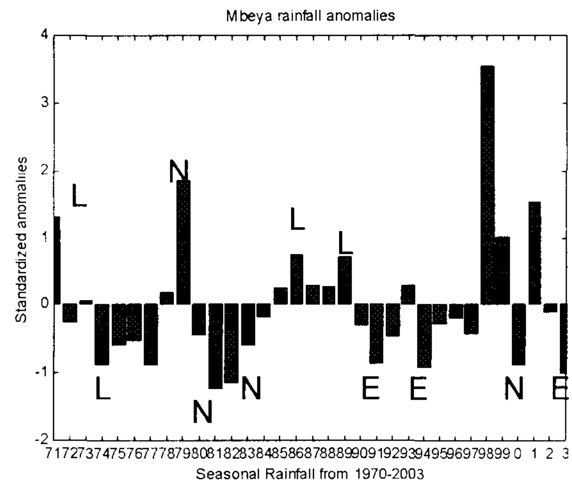
c) Tunduru rainfall Index



d) Songea rainfall Index



e) Mbeya rainfall Index



f) Iringa rainfall Index

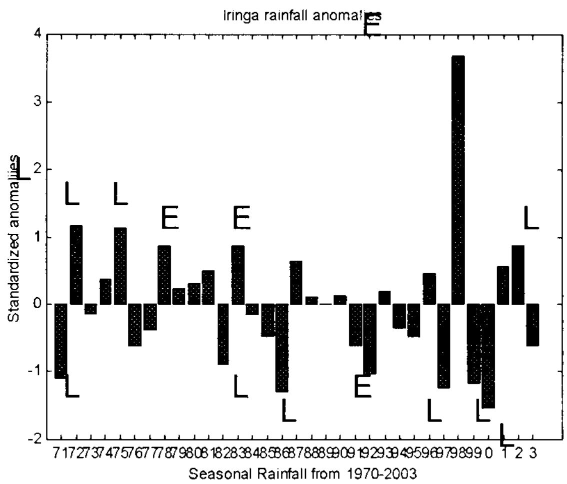


Fig. 5.2(a-f) Graphs represents station rainfall indices, starting with a) the rainfall composite for southern Tanzania and the individual stations: b) Mtwara station, c) Tunduru, d) Songea, e) Mbeya and f) Iringa, respectively, all have a mean departure of ± 0.8.

5.2.2 Wet and Dry ENSO years.

So far we have identified the anomalously wet and dry conditions over southern Tanzania for the 1970-2003 periods. Wet years were identified as 1972/73, 1977/78, 1978/79, 1985/86, 1986/87, 1988/89, 1990/91, 1992/93, 1997/98, and the dry years were 1976/77, 1980/81, 1987/88, 1996/97, 1999/00, 2001/02 and 2002/03.

Previous research has shown that ENSO events have a weak influence on rainfall over the southern coast of Tanzania (Kijazi and Reason 2005). In this study, rainfall over southern Tanzania shows strong link with ENSO events. However the link appears to be inconsistent. It has been observed that during the wet seasons of 1972/73, 1986/87, 1992/93 and 1997/98, those seasons were coincided with the El Niño years, and also the dry season of 2002/03 and was also El Niño year.

Similar observation was noted during the La Niña events. The wet season of 1988/89, was during La Niña year, while La Niña years of 1996/97 and

1999/2000, the rains were below average. It has also been observed that droughts or floods may occur during neutral (non ENSO event) years. One may suggest that there likely to be other mechanisms influencing rainfall variability over southern Tanzania.

5.2.3 The relationship between the SSTs over the Indian and Atlantic Oceans and rainfall over the southern Tanzania

The response of the surrounding oceans to rainfall over Tanzania has been documented by Kijazi and Reason (2005) and Mapande and Reason, (2005). Mapande and Reason (2005) reported that SST over the Atlantic and Indian Oceans may have less correlation or no correlation at all, with rainfall over the south western highlands. Kijazi and Reason (2005) reported that ENSO may have a weak correlation with the southern coastal rainfall. However, these authors suggested that ENSO and Indian Ocean Zone Dipole Mode (IOD) may have a strong impact on rainfall over the northeastern highlands and the northern coast during the OND rainfall. Similar findings were found by Webster *et al* (1999), Saji *et al* (1999) and Reason et al (2000). These authors suggested that ENSO events and the IOD both modulate the Indian Ocean SSTs, which then had a strong impact on rainfall over East Africa. Reason et al (2005) went further on to say that the development of dry (wet) conditions that occurred over southern Africa was associated with the warm (cold) phase of ENSO.

Correlation plots of the OISST data and the CRU precipitation during the OND and JFM periods are shown in Fig. 5.2.2. During the OND period, SSTs over the Indian Ocean were extracted form region 13.5^0 S - 17.5^0 S; 53.5^0 E - 57.5^0 E (Fig.5.2.2a), while over the Atlantic Ocean SSTs were extracted from region 22.5^0 S - 26.5^0 S; 6.5^0 E - 8.5^0 E (Fig. 5.2.2b). During the JFM, SST over the Indian Ocean were extracted from the region $9.5\ ^0$ S - 11.5^0 S; 48.5^0 E - 50.5^0 E (Fig.5.2.2c), while SSTs over the Atlantic Ocean were extracted from 20.5^0 S - 24.5^0 S; 6.5^0 E - 8.5^0 E (Fig.5.2.2d).

The central Indian Ocean, East of Madagascar have been shown to have a strong positive correlation of above 0.6 during the OND rainfall (Fig. 5.2.2a), while over northern Atlantic Ocean, above the equator along the coast of Guinea a strong negative correlation of more than -0.6 was observed(Fig.5.2.2b). During the JFM rainfall period, SST over the Indian Ocean was weak, a positive correlation of about 0.3 was observed over the Indian Ocean north of Madagascar (Fig.5.2.2c). Over the Atlantic Ocean, a strong positive correlation of about 0.6 was observed along the west coast of southern Africa and the western Atlantic Ocean, and east of South American coast (Fig.5.2.2d). The plots suggest that there is a strong link between the southern Tanzanian rainfall and the SST pattern in the Indian Ocean during the OND period than during the JFM rainfall.

Averaged CRU precipitation for the region (7.5^0 S, 33^0 E and 11.1^0 S, 40.5^0 E) was correlated with averaged OI Reynolds SST's over the Indian and Atlantic Oceans. The data was from 1982- 2002.

SST over the Indian and Atlantic Oceans during OND season

a) SST over the Indian Ocean b) SST over the Atlantic Ocean

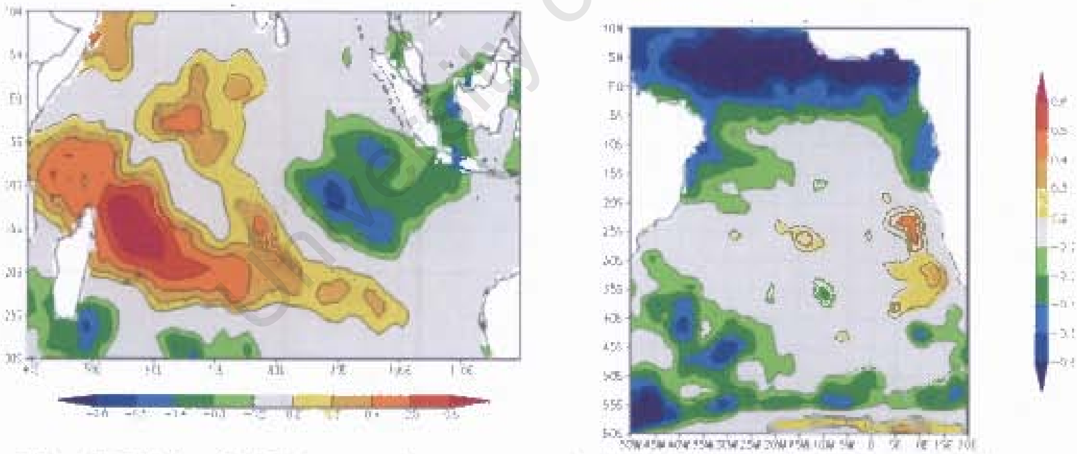


Fig. 5.2.2 (a-d): Pictures show a correlation of the SST over the Indian and Atlantic Oceans with the southern Tanzanian rainfall during the OND and JFM seasons

The SST over the Indian and Atlantic Oceans during the JFM season

c) SST over the Indian Ocean d) SST over the Atlantic Ocean

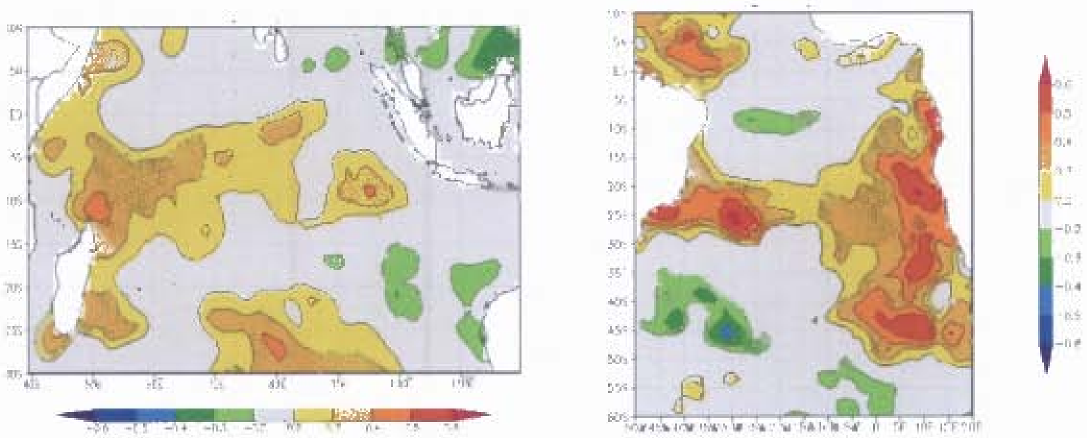


Fig. 5.2.2 (a-d): Continued...

5.2.4 The time series of the correlation of SSTs in the Indian and Atlantic Oceans with the rainfall of southern Tanzania.

The time series of the southern Tanzanian rainfall and the SST over the Atlantic and Indian Oceans for the OND and JFM seasons were analysed for the period 1982 - 2002 as shown in Fig.5.2.3 (a–b); and Fig.5.2.4 (a-b). The study seeks to delineate the behavior of the SSTs in the Indian and Atlantic Oceans with the seasonal rainfall over southern Tanzania.

Figure 5.2.3a shows the variability in rainfall over the southern Tanzanian region with the SSTs over the Indian Ocean during the OND season. The pattern of these two plots appears to be incoherent. One may find some years are in phase: others are opposite in phase and some years are completely out of phase. A Similar pattern was found with the SSTs over the Atlantic Ocean and the southern Tanzanian rainfall for the same period (Fig. 5.2.3b).

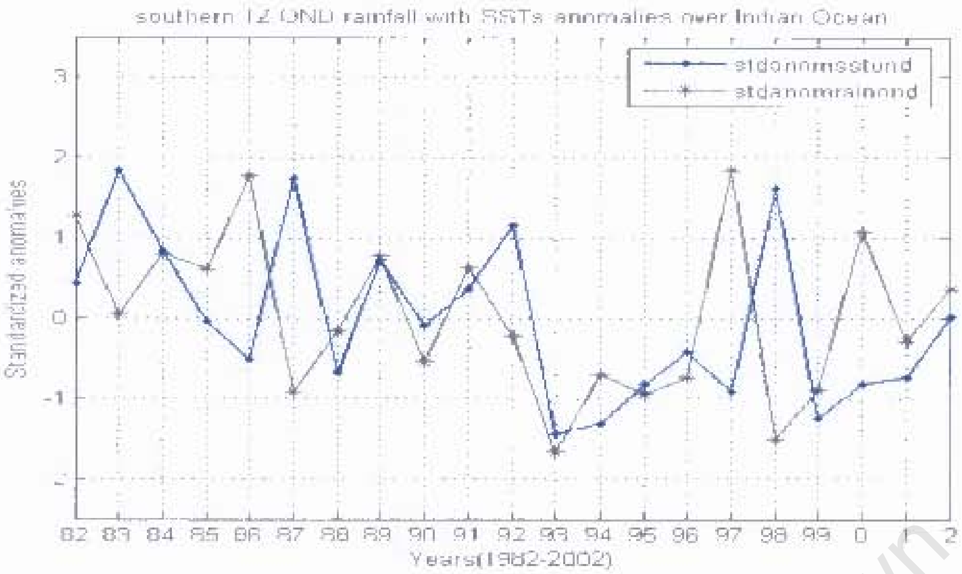
The relationship between the SSTs over the oceans and the rainfall over southern Tanzania has been tested. It has been shown that the SST over the Atlantic Ocean was 98% significant during the JFM period. The significant of 67% was obtained during the same period with the SST over the Indian Ocean. During the OND rainfall, the SSTs over the both oceans were not significant (Table 5.2.3).

The analysis of rainfall and the SST distribution was extended to those individual rainfall stations during both the OND and JFM rainfall periods. Mbeya rainfall was significant with the Atlantic Ocean during the JFM and OND periods. The significant of 95% was observed with the Atlantic Ocean during the JFM period, and significant of 98% was observed with the Indian Ocean during the OND period. For other stations observation shows that the SSTs over both Atlantic and Indian Oceans are not significant; more details are given in table 5.2.3 below.

Station	OND Indian	Sig. t-test (95%)	JFM Indian	Sig.t-test (95%)	OND Atlantic	Sig.t-test (95%)	JFM Atlantic	Sig.t-test (95%)
S.TZ	-0.0046	0.0112	0.2960	0.6738	-0.0966	0.5127	0.4530	0.9824
Iringa	-0.0296	0.0928	0.6460	0.9962	0.0202	0.0674	0.3304	0.8764
Mbeya	-0.1314	0.3595	0.3432	0.7895	-0.3497	0.9840	0.5106	0.9484
Songea	0.1235	0.3632	0.1875	0.5131	0.0832	0.3009	0.3436	0.9207
Mtwara	0.0826	0.2015	0.4085	0.8530	0.0641	0.5791	0.0203	0.0657

Table 5.2.3 the correlation and significant student t-test values for the rainfall and SSTs during the OND and JFM, where the Sig t-test presents significant t-test for the October – December (OND) and January- March (JFM) periods.

a) The rainfall and SST anomaly over the Indian Ocean during the OND period.



b) The rainfall and SST anomaly over the Atlantic Ocean during the OND period.

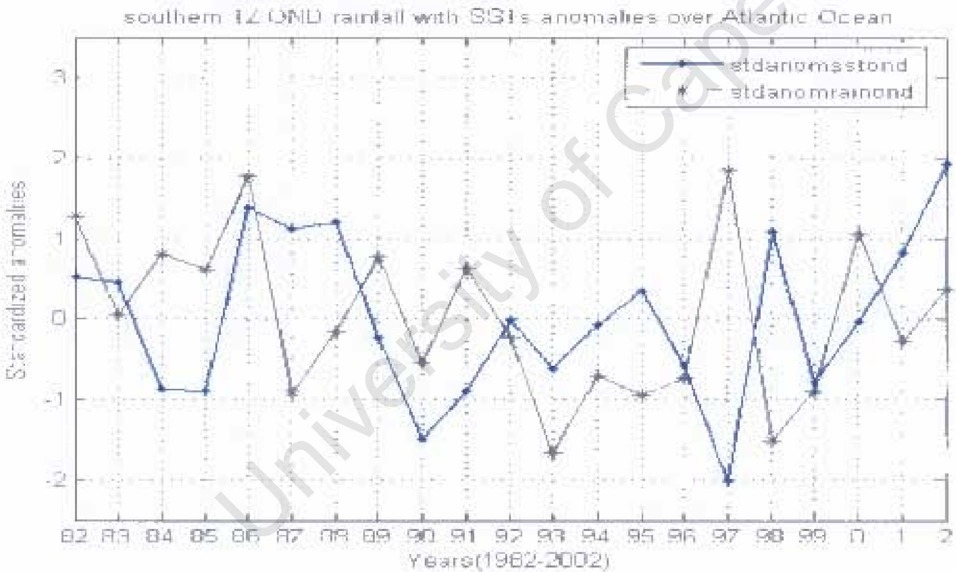
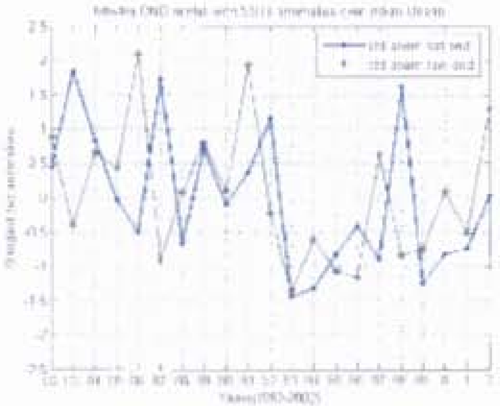
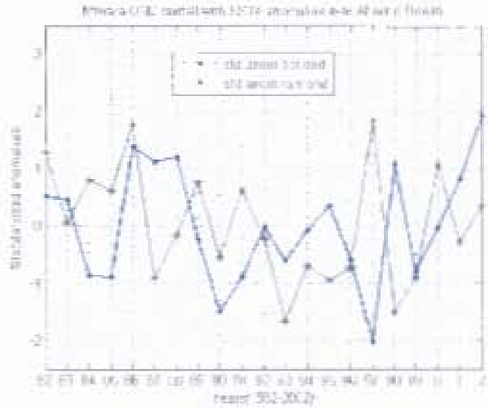


Fig. 5.2.3(a-b): Rainfall composites for southern Tanzania with the SST over the Indian and Atlantic Oceans during the OND period, where std anom sst ond presents a standard anomaly of SST during the OND period, and the std anom rain ond presents the standard anomaly of rainfall during the OND period.

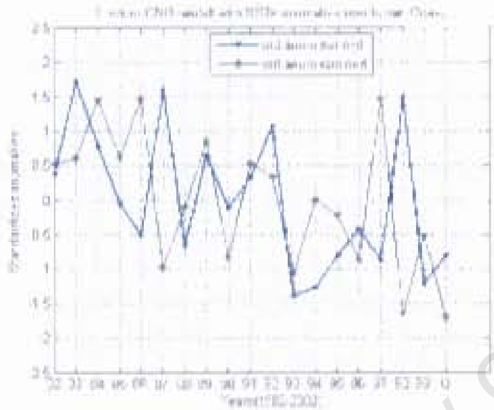
c): Mtwara and Indian during OND



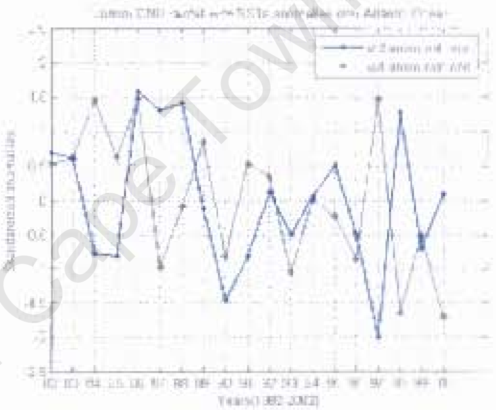
d): Mtwara and Atlantic during OND



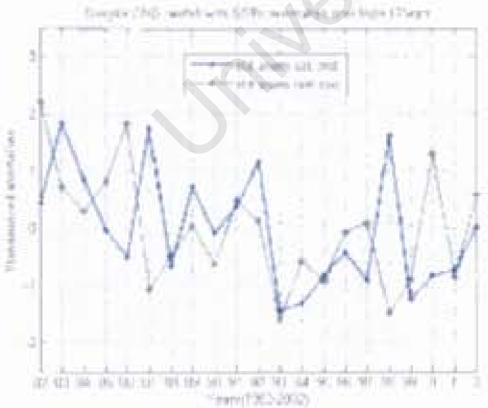
e): Tunduru and Indian during OND



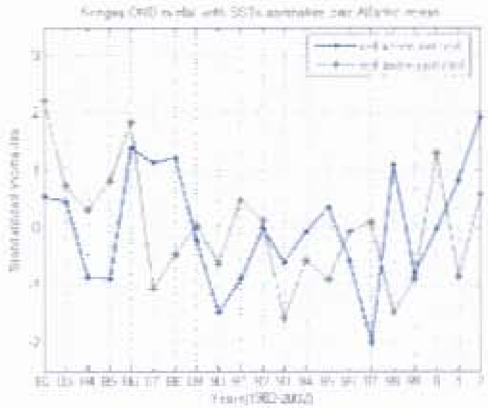
f): Tunduru and Atlantic during OND



g): Songea and Indian during OND



h): Songea and Atlantic during OND



i): Mbeya and Indian during OND

j): Mbeya and Atlantic during OND

k): Iringa and Indian during OND

l): Iringa and Atlantic during OND

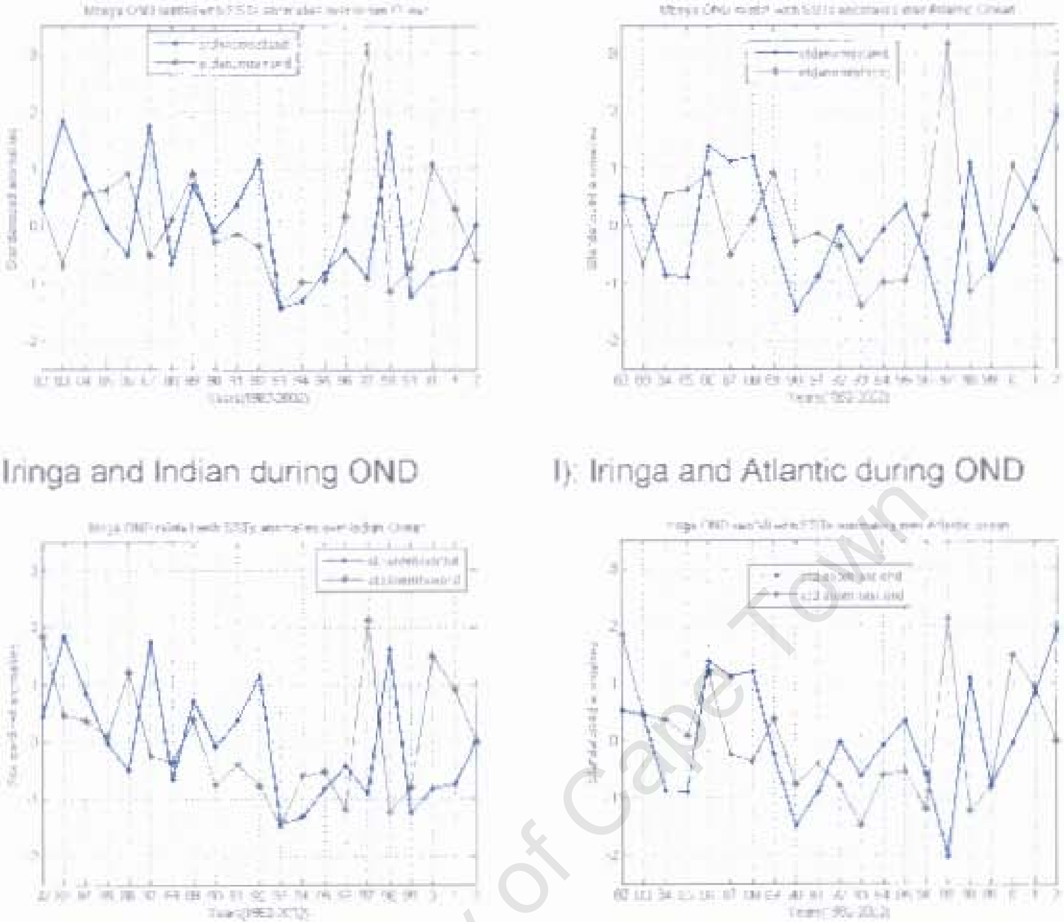
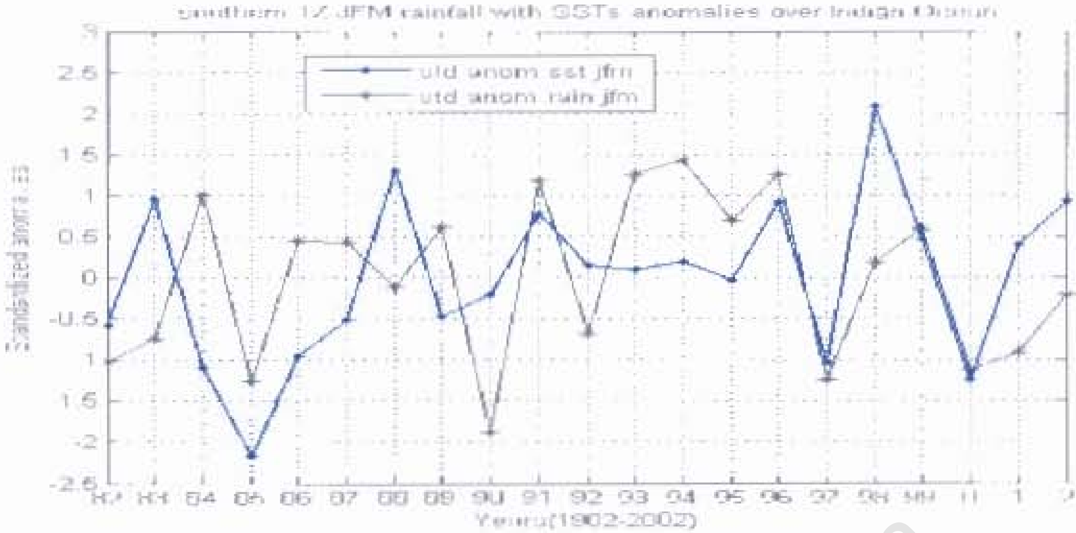


Fig. 5.2.3(c-l): Independent rainfall stations with the SSTs during the OND period, where the std anom sst ond presents the standard anomaly for the SST during the OND period, and the std anom rain ond presents a standard anomaly for the rainfall during the OND period.

a) The rainfall and the SST anomaly over the Indian Ocean during JFM period.



b) The rainfall and the SST anomaly over the Atlantic Ocean during JFM period.

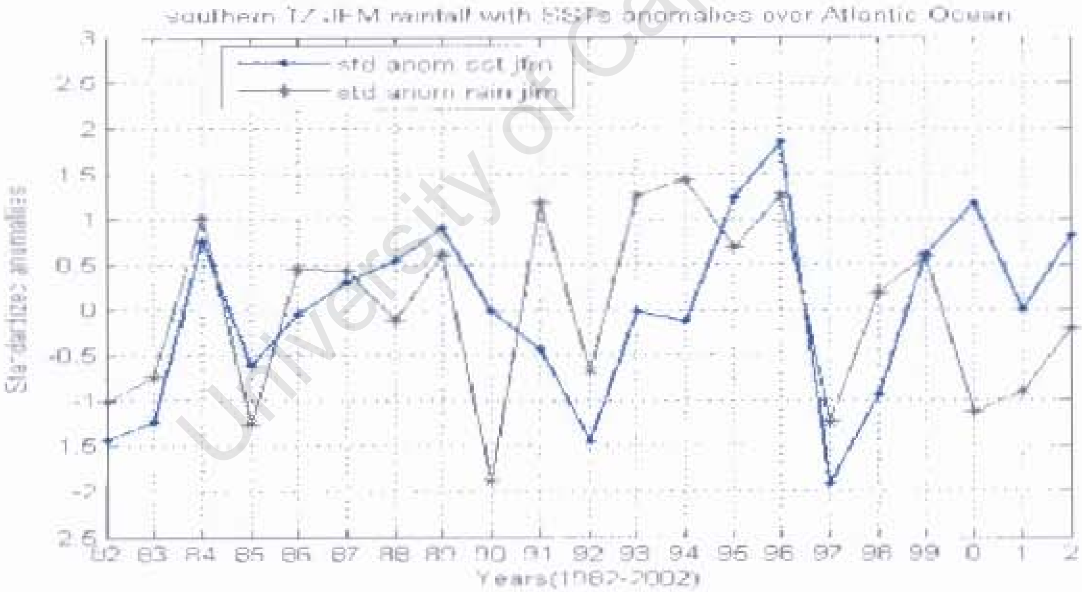
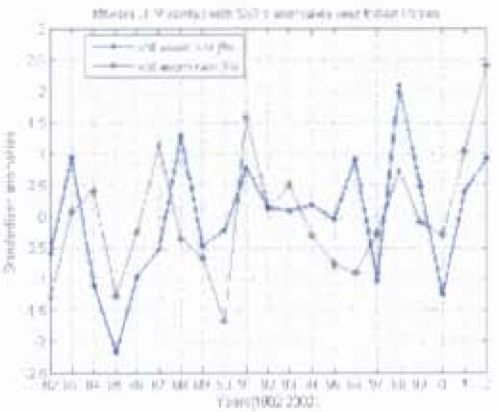


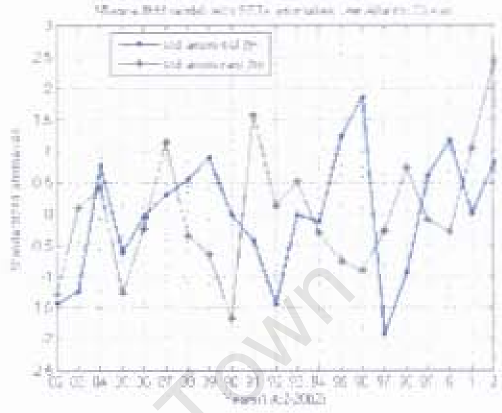
Fig. 5.2.4(a – b): Rainfall composites for southern Tanzania with the SST over the Indian and Atlantic Oceans during the JFM period, where the std anom sst jfm presents the standard anomaly for SST during the JFM period, and std anom rain jfm represents a standard anomaly for rainfall during the JFM period.

Fig. 5.2.4 (c – l): Independent rainfall stations with the SSTs over the Indian and Atlantic Oceans during the JFM period.

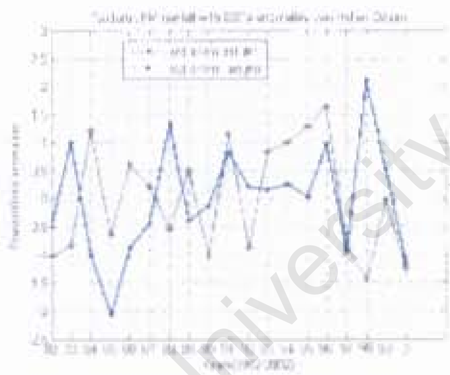
c) Mtwara and Indian Ocean



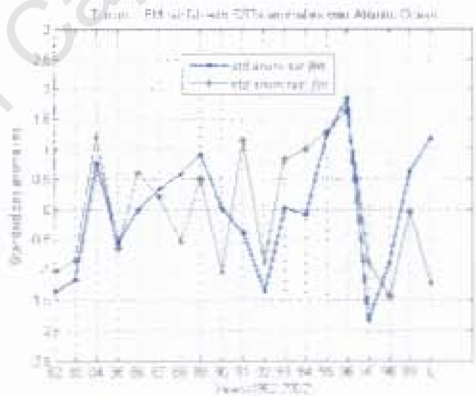
d) Mtwara and Atlantic Ocean



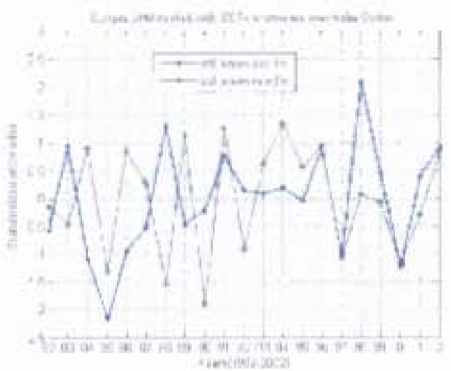
e) Tunduru and Indian Ocean



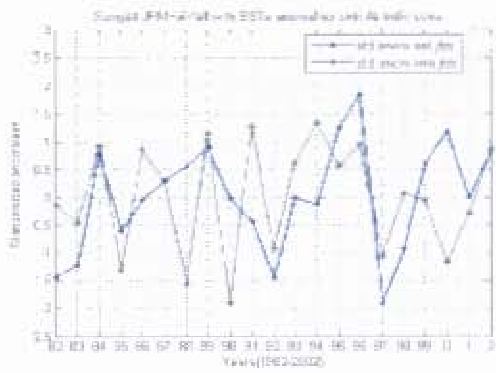
f) Tunduru and Atlantic Ocean



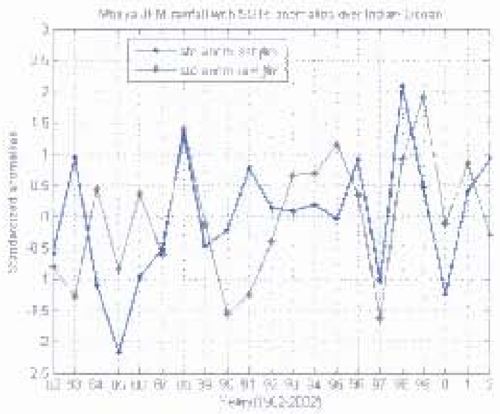
g) Songea and Indian Ocean



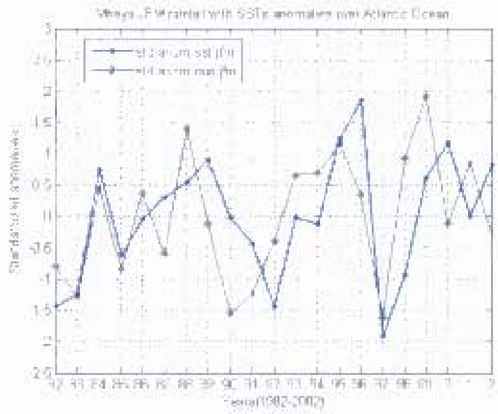
h) Songea and Atlantic Ocean



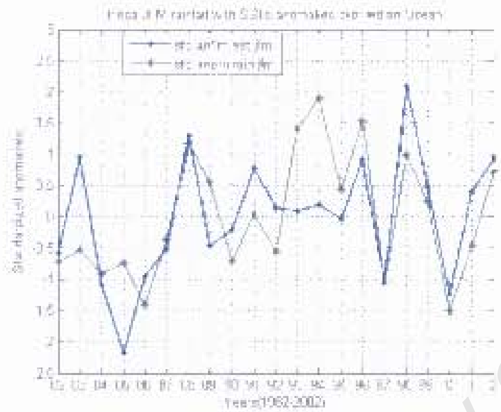
i) Mbeya and Indian Ocean



j) Mbeya and Atlantic Ocean



k) Iringa and Indian Ocean



l) Iringa and Atlantic Ocean

Fig. 5.2.4 (c – l): Continued...

5.3 SST anomalies over the Atlantic and Indian Oceans and the rainfall over southern Tanzania

In the studies of the global atmospheric and oceanic parameters, low-frequency fluctuations in the global climate system have been detected in sea surface temperature (SST), mean sea level pressure (MSLP), and the surface wind fields over both landmasses and oceans (Allan et al, 1995). Over the Indian Ocean, different features were noted. The Indian southwest monsoonal rainfall, the atmospheric circulation patterns, and the relationship between austral summer rainfall in southern and eastern Africa, and the ENSO events are all important.

In an effort of understanding the variability, SST and wind anomalies over the Atlantic and Indian Oceans need to be examined.

In this section the wet and dry years, which were defined on section 5.2.1 above were used to investigate the variability of the ocean and atmosphere.

5.3.1 Wet years

During the 1986/87 season, a positive SST anomaly pattern was observed in the equatorial western Indian Ocean (Fig. 5.3.1a below). The positive SST anomaly was observed along the northern coast of Tanzania, extending southward up to southern Indian Ocean. Patches of negative SST anomalies were observed between the coast of Kenya and Somalia near the equator. Over the southeast Indian Ocean the negative SST anomaly was also observed. These negative SST anomalies along the Kenyan and Somalian coast (Fig. 5.3.1a below) may attributed to upwelling caused by a low level northeasterly, which is dominant during the November - March period (Fig. 5.3.1 b).

Over the Atlantic Ocean a strong positive SST anomaly of above 0.8^0c was observed over the southeast Atlantic Ocean during the same period. Another positive SST anomaly of 0.4^0c was located between latitude 5^0S and 30^0S. A strong negative anomaly situated along the western coast of southern Africa near Angola extending southwards up to Namibian coast. Negative SST anomaly was observed over the northern Atlantic Ocean above the equator and was extending up to 10^0N. The negative SST anomaly was also seen over the southwest Atlantic Ocean between latitude 30^0S and 40^0S.

In figure 5.3.1b, a strong divergence of wind field was observed over northeast of Madagascar, while convergence was observed along the Tanzanian coast. That may have enhanced the inflow of moist easterly air to flow in the southern Tanzania to increase the rainfall there.

In the 1988/89 season, a positive SST anomaly was observed over the entire Indian Ocean, except over the Mozambique Channel (Fig 5.3.1c), where a negative (-0.2^{0}c) SST anomaly extended southwards to the southern Indian Ocean. During the same period, over the Atlantic Ocean, a positive SST anomaly was a dominant, which included a strong positive SST anomaly of above 0.8^{0}c was located over the central Atlantic Ocean (Fig 5.3.1c).

The weak wind field anomaly was observed over northern Madagascar, extended northward, covering the entire country (Fig 5.3.1d). This was reflected in strong convective activities over the region. The moist easterly winds were most likely penetrating into southern Tanzania, enhancing rainfall there.

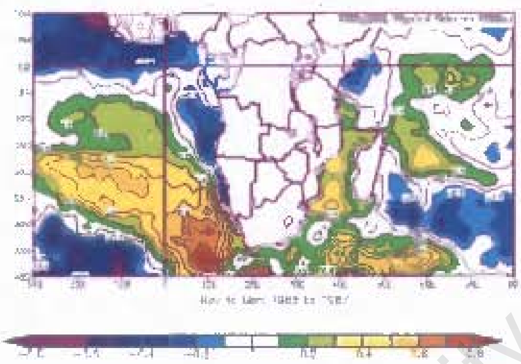
In the 1992/93 season, the positive SST anomalies were observed over the entire southwest Indian Ocean. A positive anomaly exceeding 0.8^{0}c was observed over the central Indian Ocean (Fig.5.3.1e), while a negative SST anomaly of about -0.4^{0}c was observed over the southeast Indian Ocean. Similarly negative anomaly of the same strength was observed over the southeast Atlantic Ocean. Another negative SST anomaly was located near the Angolan Coast, while a positive SST anomaly was observed over the central Atlantic (Fig. 5.3.1e). The weak wind anomaly was dominant along the Tanzanian coast, extending southwards through Mozambique Channel. It has reflected by active convective activity along the southern coast that the moist air was raised enhancing rainfall over southern Tanzania.

In the 1997/98 season, one of the strongest El Niño events, a positive SST anomaly was extending northwards from central Indian Ocean to north western Indian Ocean near the Somalian coast. The negative SST anomaly (-0.4^{0}c) was observed over the southeast Indian Ocean and extended up to the central Atlantic Ocean at about 20^{0}S (Fig. 5.3.1g). Over the northern Atlantic Ocean a strong positive SST anomaly was observed.

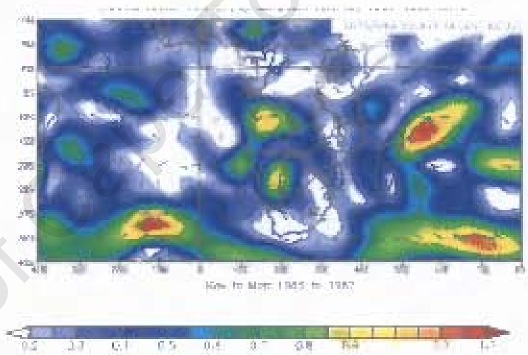
During this season, the entire western Indian Ocean was dominated by a weak wind field, which suggests that the region was under the confluent connective activities.

From the discussion above, one may infer that during the wet years, a weak wind field anomaly is a dominant feature over the western Indian Ocean. It reflects convective activities over that region. The occurrence of negative SST anomalies over the southwest and northwest Indian Ocean may signify the enhancement of the convergence of southeasterly and northeasterly winds as well as the moisture transportation to the region.

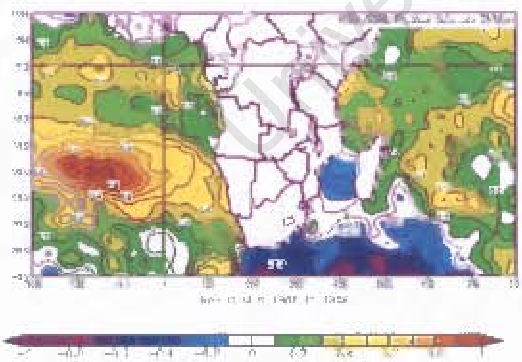
a) SSTs for Nov –Mar, 1986/87



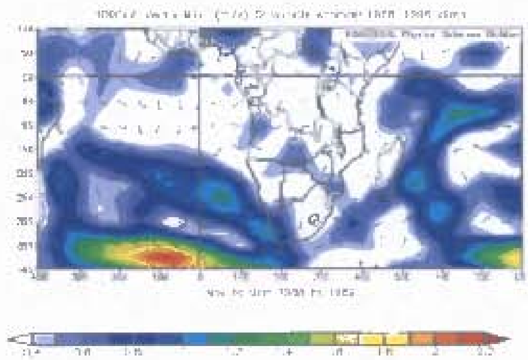
b) Winds for Nov – Mar, 1986/87



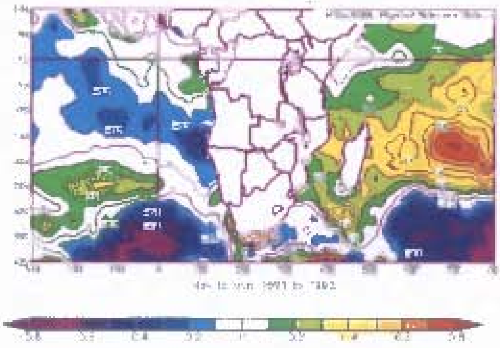
c) SSTs for Nov – Mar, 1988/89



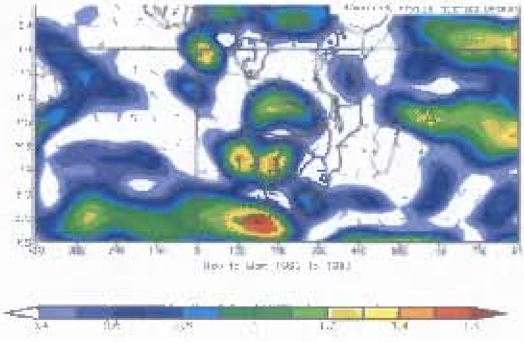
d) Winds for Nov – Mar, 1988/89



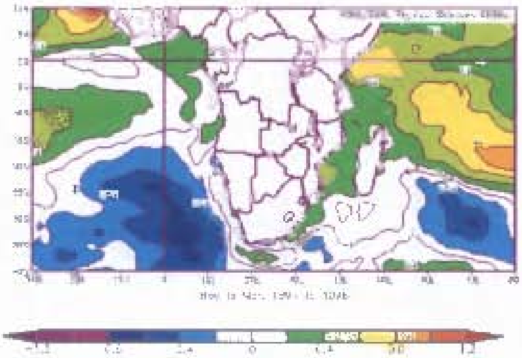
e) SSTs for Nov- Mar. 1992/93



f) Winds for Nov - Mar 1992 /93



g) SSTs for Nov- Mar. 1997/98



h) Winds for Nov –Mar. 1997/98

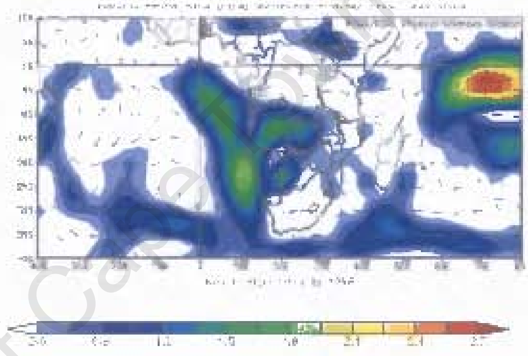


Fig. 5.3.1(a –h): The SSTs and the winds anomalies for the wet years

5.3.2 Dry years.

In 1987/88 season, a positive SST anomaly was observed over most parts of the southwest Indian Ocean, except over the extreme south of the Indian Ocean, where a negative anomaly (-0.4^{0}c) was observed. Over the Atlantic Ocean, a negative SST anomaly was observed along the Angolan coast and southern Atlantic Ocean. The strong positive anomaly of above 0.8^{0}c was located over the southwest Atlantic Ocean (Fig.5.3.2a). This resulted in offshore winds over the west coast of southern Africa, the wind will flow towards the central Atlantic Ocean (Fig. 5.3.2b), causing the reduction wind flow in the southern Tanzania. The divergence wind pattern was dominant over the central Indian Ocean. The winds were advecting, and flowing southwards towards southeast Indian Ocean.

It appears that the subtropical highs were eroded and could not supply enough moisture in the region (Fig. 5.3.2b).

In 1996/97season, positive and negative SST anomaly patterns were dominant over the western Indian Ocean. A negative SST anomaly of -0.3^{0}c was observed along the northern coast of Tanzania, and a strong negative anomaly of about -0.6^{0}c was observed over the southeast Indian Ocean. A weak positive SST (0.3^{0}c) anomaly was observed along the eastern coast of South Africa, and another positive anomaly was located over the central Indian Ocean (Fig 5.3.2 c).

Cyclonic flow was observed over the Angola. One may believe that it has attracted moist air from the southeast Atlantic Ocean and Congo basin. The southeasterly winds from the southeast Indian Ocean were converging along the eastern coast of the South Africa (Fig 5.3.2.d). It has reflected by the dry conditions observed over southern Tanzania, and it was during the La Niña year that rainfall was below average.

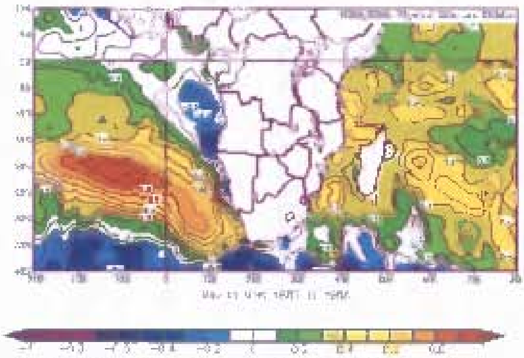
The years 1999/00 (Fig. 5.3.2 e), showed widespread positive SST anomalies over the southwest Indian Ocean extending from the Mozambique Channel passing through the southwest Indian Ocean and then southern cape up to the coast of Angola. The negative anomalies were observed over the central Indian Ocean, and the southwest Atlantic Ocean.

The easterly wind anomaly (Fig 5.3.2f), over northwest of Madagascar, near the Mozambique Channel was diverging resulting in dry condition over southern Tanzania.

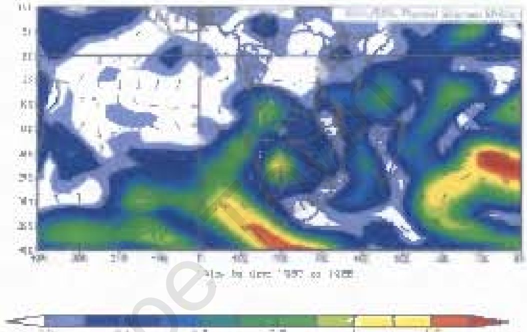
During the 2002/03 period that was El Niño year, a positive SST anomaly was observed over the central Indian Ocean. The positive SSTs were extending westwards towards the western Indian Ocean. A negative anomaly was observed over the southeast Indian Ocean (Fig. 5.3.2g). Over the Atlantic Ocean, a strong positive SST anomaly of about 0.8^{0}c was observed over the southeast Atlantic Ocean, extending to the central and northern Atlantic Ocean (Fig 5.3.2 g).

A strong divergent field was observed over the eastern Madagascar (Fig. 5.3.2h); the southerly winds from the Mozambique Channel were backing to westerly over northern Madagascar. The easterly air flow over southern Tanzania was weak, resulting in dry conditions over southern Tanzania.

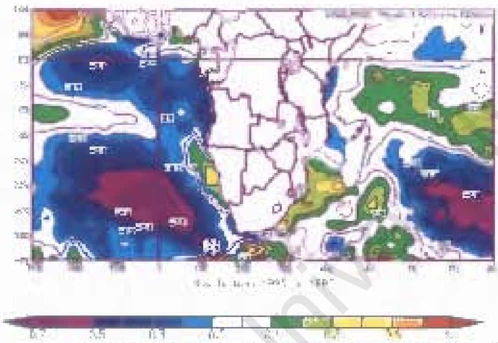
a): SSTs for Nov – Mar, 1987/88



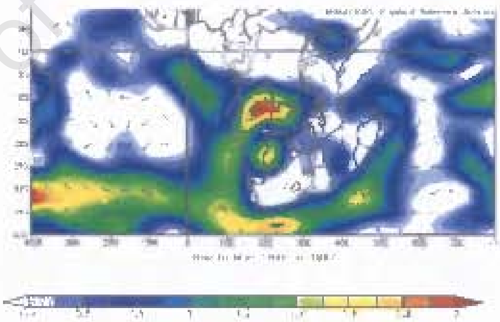
b): Winds for Nov – Mar, 1987/88



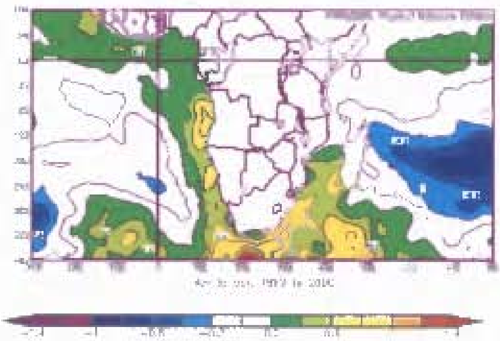
c): SSTs for Nov – Mar, 1996 /97



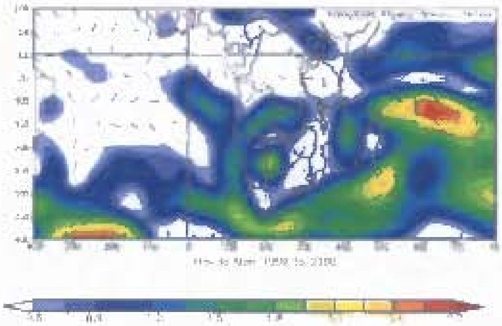
d): SST for Nov – Mar, 1996 /97



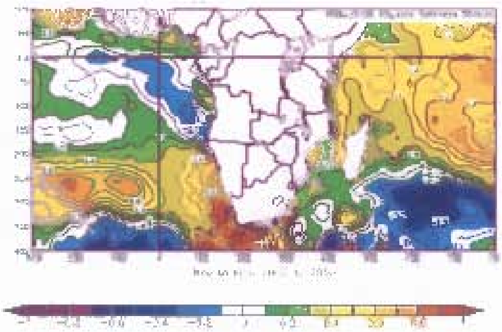
e): SSTs for Nov- Mar, 1999 /00



f): Winds for Nov - Mar 1999 /00



g): SSTs for Nov – Mar, 2002 /03



h): Winds for Nov – Mar, 2002 /03

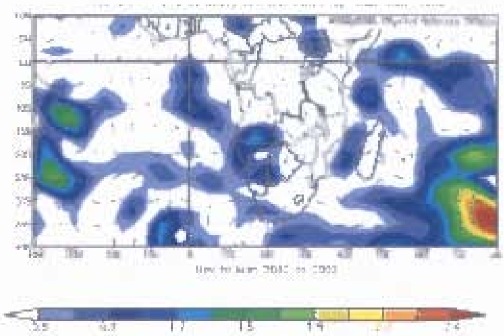


Fig. 5.3.2(a-h): SSTs and winds anomalies for the dry years

5.3.3 Variability of the rainfall and Sea Surface Temperatures

In this section, the interannual variability of the southern Tanzanian rainfall and SST patterns over the NINO3.4 region and the Atlantic and Indian Oceans were discussed.

The seasonal rainfall anomaly was calculated by subtracting the long term mean from the sum of the seasonal rainfall. The long term seasonal mean was obtained by averaging the sum of the rainfall seasons of a given period. A similar procedure was used to calculate the SST anomalies over the Nino3.4 region and the SST index over the Indian Ocean. The seasonal mean of the SST over the NINO3.4 region was obtained by averaging the SST values during the November–March period, while the SST anomaly over the Indian Ocean was averaged over the January-March period. Rainfall for the November-March period was correlated with the SST anomaly over the NINO3.4 region and the January-March rainfall was correlated with the SST anomaly over the Indian Ocean.

The NINO 3.4 region is located in the Pacific Ocean and is found at 5^0S - 5^0N; 170^0W - 120^0W. The International Research Institute for the climate and Society (IRIS) have defined the El Niño conditions as an index of the SST anomalies with the average of the SSTs over the NINO3.4 region exceeding the positive 25% of the cold conditions in the historical distribution. The magnitude of the NINO3.4 anomaly necessary to qualify as the La Niña or El Niño condition is approximately 0.45^{0}C away from the average.

Figure 5.3.3a below shows the annual variation of the SST over the NINO3.4 region for the 1970–2003 periods. From these annual records one can identify the occurrence of the ENSO events. The extremely positive peak of the SSTs corresponds with the warm ENSO years, while the extremely negative peak of the SSTs corresponds with the cold ENSO years. For example a positive peak in 1972/73 corresponded with an El Niño year (warm ENSO), and the negative peak of the 1973/74 in this figure corresponded with a La Nina year (cold ENSO).

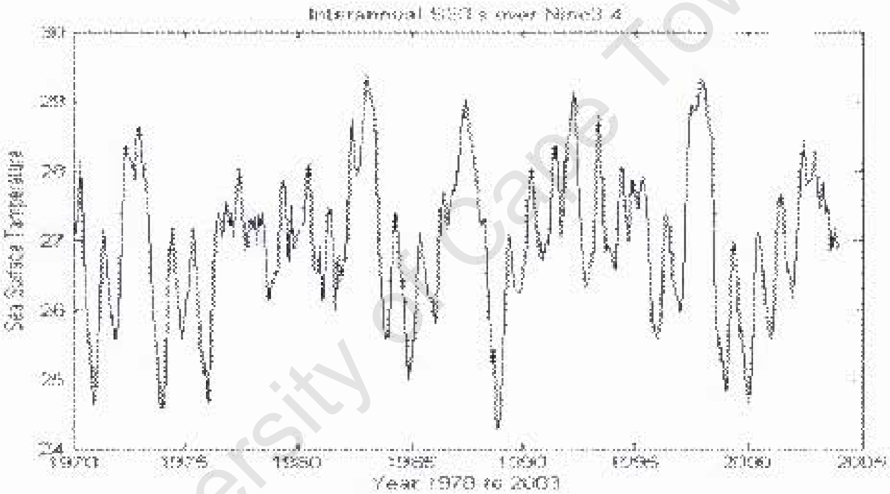


Fig: 5.3.3a Interannual SSTs over the NINO3.4 region. The SSTs are in ^{0}C, and they are annual averaged for the period 1970 – 2003.

The SST anomaly over the Nino3.4 region for the November - March period was correlated with the southern Tanzania rainfall for the period of 1970-2003 (Fig.5.3.3b). The correlations results are given in Table 5.3.3a below and were averaged in 5 yearly bases. From 1970 -1975 the SST over the NINO3.4 region and the southern Tanzanian rainfall was correlated 0.86, while from 1996 – 2003, the correlation was 0.48. A negative correlation of -0.2 was observed during the 1986 –1990 period.

The influence that ENSO events have on rainfall over southern Tanzania is not well defined. Some years the ENSO event may be associated with floods, while other years there are droughts. It should also be noted that some ENSO years have corresponded with the normal rainfall. Therefore one may suggest that it likely that other mechanisms co-exist with the ENSO events to influence the rainfall in the region. Fig.5.3.3b below illustrates the variation of the SSTs in the NINO3.4 region with the rainfall over southern Tanzania for the 1970 – 2003 period.

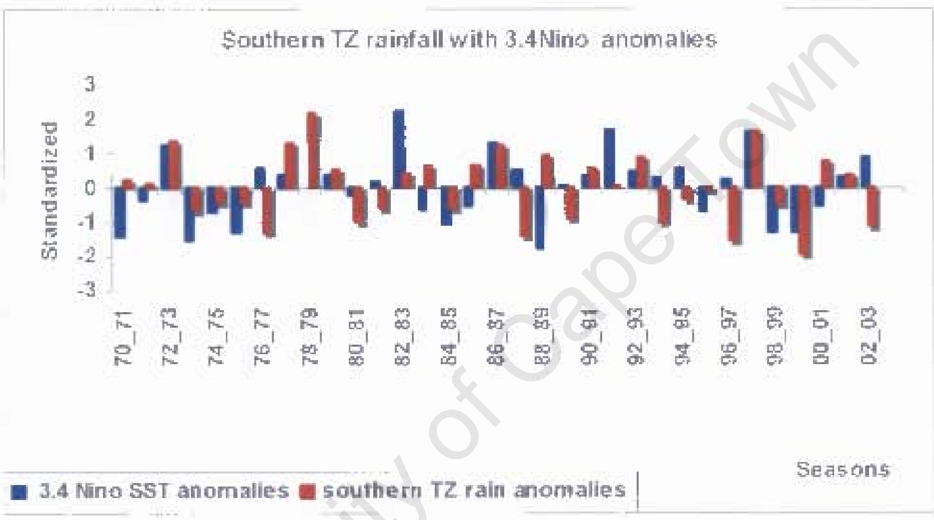


Fig: 5.3.3b: Nino3.4 SSTs and rainfall anomalies over southern Tanzania.

Year	Correlation
1970-1975	0.856791
1976-1980	0.091483
1981-1985	0.360634
1986-1990	-0.1999
1991-1995	0.071014
1996-2003	0.483062

Table 5.3.3a: Shows the correlations of the SSTs over NINO 3.4 region with rainfall over southern Tanzania are shown in the table above.

5.3.4 The influence of the Indian Ocean Zone Dipole Mode on rainfall over southern Tanzania.

The investigation of the changes in the regional climate in response to the Indian Ocean Zone Dipole Mode (IOD) shows more interannual variability with the short rains and a large impact on the society through changes of the regional hydrological cycle. The short rains (October - December) are linked to the ocean-atmospheric variability over the Indian Ocean, which has been correlated with the rainfall over East Africa (Saji *et al.* 1999). One may believe that the rainfall during the January - March period may also be influenced by the IOD, because of the stability of the ocean.

The correlation between the rainfall and the dipole index (Fig: 5.3.3c), shows that some years have good correlations. For example, a strong correlation was observed during 1992 –1996. A negative correlation of -0.8 was observed during 1987 – 1991. This negative correlation someone may link with the 1987/88 El Niño that has resulted in below average rainfall over southern Tanzania. Thus it is suggest that co-existence of the IOD during an El Niño event may have resulted in an increase in the rainfall over East Africa (Saji et al; 1999).

The demonstration of the influence of the IOD on rainfall over southern Tanzania is shown in the graph (Fig. 5.3.3c) below. The "southern TZ rain anom" in the graph represents the rainfall anomaly over southern Tanzania, while the "IOD anom" is the IOD index. Table 5.3.3b below shows the correlation results between southern Tanzanian rainfall and IOD Index, which are computed in 5 years bases.

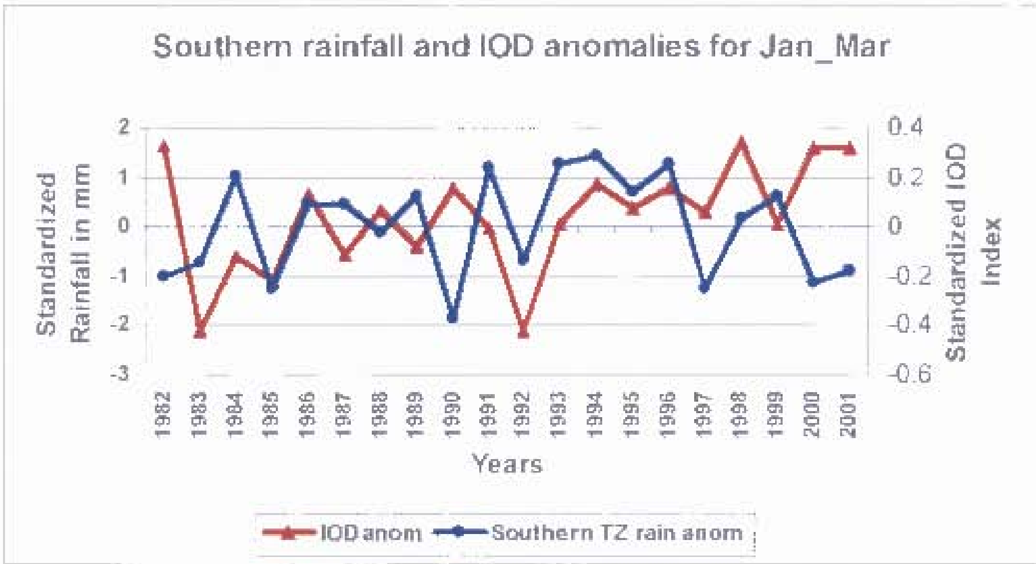


Fig: 5.3.3c: The IOD Index and rainfall anomalies over southern Tanzania.

Year	Correlation
1982_1986	0.077653
1987_1991	-0.79627
1992_1996	0.943755
1997_2000	-0.23617

Table 5.3.3b. IOD index with rainfall correlations

5.4 Derivation of the Onset and Cessation dates of the rainy seasons

In the tropics there is considerable variability in the onset and the cessation dates of the rainy season. The seasonal variation may be caused by the delay of the onset or cessation of the season or vice verse. These fluctuations of the onset and cessation dates may have a negative impact on the growing season and ultimately affects the farming activities in the region. The reliable prediction of the onset dates will greatly assist in farming preparation, selecting suitable varieties of the crops, manpower, using the right equipment and could also reduce the risks involved in planting /sowing too early or too late. Furthermore, knowledge of the onset and cessation dates enables to predict the growing season length.

which is useful for the selection of crop varieties, crop matching and cropping sequences. This ensures maximum and sustainable agricultural productivity, as well as efficient water resource management.

Prediction of the onset and cessation dates for the rainy season in the tropics is a very challenging task, because of the irregularities in rainfall distribution. A variety of methods have been proposed for the prediction of the onset and cessation dates, with the most common based only on the rainfall data (Ilesanmi, 1972; Obasi and Adefolalu, 1977; Stern *et al.* 1982; Fasheum, 1983; Alusa and Gwange, 1978; Mhita and Nassib, 1987; Mhita and Venäläinen, 1992; Kijazi and Reason, 2005). Other schemes are based on other parameters such as upper level winds (e.g. Beer *et al.* 1977; Omotosho, 1992). Omotosho *et al.* (2000) attempted to predict the onset and cessation dates of the rainy seasons over West Africa using potential temperature. Marengo *et al.* (2001) used the sea surface temperature anomalies from the tropical Atlantic and Pacific Oceans with the rainfall from the central and northern Amazon to determine the onset/cessation dates over the Amazon basin Brazili. Kousky (1998) attempted to define the onset of the Amazon basin rainfall using the satellite Outgoing Long wave Radiation (OLR) measurements.

A few authors have also looked at alternative definitions for the onset of the rainy season. Joliffe and Sarrica-Dodd, (1994) attempted to describe the onset and cessation dates over West Africa using the rainfall data. Their method was based on discriminate analysis using data of the current season to determine the onset and cessation dates. Similar attempts were made over East Africa by Ilesanmi, (1972); Obasi and Adeolalu, (1977); Alusa and Mushi (1973). These authors defined the onset and cessation dates of the rainy season of East African using cumulative rainfall plots. The onset was defined as the first pentad whose rainfall exceeded 1/73 of the mean annual rainfall. Asnani (1993) had defined the mean onset and cessation using maps based on the pentad rainfall distribution.

In Tanzania, Mhita and Nassib, (1987) defined the onset as the first week during the OND period to receive at least 15 mm of rainfall. This definition was mainly based on bimodal areas and failed to indicate whether the onset/cessation dates display a similar scenario across East Africa (Okoola, 1999). More recently, Kijazi and Reason, (2005) attempted to define the onset over unimodal and bimodal areas. These authors used two separate definitions to define the onset for the OND and MAM seasons. For the OND periods, the onset was defined as the rainfall of 5 days (a pentad) exceeding 7.5 mm followed by three consecutive pentads of the rainfall amounts of not less than 5mm per pentad. For the MAM period, the onset was considered as the pentad when the rainfall exceeds 10mm followed by three consecutive pentads with the rainfall amounts of not less than 10 mm per pentad. However, these definitions are also based on bimodal areas, so caution is advised when using them.

The rainfall pattern over southern Tanzania is of a unimodal type (Fig.3.1). In this study, the dry spells have also been considered, while the premature onset dates were discarded to avoid the possibility of them being misleading with the actual systems of the rainy season. However, not much work has been done on defining the onset and cessation dates over southern Tanzania, and therefore the robustness of this definition needs to be tested. For the purpose of this research the definition of the onset and cessation dates of the rainy season as well as the spells are defined as:

Onset date:

- When the rainfall total of one pentad has reached 15.00 mm or more, followed by no dry spell exceeding 3 pentads in the next 30 days.

Cessation date:

- If the total rainfall of one pentad from the month of April is less than 10 mm for three consecutive pentads, then the season is considered to have ended, as from the preceding pentad.

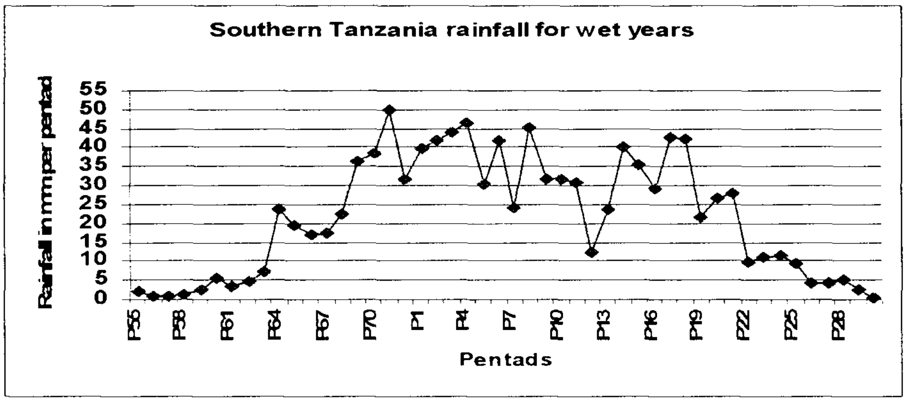
Spells:

- The dry spell is a period of one pentad (5days) that has received rainfall less than 10.0mm
- The wet spell is a period of one pentad (5days) that has received rainfall of 10.0mm or more.

5.4.1 Onset and cessation dates of the wet and dry years

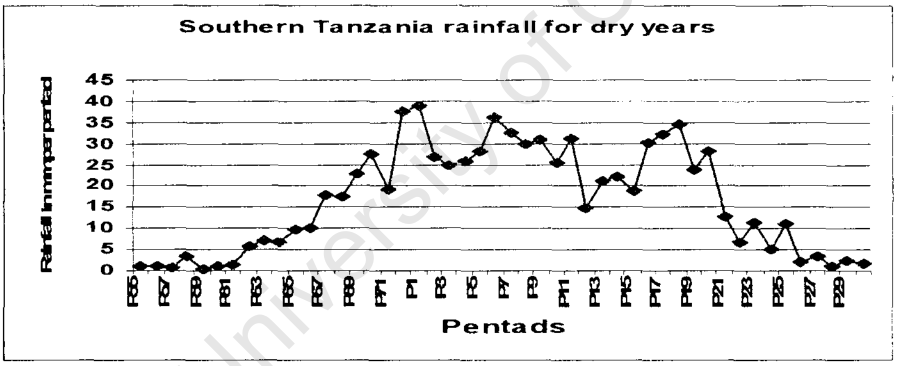
The rainfall in the southern Tanzania is highly variable on the spatial and temporal scale, which makes farming difficult. The farming communities rely heavily in rain fed, and are therefore vulnerable to the impact of rainfall variability, posing challenges for food security and planning (Vogel and O'Brien, 2003). In this region, the rainfall typically starts with a light intensity with the dry spells, where the rainfall amount received would be less than 10mm per pentad (see Fig.5.4.1a below). You may find continuous good intensity rain during pentad 63 and 65, which corresponds with days 12^{th} -16^{th} and 22^{nd} – 26^{th} of November (appendix.1). The minimum rainfall for all stations is during the pentad 12, which corresponds with the last pentad of February (day 26^{th} February - 1^{st} March; Fig.3.1 above). It is also observed that maximum rainfall received in different dates. For example, Songea and Tunduru stations attained their maximum rainfall in pentad one (1^{st} pentad of January), followed by Iringa, which received its maximum rainfall during the pentad 3 (3^{rd} pentad of January). Mbeya rainfall showed its maximum during pentad 9 (11^{th} – 15^{th} of February), while Mtwara which is on the southern coast of Tanzania, received its maximum rainfall during the pentad 18, the last pentad of March (27^{th} March – 1^{st} April; Fig.3.1). Mtwara station also had the longest seasonal length in the region.

a) The wet years for rainfall composite over southern Tanzania.



Fi. 5.4.1a was used to define the onset and cessation dates for the wet years and found that the mean onset date is during the fourth pentad of November (pentad 64). The region has a mean wet spell of 32 pentads. The mean seasonal length of 33 pentads was observed. The mean cessation is on the first pentad of May (pentad 25).

b) The dry years for the rainfall composite over southern Tanzania



The onset and cessation dates for the dry years were defined using Fig.5.4.1b. The mean onset of the rainy season for the dry years was during the first pentad of December (pentad 67). The cessation date is during the last pentad of April (pentad 24).The mean seasonal length of 31 pentads was found for the dry years, while the mean wet spell is 29 pentads. It is observed that the dry years have less intensity rainfall compared to the wet years.

The earliest onset date for wet years is in the last pentad of October (pentad 60), while the latest onset date is in the third pentad of December (pentad 69).The earliest cessation date is in the second pentad of April (pentad 20) and delayed ending date is in the third pentad of May (pentad 27).

The dry years have the earliest onset date, which in the third pentad of November (pentad 63), while the latest onset date is on the first pentad of January (1^{st} – 5^{th} January). The earliest ending date for the dry years was during the first pentad of April (pentad 20), and the delayed cessation date is during the second pentad of May (pentad 26). The analyses for those individual stations are in appendix 2.

CHAPTER 6

Summary and Conclusion

This research has investigated the influence of sea surface temperatures (SSTs) of the surrounding oceans on rainfall variability over southern Tanzania. It has been observed that ocean SST variability may influence rainfall variability over the region. The Indian Ocean is known to modulate the mesoscale circulations and synoptic systems found in the region. Warming or cooling over the Indian Ocean may interact with these systems to then alter rainfall patterns over southern Tanzania.

Southern Tanzania has a unimodal type of rainfall pattern, which is predominantly influenced by the zonal arm of the ITCZ. The rainfall starts around mid November and ends around the end of April. The easterly air flow from northern Madagascar and the south-easterly air flow from the Mozambique Channel are the dominant flows, which are responsible for moisture transportation into southern Tanzania. It appears that the ITCZ is the major mechanism of the rainfall production over the region.

The relationship of the SSTs over the Indian and Atlantic oceans with rainfall over southern Tanzania was studied. The results demonstrate the relationship between the SST and the rainfall of southern Tanzania during the JFM and OND periods. It has been observed that during the JFM period southern Tanzania rainfall is more significantly related to the SSTs over both Indian and Atlantic Oceans. Rainfall is not significantly related to SST over the both oceans during the OND period. It has been observed that only negative relation with variation of the SST over the north equatorial Atlantic Ocean during the OND periods.

The interannual and longer term variability of the SST in this region is associated with the ENSO variability. The warm ENSO events generate SSTs higher than usual over the western Indian Ocean and the latter is believed to be associated with greater coastal rainfall during the short rainy seasons (October - December). In recent years, it has been observed that the ENSO events may influence rainfall variability over most parts of the region.

It has been observed that the ENSO events may be associated with the rainfall variability over southern Tanzania, although the relationship is not well defined. It has been shown that during the El Niño events (warm ENSO), floods may occur as well as droughts. Similar effects have been observed with the La Niña events (cold ENSO). It has been believed that there is other existing mode, which has relation with the rainfall variability in the Indian Ocean and that mode is the Indian Ocean zone dipole mode (IOD). The IOD has been observed to have an influence on the rainfall over the region. It has been observed that some years do correlate well with rainfall over southern Tanzania, and some other years do not. The link of the ENSO and the IOD on rainfall variability over this region is not well understood, studying their relationship is important that may help to improve the seasonal rainfall prediction over the region.

Circulation patterns during the JFM rainfall period shows that moisture fluxes that originate from the northwest Indian Ocean (northeasterly monsoon flow) and that from the southeast Indian Ocean, flow through the Mozambique Channel (southeasterly trade flow) to pick up warm moisture to converge over the zonal arm of the ITCZ. That may enhance the rainfall activities over southern Tanzania. The trade easterly flow through northern Madagascar becomes a dominant flow over southern Tanzania during this period.

The effectiveness of wind circulation strongly depends on the intensification of the cyclonic flow over southern Angola and northern Namibia. The southeasterly flow from the southeast Atlantic and the northwesterly air flow from the north equatorial Atlantic would flow over the Congo basin to pick up more moisture and then converge into the meridional arm of the ITCZ. The southeasterly flow from the southwest Indian Ocean and easterly flow from northern Madagascar are prominent flows, which converge along the zonal arm of the ITCZ.

The ITCZ plays a significant role in the JFM rainfall period over southern Tanzania. The weak inflow of moisture prevails during the OND rainy season when the ITCZ is more active over the northern part of the country. During the JFM period, the ITCZ is well located over the Southern Hemisphere, its effectiveness results in a rainfall increase over southern Tanzania. That's the time when the tropical easterly jet dominates the circulation in the upper levels over low latitudes of southern Africa, while the subtropical westerly jet apparently lies at latitude 25^0S.

During the wet years, a weak wind field anomaly is a dominant feature over the western Indian Ocean. It reflects convective activities over that region. The occurrence of negative SST anomalies over the southwest and northwest Indian Ocean may signify the enhancement of the convergence of southeasterly and northeasterly winds as well as the moisture transportation to the region.

During the dry season, the strong positive SST anomaly would become dominant over the southwest Atlantic Ocean, and the strong negative SST would appear along the coast of Angola and southern Atlantic Ocean. That will result in offshore winds over the west coast of southern Africa; the winds will flow towards the central Atlantic Ocean resulting in the reduction of wind flow in southern Tanzania.

The existence of a strong negative SST anomaly over the southeast Indian Ocean and positive SST anomaly along the eastern coast of South Africa, imply the southeasterly winds from the southeast Indian Ocean will converge along the eastern coast of South Africa resulting in dry conditions in the southern Tanzania.

During the OND, the cyclonic flow over southern Angola, and the easterly flow over the southwest Indian Ocean are relatively weak. The position of the anticyclone over the southern Indian Ocean favours the onset of the short rains over the north eastern highlands and the northern coast. The rainy season over southern Tanzania starts in mid November. You may find continuous rain during the pentad 63 and 65, which corresponds with days 12^{th} – 16^{th} and 22^{nd} – 26^{th} of November.

This study shows that the mean onset date for wet season was in the fourth pentad of November (pentad 64), and the mean cessation date was on the first pentad of May (pentad 25). The mean wet spell was 32 pentads with the mean seasonal length of 33 pentads.

For dry years, the mean onset date is during the first pentad of December (pentad 67). Its mean cessation date is in the last pentad of April (pentad 24). The mean seasonal length was found to be 31 pentads, and dry years have wet spell of 29 pentads. The rainfall will have less intensity with short seasonal rainfall length.

The JFM rainfall intensifies over southern Tanzania is when the low-level cyclonic circulation over Angola strengthens, and the anticyclonic flow over the southern Indian Ocean shifts further south, to allow the easterlies air from the central Indian Ocean to flow over southern Tanzania. The intensification of the cyclonic flow over southern Angola results in the tropical easterly jet becoming dominant at the upper level, when the mean vertical becomes important and is associated with the Walker circulation (Kijazi and Reason, 2005).

The lower and upper levels show that the ascending branch of the Walker circulation is located over northern Australia and Indonesia during the DJF with the descent over the eastern Pacific. In the African region, relatively weak ascent occurs over the western Indian Ocean and eastern Africa with subsiding motion over the southeast Atlantic and western southern Africa.

The cyclonic flows over the ocean are very important. The cyclonic flow over the southeast Atlantic Ocean may intensify together with the ascending limb of the Walker circulation over Angola to weaken the southeasterly air flow from the southwest Indian Ocean and northwesterly air flow from the northern Atlantic Ocean. The southeasterly wind would flow through Zambia and converge over Angola, and also the northwesterly air would flow towards Angola allowing little moisture to converge along the meridional arm of the ITCZ, resulting in dry conditions over western and southern Tanzania. Similarly, if the cyclonic flow over the central Indian Ocean occurs, the moist air would deflect along the southern coast. The offshore winds would result in dry conditions over the region.

The subtropical anticyclonic cells become important on moisture supply for the effectiveness of the ITCZ. The southeasterly wind from the subtropical region would bring moist air over southern Tanzania to enhance rainfall activities during the JFM period.

Weather systems such as tropical cyclones have great influence on the rainfall distribution over the southern coast of Tanzania (Mtwara and Lindi) and its surroundings. For example during the 26 - 27 March 1978, Mtwara station recorded a rainfall total of about 453.5 mm on two days (appendix. 3c). On the 26th, Mtwara recorded 232.7 mm, and on the following day 210.8 mm of rainfall was recorded. This rainfall was associated with the tropical depression situated over the central Indian Ocean, which did not develop into a tropical cyclone. The subtropical anticyclone located over the southern Indian Ocean was anomalously intense. This led to moist southeasterly and northeasterly backing over the southern coast and later convergence over northern Madagascar (appendix 2). The curvature of wind backing might have released the latent heat energy leading to enhancement of the convective activities, hence resulting in the excessive rainfall over the southern coast.

Southern Tanzania is among one of the most productive regions in the country. The region is vulnerable to the impacts of rainfall variability. Small differences in the timing of the rain may determine the success or failure of the season's crops, which will then have an impact on the national economy. This study has tried to depict some precursors that contribute to the rainfall variations. It is evident that more work is needed to gain an understanding of the climate variations over southern Tanzania on a seasonal timescale that may improve seasonal forecasting over the region. Ultimately, this may contribute, and hopefully bring economic benefit to farming, water management and decision makers.

Appendix

Appendix1: Calendar of months and Pentads.

Date	Pentad	Date	Pentad
01-05Jan	1	07-11Aug	44
06-10Jan	2	12-16Aug	45
11-15Jan	3	17-21Aug	46
16-20Jan	4	27-01Sep	48
21-25Jan	5	02-06Sep	49
26-31Jan	6	07-11Sep	50
01-05Feb	7	12-16Sep	51
06-10Feb	8	17-21Sep	52
11-15Feb	9	22-26Sep	53
16-20Feb	10	27-01Oct	54
21-25Feb	11	02-06Oct	55
26-01Mar	12	07-11Oct	56
02-06Mar	13	12-16Oct	57
07-11Mar	14	17-21Oct	58
12-16Mar	15	22-26Oct	59
17-21Mar	16	27-01Nov	60
22-26Mar	17	02-06Nov	61
27-01Apr	18	07-11Nov	62
02-06Apr	19	12-16Nov	63
07-11Apr	20	17-21Nov	64
12-16Aprl	21	22-26Nov	65
17-21Apr	22	27-01Dec	66
22-26Aprl	23	02-06Dec	67
27-01May	24	07-11Dec	68
02-06May	25	12-16Dec	69
07-11May	26	17-21Dec	70
12-16May	27	22-26Dec	71
17-21Mar	28	27-31Dec	72
22-26Mar	29		
27-01Jun	30		
02-06Jun	31		
07-11Jun	32		
12-16Jun	33		
17-21Jun	34		
22-26Jun	35		
27-01Jul	36		
02-06Jul	37		
07-11Jul	38		
12-16Jul	39		
17-21Jul	40		
22-26Jul	41		
27-01Aug	42		
02-06Aug	43		

Appendix 2(a-f): Wet and dry years for southern Tanzania

a): Southern Tanzania rainfall seasons

Wet year	1972/73	1977/78	1978/79	1986/87	1988/89	1992/93	1997/98
Dry year	1976/77	1980/81	1987/88	1989/90	1993/94	1996/97	1999/00
	2002/03						

b): Mtwara rainfall seasons

Wet year	1972/73	1977/78	1978/79	1982/83	1986/87	1990/91	1991/92
	2001/02						
Dry year	1976/77	1980/81	1987/88	1993/94	1994/95	1995/96	1996/97
	1999/00						

c): Tunduru rainfall seasons

Wet year	1970/71	1977/78	1983/84	1985/86	1986/87	1988/89	1990/91
	1992/93	1994/95	1995/96				
Dry year	1973/74	1974/75	1982/83	1987/88	1989/90	1991/92	1996/97
	1998/99	1999/00					

d): Songea rainfall seasons

Wet year	1972/73	1977/78	1978/79	1979/80	1982/83	1988/89	
Dry year	1976/77	1984/85	1987/88	1989/90	1991/92	1996/97	1999/00

e): Mbeya rainfall seasons

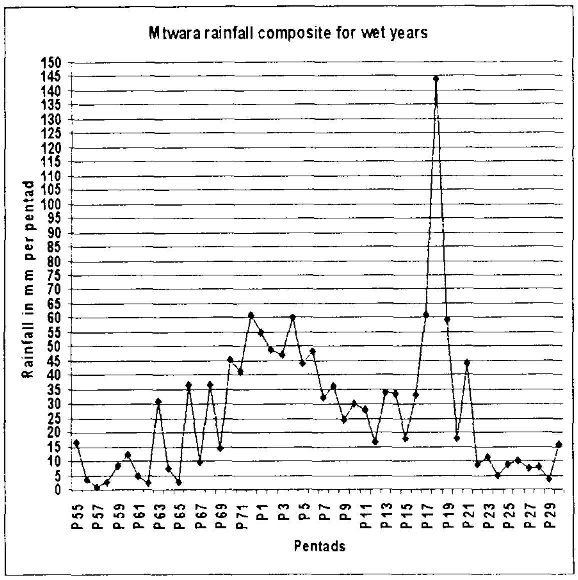
Wet year	1970/71	1978/79	1985/86	1997/98	1998/99	2000/01	
Dry year	1973/74	1976/77	1980/81	1981/82	1990/91	1993/94	1999/00
	2002/03						

f): Iringa rainfall seasons

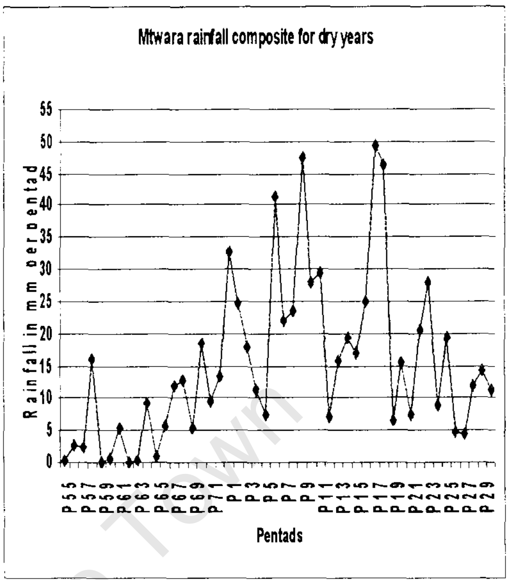
Wet year	1971/72	1974/75	1977/78	1982/83	1997/98	2001/02	
Dry year	1970/71	1981/82	1985/86	1991/92	1996/97	1998/99	1999/00

Time series of station rainfall

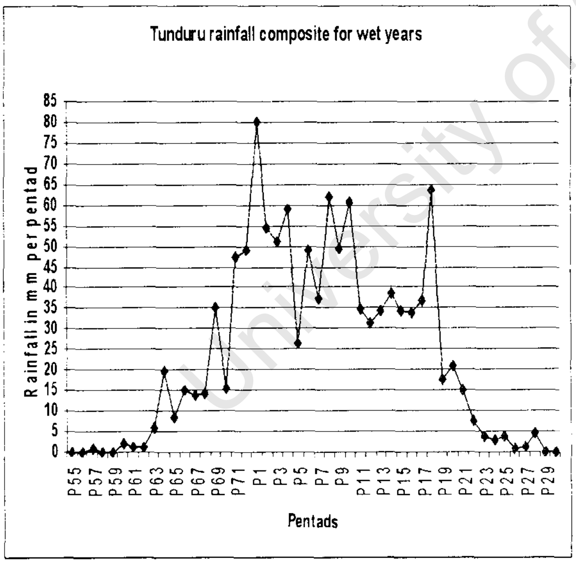
a): Mtwara wet years



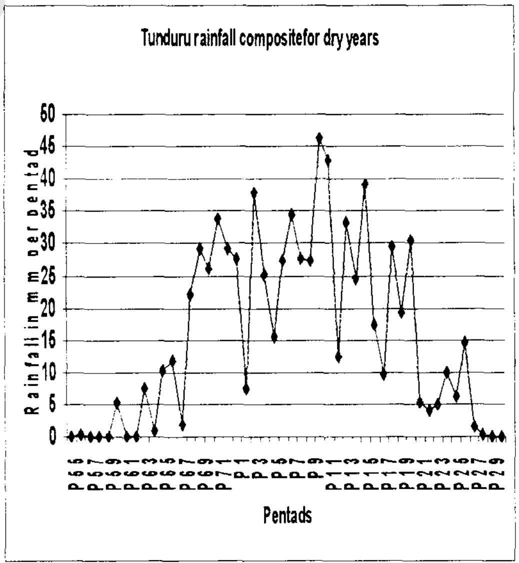
b): Mtwara dry years



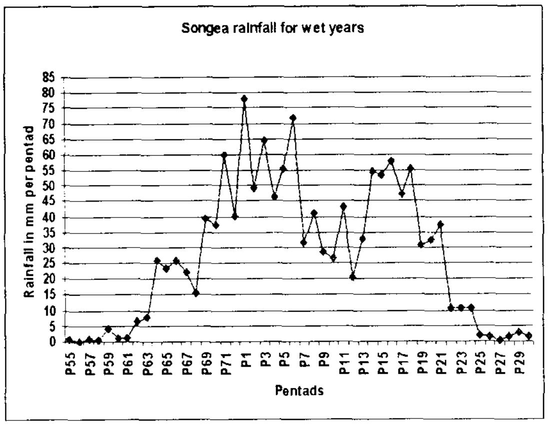
c): Tunduru wet years



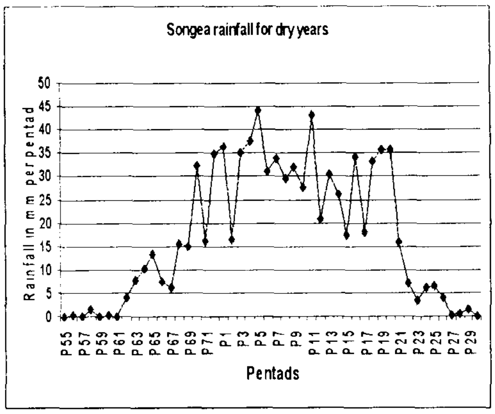
d): Tunduru dry years



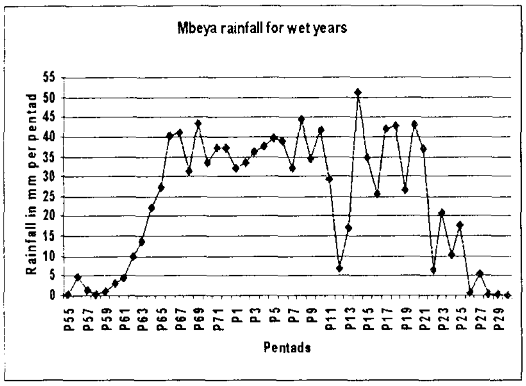
e): Songea wet years



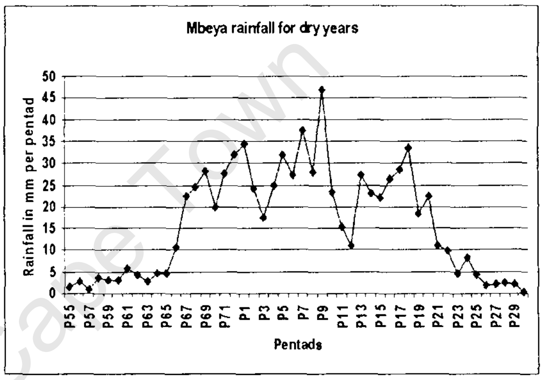
f): Songea dry years



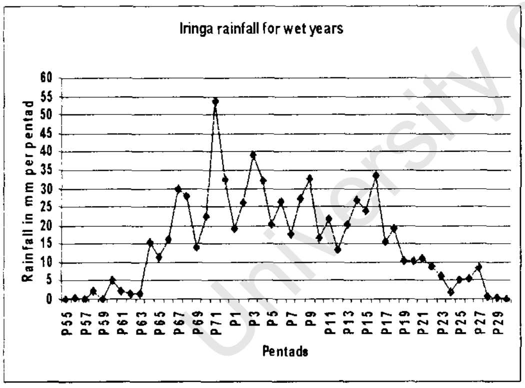
g): Mbeya wet years



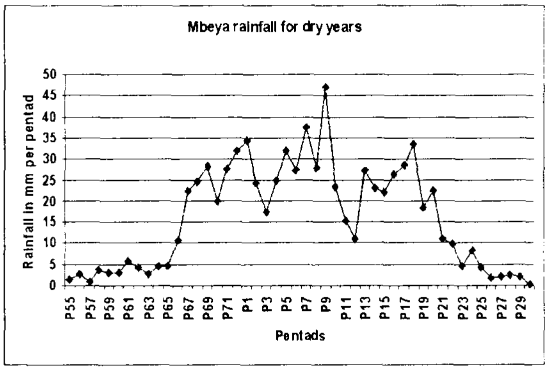
h): Mbeya dry years



i): Iringa wet years



j): Iringa dry years



Appendix3 (a-j) above shows the station rainfall time series, computed using rainfall data for the period of 1970-2003 and the rainfalls are in mm per pentad. The graphs were used to define the onset and cessation dates, seasonal length and the wet spells for the independent stations.

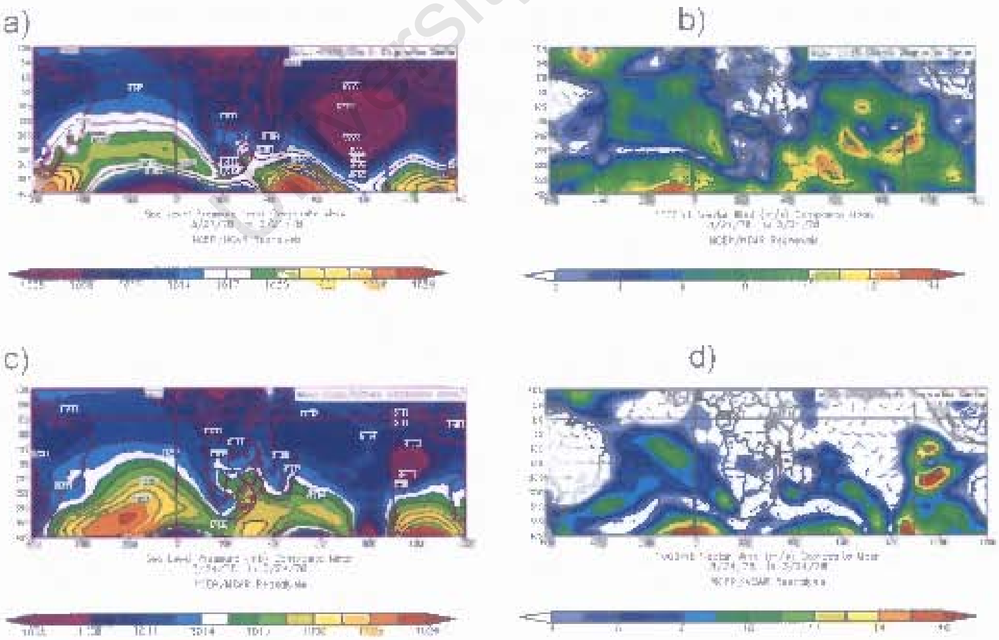
k): Onset dates and Cessation dates for wet years

Station	Onset date (pentad)	Cessation date (panted)	Seasonal length (pentad)	Wet spells (pentad)
Mtwara	63	26	36	31
Tunduru	68	21	26	19
Songea	64	22	31	25
Mbeya	63	25	36	34
Iringa	64	22	30	30

l): Onset dates and Cessation dates for wet years

Station	Onset date (pentad)	Cessation date (pentad)	Seasonal length (pentad)	Wet spells (pentad)
Mtwara	70	26	29	16
Tunduru	68	20	25	23
Songea	65	21	27	27
Mbeya	67	22	29	29
Iringa	67	21	28	28

The Appendix 3(k –l) are the tables of the wet years and dry years respectively. The table contains the onset dates, cessation dates, wet spells and the seasonal length for the separate stations over the region.



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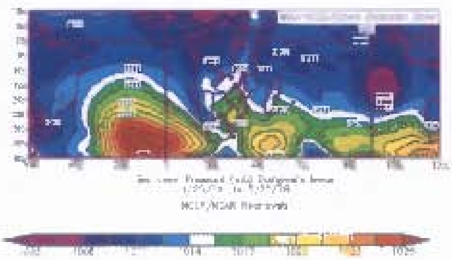

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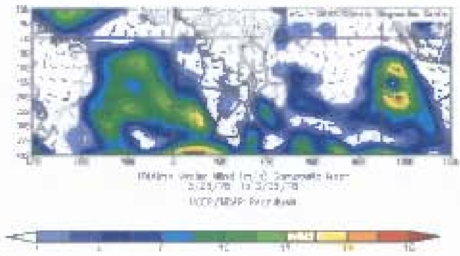

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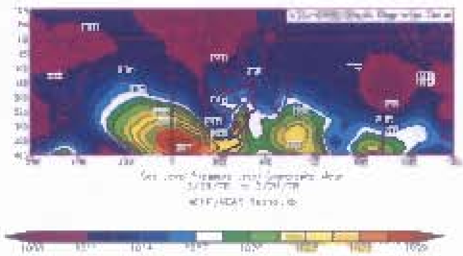
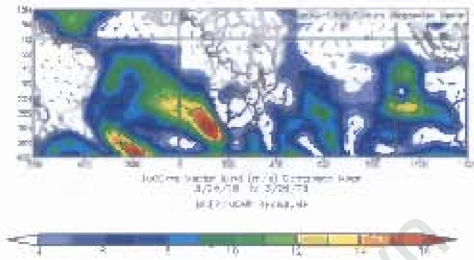


h)



Appendix 4 (a – h) of tropical depression of the 1978 observed over the Indian Ocean, which caused excessive rainfall over Mtwara and adjacent stations. The depression occurred on 21st. By 26th and 27th March 1978 it had intensified causing excessive rainfalls over Mtwara for two consecutive days.

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